A STUDY OF ISOTOPIC COMPOSITION OF XYLEM WATER OF WOODY VEGETATION AND GROUNDWATER ALONG A PRECIPITATION GRADIENT IN NAMIBIA

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Abstract

An understanding of the water used by vegetation in water limited environment is critical to fully understand water relations of natural areas with vegetation. Such information can be integrated in water management plans to estimate the influence of groundwater abstraction on the vegetation. Trees and shrubs are able to access water from: the upper unsaturated soil profile, the capillary zone of a groundwater store, from nearby streams and rivers. Previous studies have proven that uptake of water by roots is not associated with isotope fractionation. Stable isotope ratios of oxygen and hydrogen were analyzed in groundwater, surface water and plant xylem water. Groundwater samples from the north east part of the country (Enyana and Fair constantia) were most depleted, while samples from the southern part (Guruchas) were enriched. A very weak negative correlation (R^2=0.07), statistically insignificant ($P>0.05$) relationship has been noted between $\delta^{18}O$ values of precipitation and altitude. The estimated depletion rate was 1.3‰ $\delta^{18}O$ per km. The correlation between distance from the coast and $\delta^{18}O$ composition of precipitation was negatively weak (R^2=0.29) and statistically significant ($P<0.05$) with an estimated depletion rate of 0.31 ‰ per 100 km inland. The correlation between longitude and $\delta^{18}O$ composition of precipitation was very weak (R^2=0.016) and statistically insignificant ($P>0.05$) at roughly 0.09‰ $\delta^{18}O$ depletion per degree. A strong negative correlation (R^2=0.64) existed between $\delta^{18}O$ of precipitation and latitude and it was statistically insignificant ($P>0.005$). The observed high variability in $\delta^{18}O$ and $\delta^{2}H$ values of groundwater at different sampling sites was attributed mainly to continental, elevation and amount effect. Both groundwater and xylem water samples plotted below the GMWL, however plant xylem were more depleted in comparison to groundwater. Throughout all the sampling sites there was a considerable variation in average isotope ratio of xylem water of different species examined, but there were still noticeable patterns regarding their main water source. The results displayed that *P. juliflora*, *A. hebeclada* and *V. erioloba* relied mainly on soil water for transpiration. *S. mellifera* mostly utilized a mixture of groundwater and soil water while *B. albitrunca*, *C. mopane*, C. *imberbe* and *T. sericea* and *R. trichotomum* predominantly utilized groundwater. The water uptake pattern is highly attributed to the rooting morphology. These vegetation uptake groundwater and soil water in a hierarchical manner at different depths to avoid competition between species.

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DECLARATIONS

I, Cristofina M. Kanyama, declare hereby 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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Cristofina M. Kanyama Date

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CHAPTER 1

1. Introduction

1.1 Overview

Namibia Savanna ecosystem covers approximately 64% of the country. In this ecosystem encroaching and non-encroaching woody species coexist due to vertical partitioning of source water (Rossato et al., 2014). The study focuses on determining the sources of water uptake of woody savanna vegetation along Namibia's precipitation gradient in order to evaluate the water use strategy of these plants along a precipitation gradient. This helps in achieving an understanding on hydrogeological processes such as groundwater recharge and water use by woody vegetation. Natural woody vegetations in arid and semi-arid regions are under stress owing to lack of water and/or excess salt, therefore to balance water resources for these vegetation and agriculture it is important to have knowledge on water source transpired by natural vegetation (Brunel et al, 1995).

Trees and shrubs are able to access water from the upper unsaturated soil profile, the capillary zone of a groundwater store, or when growing sufficiently close, from nearby streams and rivers (Eamus, 2006). Stable isotope methods have recently emerged as one of the more powerful tools for advancing understanding of relationships between plants and their environment (Dawson et al., 2002). It has been used as a tool for understanding processes in plants such as water use, water source, and response to different types of water sources, water utilization processes, water use efficiency and the ability to adopt in arid environments (Yang et al., 2010).

The plant water source can be determined by analyzing and comparing stable isotope ratios of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ in water from plant xylem to potential water sources in the respective focal study areas. This method emanated from findings by Zimmermann et al. (1967) that uptake of water by roots is not associated with isotope fractionation, therefore the stable isotopic composition of plant xylem water represents a mixture of water from different water sources acquired by all functional roots. This assumption may only be correct for $\delta^{18}O$ as recent research has shown that in arid environments such as at my study site there may be some fractionation of the hydrogen isotope while the oxygen isotope ratios of soil water remain unchanged (Schachtschneider and February, 2013).

1.1.1 Stable isotopes in the hydrological cycle

The ^{16}O, ^{17}O, ^{18}O, ^{1}H and ^{2}H are the stable isotopes that make up the water molecule. These isotopes of oxygen and hydrogen do not undergo radioactive decay and are therefore stable over time, hence the name. The most abundant isotope of oxygen on Earth is ^{16}O, it accounts for 99.76 % of all oxygen, ^{18}O accounts for 0.2 % of all oxygen and ^{17}O accounts for the rest. Meanwhile proteum (^{1}H) accounts for about 99.985 % of all hydrogen and deuterium (^{2}H) accounts for 0.015 %.

Water sources can be composed of a range of combinations of ^{16}O, ^{18}O, ^{1}H and ^{2}H such as: $^{1}H^{1}H^{16}O$, $^{1}H^{1}H^{18}O$, $^{1}H^{2}H^{16}O$, $^{1}H^{2}H^{18}O$, $^{2}H^{2}H^{16}O$, $^{2}H^{2}H^{18}O$. The molecular weights of each of these molecules are slightly different, because of the number of neutrons in each nucleus of every atom (Eamus, 2006). The difference in the mass of oxygen and hydrogen isotopes in water results in distinct partitioning of the isotopes (fractionation) as a result of evaporation, condensation, freezing, melting or chemical and biological reactions (Kresic, 2008). As a consequence, different bodies of water have variable ratios of $^{2}H/^{1}H$ or $^{18}O/^{16}O$.

When water evaporates from the ocean, lakes and wet surfaces lighter molecules of water evaporates slightly faster than heavier molecules of water, therefore clouds are slightly depleted in the heavier isotopes than the water body from which the water evaporated from. When water condenses and falls as rain, the rain is again slightly enriched in heavier isotopes.

The correlation between $^{18}O/^{16}O$ and $^{2}H/ ^{1}H$ isotope ratios in precipitation on a global scale is described by the Global Meteoric Water Line (GMWL) (figure 1) developed by Craig (1961) and expressed by

Equation 1.1: $\delta^{2}H = 8\ \delta^{18}O + 10$ (figure 1).

Craig's line is actually an average of many lines which differ from the global line due to the varying climatic and geographic parameters. Local lines will differ from the global line in both slope and deuterium intercept. The Global Meteoric Water Line (GMWL) provides a reference for interpreting the provenance of groundwaters (Clark and Fritz, 1997).

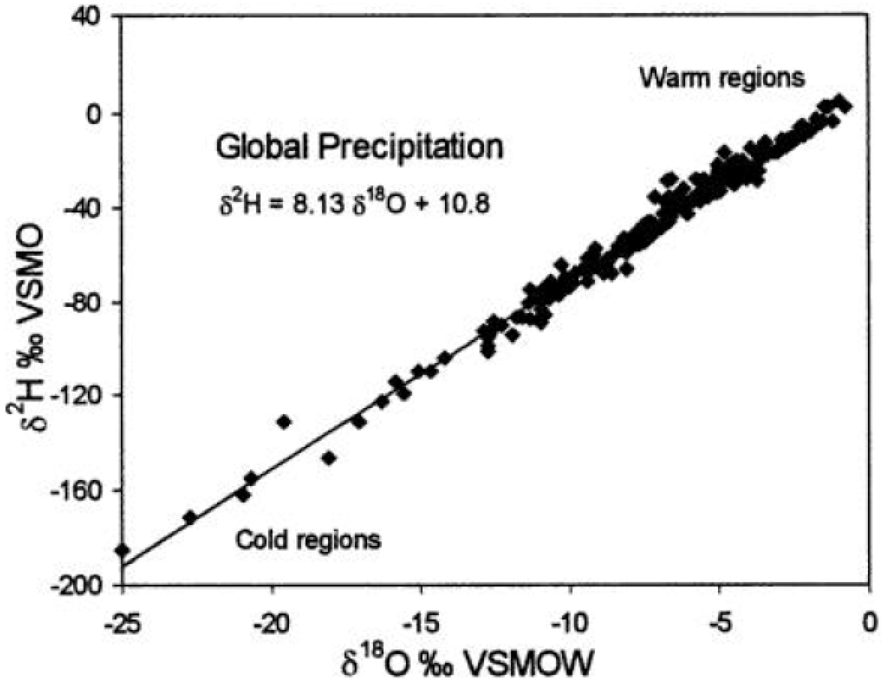


Figure 1.1 The meteoric relationship of ^{18}O and ^{2}H in precipitation (after Clark and Fritz, 1997).

Stable isotope composition of local precipitation can be described by a Local Meteoric Water Line (LMWL) (Ingraham, 1998; Jonsson et al., 2009). The ratios $^{18}O/^{16}O$ and $^{2}H/\,^{1}H$ there in are mainly a function of the place of precipitation. Therefore, Local Meteoric Water line (LMWL) serves a useful purpose in defining the isotopic composition of the input into hydrological systems that are fed by meteoric water.

1.1.2 Oxygen and Hydrogen isotopes in soil

The original isotopic composition of infiltrated water and degree of evaporation are the major factors that influence the soil water. Dawson and Ehleringer (1991) elaborated that variations in isotopic composition of water within soils can arise because of differences in the seasonal input of moisture into the soil, evaporation in the uppermost surface or differences between bulk soil moisture and groundwater.

The difference in molecular weight and the fact that different water sources have different compositions allows comparing the stable isotope composition of water in the plant xylem with that of water in soil, groundwater and streams and rivers (Eamus, 2006). When xylem water isotope composition is compared to that of potential sources, it is possible to determine from which source(s) the water in the xylem was derived. Eamus (2006) further emphasized that this method is only reliable where differences in isotopic composition are significant. Therefore in arid and semi-arid climate such as Namibia where fractionation due to evaporation is high, the method is applicable.

1.1.3 Oxygen and Hydrogen isotopes in vegetation

Plant water source can be estimated by comparing the obtained stable water isotopic ratios to the GMWL and LMWL. Proportional contribution of the different water sources can then be estimated using two- or three-layer mixing models; a method proven to be highly accurate by Yin et al. (2015) during dry periods when the soil water is enriched and isotopically distinct from groundwater due to isotopic fractionation.

The methodology for using stable isotopes of water to determine water sources of vegetation relies upon a number of specific assumptions (after Brunel et al., 1995).

- There are no significant errors associated with the sampling of isotopes or in the extraction and analysis of water from plants and soils.
- There is no significant variability of isotopic composition in the xylem water within the tree except in the vicinity of the leaf.

- The isotopic composition of the soil water is laterally homogeneous within the rooting area of the tree.

1.1.4 The importance of knowing plant water source

Walker et al. (2001) identified several reasons why it is necessary to know from where plants source their water:

1. There is a need to fully understand water relations of natural areas with phreatophytic (deep rooted plants that obtain water from the water table or the layer of soil just above it) or wetland vegetation.
2. Water use by vegetation may conflict with demands for extraction of groundwater for industry, or decrease base flow to streams at times of important environmental requirement.
3. Manipulation of streams for salinity mitigation may affect plant's reliance on stream water.
4. Where plantations are being suggested as a means to lower water tables in areas of salinity.

Over all there is a need to better understand how vegetation responds to change in environment or how vegetation may modify the environment.

1.2 Research problems and objectives

It is not sufficiently known if woody vegetations in savanna ecosystems of Namibia are accessing water only from the groundwater (groundwater dependent) or from the soil water reservoir or both. There is currently no correlation existing between plant water source and precipitation amounts throughout the entire country. Therefore this study is aimed at filling these knowledge gaps.

1.3 Specific objectives of the study

The objective of the study is to determine the isotopic composition of xylem water of woody vegetation and groundwater in savanna ecosystems along Namibia's precipitation gradient. To assess if woody vegetation in savanna ecosystems in Namibia uptake groundwater or soil water and how this is controlled by local climate. As well as to assess if typical encroacher species like *Senegalia/Acacia mellifera* take water from the same source as non-encroachers such as *Vachalia/Acacia erioloba or Boscia albitrunca.*

1.4 Hypothesis

Hypothesis 1: As an adaptation for survival in variable rainfall environments, woody vegetation of the savanna ecosystem utilizes groundwater in dry areas and soil water in wetter areas.

Hypothesis 2: Encroacher species utilizes soil water and this gives an advantage over non-encroachers.

1.5 Significance of the study

The study will facilitate in assessing the groundwater dependence of the savanna ecosystem. It will provide a comprehensive understanding on ecological-hydrological interaction between water sources and woody vegetation. Furthermore it is hoped that that results from this study will help to understand plant water use mechanisms in arid to semi-arid environments. This knowledge can help to estimate the influence of groundwater abstraction on the vegetation and such can be integrated in water management plans.

1.6 Limitation of the study

The plant water sources are identified based on a simple liner mixing models that restricts the number of water sources to two (groundwater and precipitation) by the assuming isotopically distinct water sources.

CHAPTER 2

2. Literature review

2.1 The displacement of non-encroacher woody species by encroacher species

2.1 Savanna land degradation

Bush encroachment is a form of land degradation that can be found worldwide, but it has been found to be more prominent in arid and semiarid rangelands (Oldeland et al., 2010). According to Mannheimer and Curtis (2009) bush encroachment is the invasion of woody species in areas that have always had either very low densities of trees and shrubs or have been devoid of them. It is a serious problem throughout much of Namibia, especially in the commercial farming areas of the north central areas. Bush encroachment negatively affects the efficiency of water use and groundwater thereby contributing to the process of desertification (Mannheimer and Curtis, 2009).

The cause of bush encroachment is supported by Walter's two layer- hypothesis (De Klerk, 2004). The theory underlying this model states that the roots of trees are at the surface as well as the deeper layers of soil, while roots of grasses only occur in the top layer. The hypothesis suggests preferential rather than exclusive access of roots of trees to water in the subsoil and the two layers are indirect competition with each other. However if the grass layer is over utilized mainly by overgrazing, it loses its competitive advantage and can no longer utilize water and nutrients effectively. This in turn results a higher infiltration rate of water and nutrients into the subsoil. Such a scenario will benefit trees and bushes only and allow them to be dominant.

However Ward (2005) indicated that bush encroachment occurs when disturbances such as: human impact, fire, herbivory, drought, spatial heterogeneities in water, nutrients and seed distribution shifts savanna from the open grassland towards the forest end of the environmental spectrum. Mannheimer and Curtis (2009) argued that rainfall and its variability plays a more tremendous role in determining vegetation composition than does grazing and that savanna could be changed to grass dominated land by favorable management and environment conditions.

2.2 Groundwater recharge mechanisms

About 30% of the land area on Earth is arid or semi-arid where potential evapotranspiration exceeds rainfall (Herczeng and Leaney, 2011). In most arid areas recharge from precipitation is limited, widely variable and other form of precipitation may not be present at all. The rate of recharge is the single most important factor in the analysis and management of groundwater resources in these regions (Kinzelbach et al., 2002). In areas of natural savanna ecosystems recharge range from 1 to 5 mm year per annum. Herczeng and Leaney, (2011) indicated that spatial variation in recharge rate occurs with climate, topography, soil, geology, and vegetation.

Groundwater flow pattern is controlled by the configuration of the water table and by the distribution of hydraulic conductivity in the rocks. The water table in turn is affected by topography, and is controlled by the prevailing climate (Sophocleous, 2004). In addition, biotic influences affect most aspects of the hydrologic cycle including groundwater. Vegetation, for instance regulates the rate at which land surface returns water wapour to the atmosphere.

2.3 Previous work done in savanna aquifers

Eco-hydrology is concerned with the importance of hydrological processes in ecosystems and the effects of plants on hydrological processes (Roberts, 2000). With multiple source of water that available to plants, it might be expected that the most obvious source is the one preferred for use. Plants may uptake either soil water or groundwater or both depending on their rooting depths. Rooting depth and distribution defines the depth to or volume from which plants can potential extract these water sources (Zencich et al, 2002), however root presence may not be a reliable indicator of actual water uptake (Dawson and Ehleringer, 1991). Although the opposite could also be true for instance, Lubis et al. (2004) determined plant water sources using stable water isotopes method in Riau, Indonesia. The study points out that oil palm absorbed water from the depth of 0 - 50 cm, which corresponds to the most active root of oil palm that absorbs nutrients, water and oxygen

Obakeng (2007) pointed out that some vegetations in savanna ecosystem are able to shift from one water source to another depending on developmental stage and seasonal factor. This was based on studies by Midgeley et al. (1994) that South African plantain trees, that normally depends on soil water shifts to groundwater during the drought. Meanwhile in Arizona, Snyder and Williams (2000) showed that some trees such as *Salix gooddiingii* used groundwater during the rainy season in contrast to South African plantain trees.

Vegetations in arid and semi arid communities are often exposed to strong bimodal / summer and winter rainfall patterns with different isotopic composition. This provide an ideal opportunity to study the water uptake patterns for by the diverse plant growth forms tat characterise these communities. Studies by Dawson and Ehleringer (1991) have demonstrated that there is a strong relationship between water source and water use pattern, regardless of the environment.

2.4 Methods for estimation of water uptake by plants

There are several methods for estimating water uptake by plants in arid and semiarid environments like Namibia. These methods are: direct measurement with lysimeters, water balance methods, Darcyan methods and environmental tracers such as stable oxygen and deuterium isotopic method. In this study the latter method will be used**.**

2.4.1 Direct Measurements with Lysimeters

Lysimeters have been used for determining plant water use by reconstructing the 'water budget' by continuously measuring rainfall flux and outflow. The missing term evaporation calculated deducing recharge from these calculations. The method may be irrelevant in arid regions where singular recharge features are dominant over areal recharge (Kinzelbach et al., 2002). Eamus et al. (2002) stressed that lysimeters are difficult to use in natural field conditions, or in an attempt to replicate natural groundwater conditions.

2.4.2 Water Balance Methods

The water budget is an integral component of any conceptual model of the system under study Nimmo, (2005). It uses empirical formulas to compute all fluxes involved in the soil water balance. However this method is highly inaccurate because, recharge is estimated based on the difference between two inaccurately known large quantities: precipitation and evapotranspiration.

2.4.3 Darcyan methods

Estimate the flux from a head gradient and a hydraulic conductivity. This approach mimics the infiltration process and can be adapted to any soil, weather conditions or vegetation type (Kinzelbach et al., 2002).

2.5 Isotopic variation among water sources

There are marked differences in stable isotopic composition due to various water cycles resulting in distinct difference of $\delta^{18}O$ and δD in various water bodies. These variations can be as large a 200‰ in a in a single location which makes it possible to understand utilization processes, of various potential water sources, mechanism and co-existence and competition between plats and neighboring plants (Yang et al., 2010).

Eamus (2006) showed a typical representation of isotope ratios within the soil and groundwater (Figure 2.2). They illustrated that near the surface, water is usually enriched in the heavy isotopes due to evaporation processes and more depleted with increase in depth. For instance, measuring an isotope value of C within the plant xylem would indicate that all (or most) of the water used for recent transpiration was sourced from very near the soil surface. If value of A was to be measured then it would indicate that water must be derived from the water table or immediately above it. However, if a ratio of value of B was measured in plant xylem, the outcome will show that water was either sourced from the middle of the unsaturated zone (depth x') or could be a mixture of water from shallower and deeper depths.

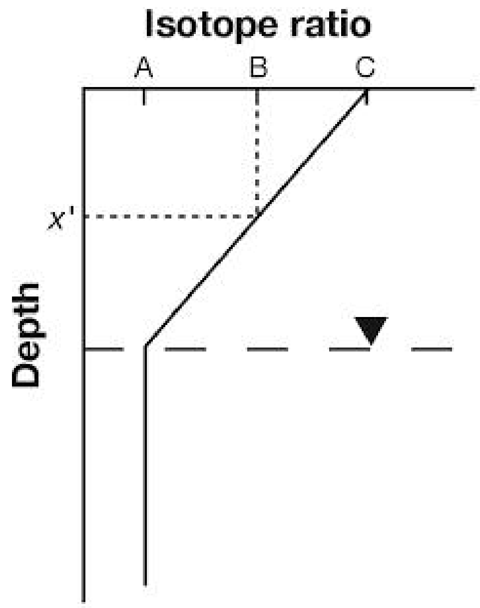


Figure 2.1: Schematic representations of isotope ratios within the soil and groundwater and their use in discovering plant water source. Black triangle indicates the water table (Eamus 2006).

CHAPTER 3

3. Materials and Methods

This is a quantitative study based on stable isotope fractionation, conducted to determine the plant source water by comparing the isotopic composition of woody Savanna vegetation to that of potential sources such as groundwater and soil water. Sampling was conducted during the beginning of the dry season. The dry season is chosen because this is when isotopic variation in water sources is distinct due to fractionation by evaporation.

3.1 Study area

3.1.1 Climate

Namibia is a driest country in sub-Sahara Africa. Some 22% of Namibia is classified as desert, while 33% is classified as arid, 37% semi-arid and 8% as semi humid (De Klerk, 2004). Long-term average rainfall is lowest along the west coast and it gradually increases towards the north-easterly direction. The annual rainfall varies between 20 mm along the west coast to more than 850 mm in the extreme northeast (Figure 3.7). It rains in summer (October - March) throughout most of the country except in the extreme south-west where rain more commonly falls in the winter months (May - August).

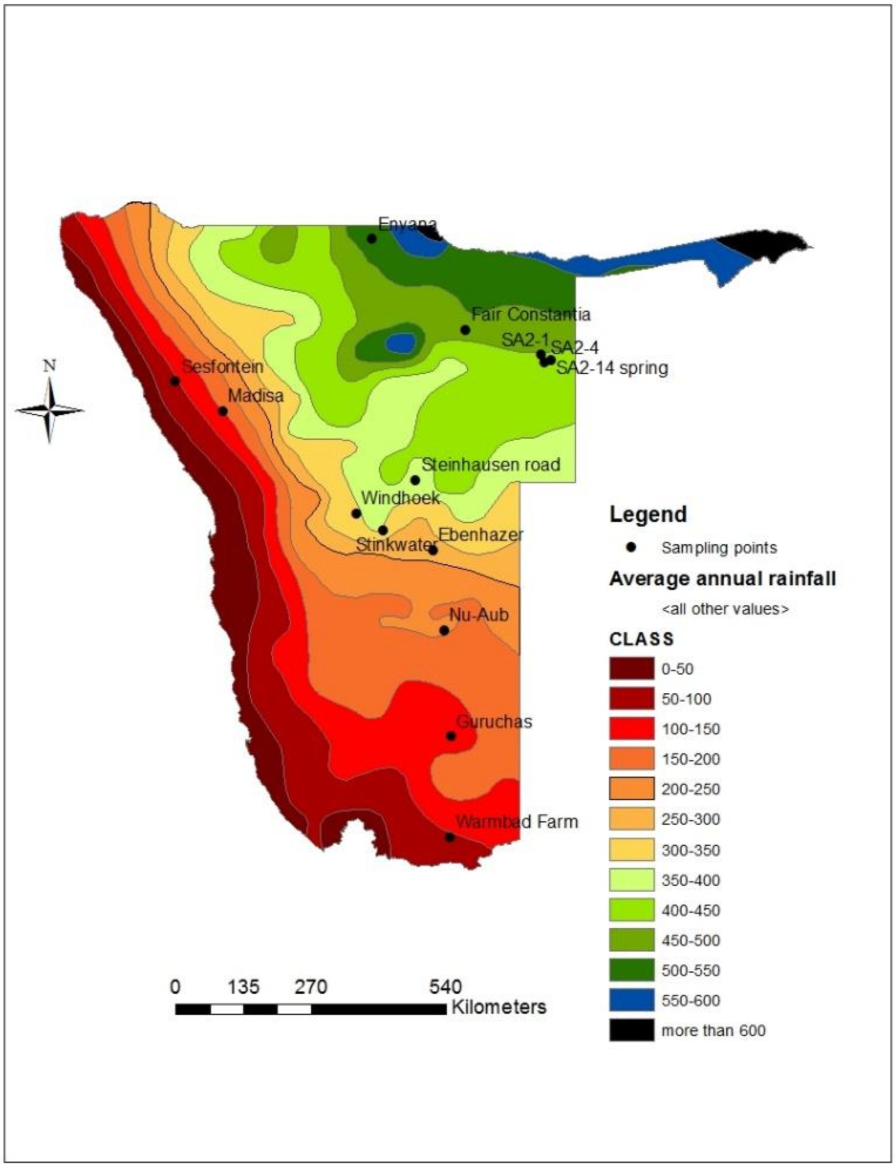


Figure 3.1: Annual average rainfall across Namibia (adapted from Mendelsohn et al., 2002).

Namibia's climate is a resultant of various factors including its relative position on the south-western part of Africa continent spanning a zone between 17^o and 29^o south of the equator. Consequently, Namibia is exposed to air movement driven by three major climatic systems namely : the Inter-tropical Convergence Zone (ITCZ), the Sub-tropical High Pressure System and the the Temperature Systen. The Inter-tropical Convergence Zone (ITCZ) feeds in moisture laden air from the north. Summer rainfall is generated when moisture had been driven into through of low presure in Namibia by winds generated in a low pressure cell lying over this zone. While the Sub-tropical High Pressure System positioned across the country pushes moist air back with dry cold air .The effect of this system is more pronounced than that of ITCZ, so that Namibia is characterized by dry hot weather for most of the year (Mendelsohn et al. 2002; Msangi, 2014).

The Temperature Systen to the south of the country with predominantly moisture laden westernly winds. It carries a succession of low pressure system and cold fronts from west to east feeding bursts of cold air air from the antarctic sweep across Southern Africa during southern hemisphere winter (Figure 3.8). Winter rainfall occurs when cold fronts sweep across the southern Atlantic and Indian oceans, bringingin rain to the southern part of the country. These three systems move south and northward in response to the overhead sun (Mendelsohn et al. 2002; Msangi, 2014).

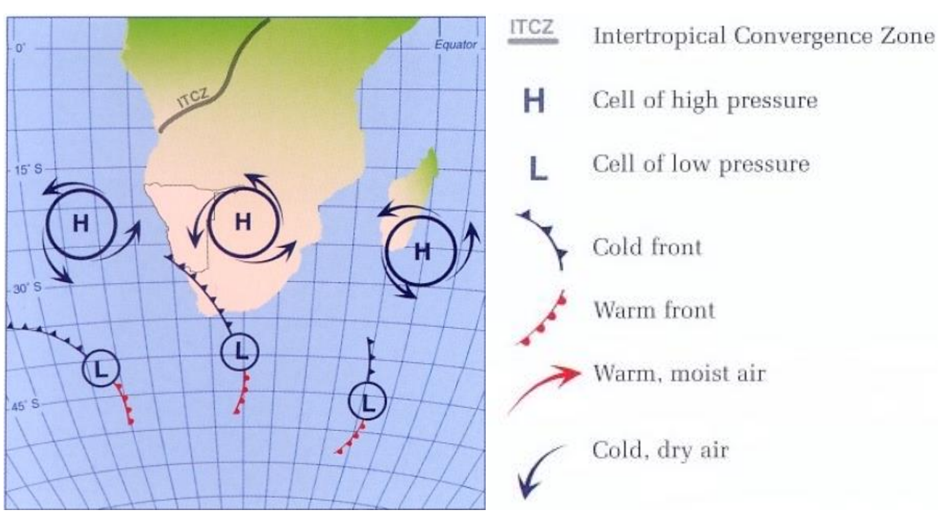


Figure 3.2: Low pressure system responsible for winter rainfall in the south western part of the country (after Mendelsohn et al., 2002).

3.1.2 Namibia's Savanna types

According to Giess (1971) Namibia has 14 major vegetation types of which 7 are savanna type. The savanna range type covers 64 % of the country and can be divided into three main veld (range) types, namely the dwarf shrub savanna in the central-south, the various acacia-based tree and shrub savanna associations in the center and eastern parts, and the mopane savanna in the north-west (Figure 2). The dwarf shrub savanna is characterized by *Rhigozum trichotomum, Catophractes alexandrii, Eriocephalus* species and various small Karoo bushes. This area forms part of the Etosha National Park and supports a diverse and abundant wildlife population.

The mixed tree and shrub savanna of the southern Kalahari is characterized by deep sand and *Acacia haematoxylon*, with various species of *Acacia* and *Boscia* on the harder ground between the parallel dunes. The camelthorn savanna (300-400 mm/a rainfall) of the central Kalahari is an open savanna with *Acacia erioloba* as the dominant tree. Common shrubs include *Acacia hebeclada, Ziziphus mucronata, Tarconanthus camphoratus, Grewia flava, Ozoroa paniculosa* and *Rhus ciliate*.

The thornbush savanna (400-500 mm/a rainfall) is the dominant vegetation type in the central part of the country. Bush encroachment by *Acacia mellifera* and *Dichrostachys cinerea* is widely problematic. Other characteristic species include *Acacia reficiens, A. erubescens* and *A. fleckii*. The highland savanna (300-400 mm/a rainfall), situated south of the thornbush savanna, is characterized by trees such as *Combretum apiculatum, Acacia hereroensis, A reficiens* and *A. erubescens*.

The mountain savanna (500-600 mm/a rainfall), found north of the thornbush savanna, has less *Acacia* and is characterised by trees such as *Kirkia acuminata, Berchemia discolor,* *Pachypodium lealii* and *Croton* spp. A complex of this region is the Karstveld (areas with recent surface limestone deposits and shallow soil) which supports *Combretum imberbe, Dichrostachys cinerea* and *Terminalia prunioides*. The mopane savanna is a distinct vegetation type dominated by *Colophospermum mopane,* which occurs in tree and shrub forms, in the north-west of the country. It spans a wide rainfall range from 50-500 mm/a rainfall.

The semi-desert savanna transition zone is characterised by a mix of savanna and desert species. While *Acacia* species are dominant in many parts, various stem-succulents such as *Commiphora* and *Cyphostemma* species occur. The dry woodlands of the north-east are in the highest rainfall part of the country (500-700 mm/a) and merge from the tree savanna of the north-central area. They are characterised by *Baikea plurijugia*, *Burkea africana, Guibourtia coleosperma* and *Pterocarpus angolensis* (Sweet and Burke, 2000).

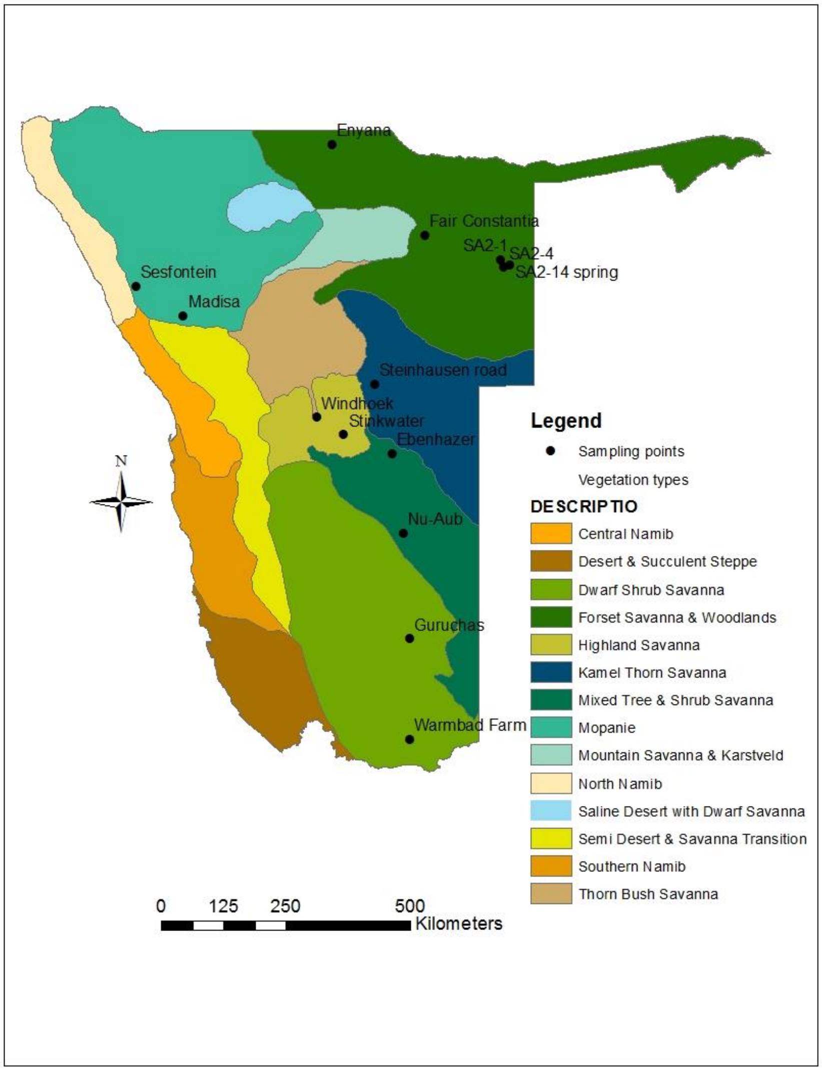


Figure 2.3: The principal vegetation types of Namibia (after Giess, 1971).

3.1.3 Geology and Hydrogeology

Groundwater is the primary water resource in arid/semi-arid zones and it is well established that groundwater flow systems are vital to allowing human populations and other biota to survive (Herczeg and Leaney, 2011). The occurrence and availability of groundwater at any locality is determined by the storage and transmissive properties of the geological formation, the volume and frequency of recharge, the rate of groundwater movement to discharge areas and loss through evapotranspiration (Fuggle and Rabie, 1992).

Namibia has been divided into sixteen groundwater basins based mainly on geological structure and groundwater flow (Figure 3.9). Their boundaries were chosen to encompass areas of similar geology and hydrogeology. The following aquifer systems exists in the country: fractured and altered zones in the Archean basement, fractured rocks with a good proportion of limestones and dolomites in Proterozoic Damara facies and Otavi series, porous rocks in Cambrian Nama fromation and Post Cambrian formations and unconsolidated formations with good primary porosity.

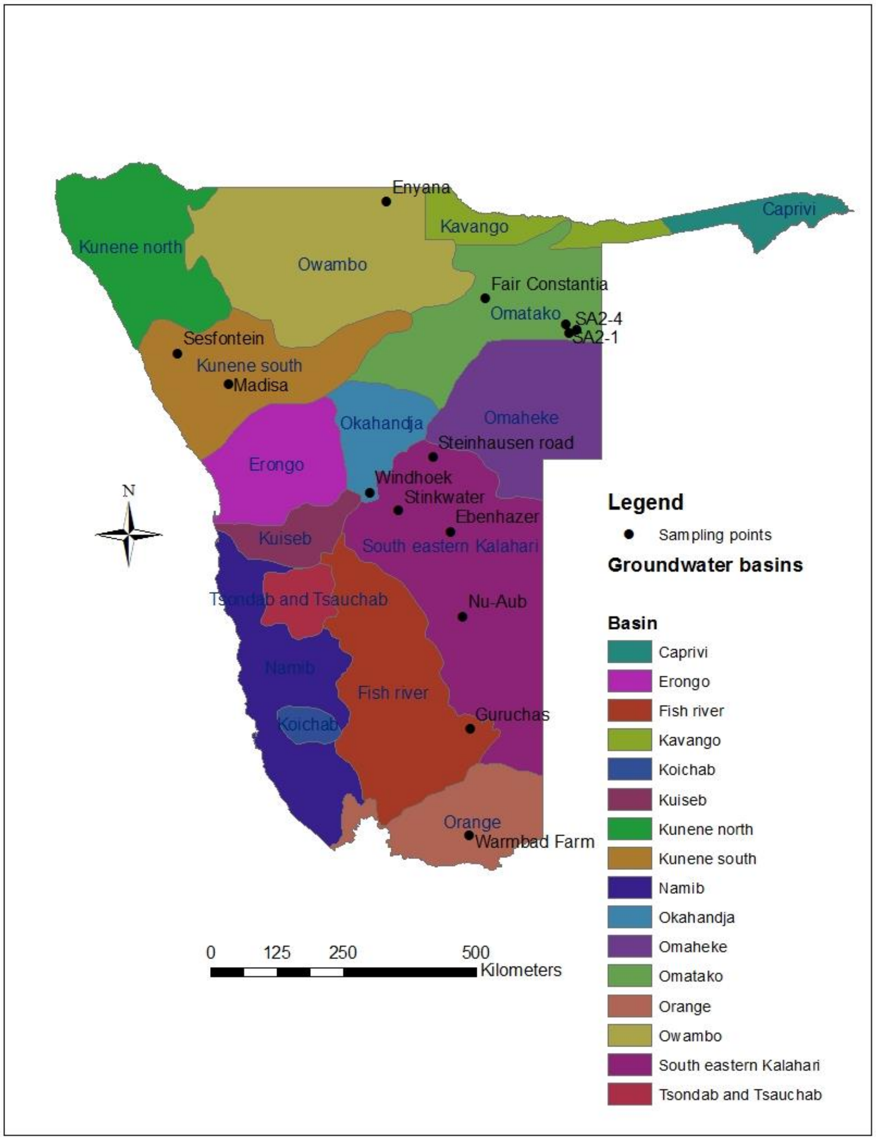


Figure 3.4: Study sites and groundwater basins, modified from Mendelsohn et al.(2002).

3.1.3.1 Owambo / Cuvelai-Etosha basin – Sampling site Enyana

Owambo basin is the Namibian part of the Cuvelai River catchment, fed by perennial tributaries and the Cuvelai River flowing from the Serra Encoco Mountains of Angola. It is the most active river system of shallow rivers found on an enormous flat plain, partly in Angola and partly in Namibia. These shallow rivers, spread out in Angola to form a large ephemeral river system, then come together in Namibia at Lake Oponono, which in turn drains into Etosha. The Etosha basin is the outlet of the Cuvelai slopes. It was formed by faulting probably associated with the Rift and the subsidence of the northern areas of Otavi facies (Christelis and Struckmeier, 2011).

Major groundwater recharge originates from Angola highland (Christelis and Struckmeier, 2011). The area is part of The Kalahari Sequence, entirely of continental aeolian to fluvial origin, composed of Ombalantu, Beisib, Olukonda and Andoni formation. These formations are porous and can absorb the surface flows and transmit them underground toward the areas where they find their outlets. The groundwater aquifers are unconfined in the areas of recharge and discharge, and artesian in the intermediate areas of groundwater flow.

The area is hosted in a multilayered aquifer system made up of one unconfined Perched discontinuous Aquifer (PDA) and three confined continuous aquifers namely; Main shallow aquifer (MSA), Main deep aquifer (MDA) and very deep aquifer (VDA). The Discontinuous Perched Aquifer (DPA) is not a single aquifer, but consists of a series of small perched aquifers, which occur predominantly in the dune-sand. These aquifers are mainly recharged by direct infiltration of rainwater and exploited by means of traditional shallow hand dug wells. These wells provide shallow, easily accessible and good quality drinking water to the villagers (Christelis and Struckmeier, 2011).

3.1.3.2 Omatako basin - Sampling site Fair-Constansia

Groundwater within the area is hosted in two distinct aquifer systems, Kalahari aquifers and fractured bedrock aquifers. Kalahari aquifers hold water in inter granular pore spaces, whereas water in fractured aquifers is held in cracks and fractures in otherwise impermeable strata. Shallow aquifers with water levels above 20m receive good recharge either directly from rainfall or indirectly from ephemeral runoff. Deeper aquifers are recharged from the Kalahari basin margins and under lying fractured aquifers. Groundwater level elevation (piezometric surface) and hydro-chemical evidence suggest significant recharge from the Otavi Group dolomites in the Tsumeb - Grootfontein area.

Boreholes closer to the center of the basin, tap deeper water as the depth to groundwater gradually increases to more than 100 m. boreholes intersecting fractured bedrock aquifers may show higher yields than boreholes tapping Kalahari aquifers. In areas of thin or absent Kalahari cover lithological contacts and faults are discernible and borehole success rates are moderate. Here, water quality is variable and saline groundwater can be expected in some boreholes. In the bedrock areas adjacent to the Botswanan border water levels tend to be shallow although groundwater levels can vary up to 10m in places between dry and wet seasons (Christelis and Struckmeier, 2011).

3.1.3.3 South eastern Kalahari / Stampriet artesian basin - Sampling sites Nu-Aub, Ebenhazer and Stinkwater

Groundwater occurs in the Nossob and Auob sandstones of the Ecca Group (lower Karoo Sequence), which are divided by shale layers and overlain by Rietmond shale and sandstone. Younger Kalkrand Basalt occurs in the north-west and Kalahari Sequence deposits. Predominantly covered by Kalahari sediments: sands, clays, argillaceous, schists, calcareous concretions and laterites. Several springs are located in the eastern outcrop area of the basalt.

The Karoo succession rests unconformably on Kamtsas Formation in the north and north-west and on Nama Group rocks in the remainder of the basin. Sediment transport came from the north-east. The sandstones, in particular, were deposited in a deltaic environment. The dip of the Karoo formations is slightly towards the southeast and the groundwater flow generally follows that direction.

Groundwater occurs in the Kalahari layers, in Kalkrand Basalt in the north-west, and in the Prince Albert Formation of the Karoo Sequence. Elsewhere sub-artesian conditions prevail, that is, the water in the aquifer is confined, but the pressure is not sufficient for the water to rise above the surface. The artesian aquifers are recharged through sinkholes during years with abnormally high rainfall.

3.1.3.4 Fish river Basin – Sampling site Guruchab

The area is composed of Fish River, Schwarzrand and the Kuibis subgroups of the Nama Group. Groundwater is hosted in secondary features like faults and joints in sedimentary rocks of clastic origin (sandstone, quartzite and shale) and in solution features in limestones and dolomites. Rock types of the Nama Group are inherently impermeable with little or no primary porosity

3.1.3.5 Orange basin/ Karas basement - Sampling site Warmbad

Very limited volumes of groundwater are available in the basement rocks of the southern Karas Region, since there are no productive aquifers due to lack recharge. The area has long been inhabited, as the abundance of old hand-dug wells indicates. Most wells are situated along river courses in shallow alluvium and deeply weathered channels and basins. Natural fountains occur predominantly in riverbed. A thermal, fault controlled (±34° C) spring is found at Warmbad. Exploration for groundwater should be concentrated along faults, and where possible close to river beds, in order to facilitate and enhance recharge. The area is mainly underlain by granite-gneiss of the Namaqualand Complex, along the riverbed it is deeply fractured and contains highly mineralized water. Groundwater flow direction is north-west to south-east.

3.1.3.6 Okahandja basin/ central Namib – Sampling site Windhoek

Groundwater in Windhoek aquifer is recharged from rain water collecting along fractures in quartzites of the Auas Mountains. Unsaturated zone storage is not always available due to rocky terrain and shallow sand cover therefore component of rainfall that is not run- off rapidly recharges the aquifer via preferred pathways. The rivers in this area are ephemeral and only flow in thesummer rainy season. Windhoek is supplied water by the Omaruru and Swakop River. The city was built around a series of natural springs, which occur close to the source of the Swakop River.

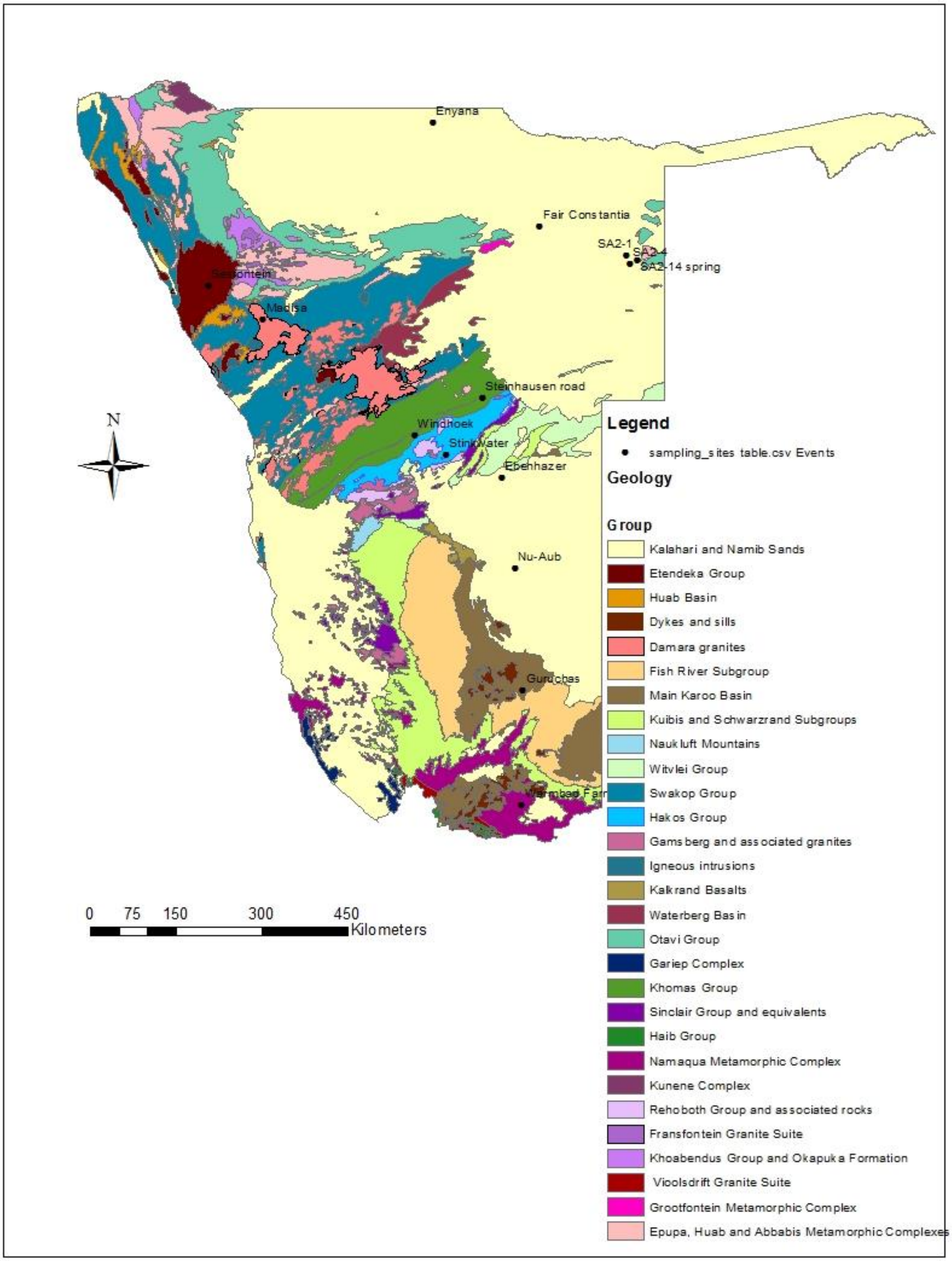


Figure 3. 5 Simplified geology of Namibia (after Miller, 2008).

3.3 Determination of sampling sites

Study sites in the Savanna ecosystem were identified based on the average annual rainfall. The aim was to sample at every rainfall range. Most samples were collected from summer rainfall areas except for two sites Guruchas and Warmbad that receive winter rainfall which have average annual precipitation 100 mm/a and 150 mm/a, respectively. Thus, also two sites were sampled with a similar rainfall amount but that are located in the summer rainfall area.

Table 3.1: Groundwater sampling locations along the Namibian precipitation gradient. Precipitation amounts after Mendelsohn et al. (2002)

Number	**Site**	**Latitude [°]**	**Longitude [°]**	**Average annual Precipitation [mm/a]**
1	Sesfontein	-20.1959	13.8210	100
2	Warmbad	-28.3820	18.7600	100
3	Madisa	-20.7273	14.6814	150
4	Guruchas	-26.5664	18.7718	150
5	Nu-Aub	-24.6590	18.6525	200
6	Ebenhazer	-23.2211	18.4503	250
7	Stinkwater	-22.8647	17.5679	300
8	Steinhausen	-21.9626	18.1472	380
9	Windhoek	-22.5589	17.0825	395
10	SA2-4 Kae-sca	-19.8559	20.4634	440
11	SA2-14 Gautscha Pan	-19.8054	20.5830	445
12	SA2-1 Eagle Post	-19.7109	20.4012	450
13	Fair Constantia	-19.2677	19.0386	475
14	Enyana	-17.6311	17.3600	500

3.4. Study species

The following species were includes in the study: *Vachellia erioloba/Acacia erioloba, Senegalia mellifera/Acacia mellifera, Boscia albitrunca, Rhigozum trichotomum, Combretum imberbe, Peltophorum africanum, P. juliflora, Terminalia sericea and Colophospermum mopane.*

Table 3.2 Woody species sampling locations along the Namibian precipitation gradient.

No	**Site**	**Species 1**	**Species 2**	**Species 3**	**Species 4**
1	Sesfontein	*V. erioloba*	*C. mopane*	*B. albitrunca*	-
2	Warmbad	*V. erioloba*	*R. tricotomum*	-	-
3	Madisa	*V. erioloba*	*C. mopane*	*S. mellifera*	-
4	Guruchas	*V. erioloba*	*R. trichotomum*	*S. mellifera*	-
5	Nu-Aub	*V. erioloba*	*R. trichotomum*	*P. juliflora*	-
6	Ebenhazer	*V. erioloba*	*S. mellifera*	*B. albitrunca*	-
7	Stinkwater	*V. erioloba*	*S. mellifera*	*B. albitrunca*	-
8	Steinhausen	*V. erioloba*	*T. sericea*	-	-
9	Windhoek	*V. erioloba*	*S. mellifera*	*B. albitrunca*	*A. Hebeclada*
10	Fair Constantia	*V. erioloba*	*S. mellifera*	*B. albitrunca*	-
11	Enyana	*V. erioloba*	*S. mellifera*	*C. imberbe*	*P. Africanum*

Woody tissue samples from SA2-1 Eagle post, SA2-14 Gautscha pan and SA2-4 Kae-sca were not analysed for their isotopic composition due to high content of organic contaminants.

3.5 Data collection procedure

Plant sample from woody vegetation of the savanna ecosystem, groundwater and stream water were collected randomly at all precipitation ranges. Woody tissue samples were taken from mature, healthy appearing vegetation. These plants were correctly identified in the field with the aid of Field's guide to Trees and Shrubs of Namibia book by Mannheimer and Curtis (2009).

Xylem samples were collected using a xylem drill at approximately 1.4 m above the ground in order to minimize contamination of xylem water with organic matter. The sampling spot is freshly de-barked before drilling. Where the xylem drilling proved to be futile, twig segments were opted for. Twigs less than one centimeter in diameter were cut from the tree with a pruning shears. Leaves, thorns and loose barks are removed from the twig segments and cut into lengths short enough to be placed into collection vials. Walker et al (2001) recommend removing of leaves, bark from woody twigs before sampling as well as avoiding any green parts of a plant as precautions to avoid mixing of xylem water with enriched, evaporated water from those parts. To establish if there was a relationship between plant size and depth of water uptake, diameter at breast height (DBH) was measured and height was estimated for every sampled tree/shrub.

Groundwater samples were collected from fourteen boreholes in close proximity to the sampled plants. On-site parameters such as electrical conductivity and temperature were measured. Further data for isotopic composition of groundwater in the area were obtained from Turewicz (2013). Samples were stored at room temperature out of direct sunlight in screw-top glass and plastic vials, sealed with parafilm in the field in order to avoid isotope fractionation due to evaporation. Throughout the sampling campaign a total of 76 samples were collected, 14 groundwater samples, 20 twigs and 48 xylem drill samples.

3.6. Descripion of sampled species

3.6.1 Combretum imberbe

Common names: Leadwood, Omukuku

Family: Combretaceae

C. *imberbe* is one of the protected species in Namibia. It is the largest sized tree of about 40 tree species or sub-species in the *Combretum* genus occurring in southern Africa. The growth form is generally a small to large winter deciduous tree. It can grow up to 20m depending on water availability .It may have a single main stem attaining a diameter of 1.5m, with heavy main branches commencing at 3 to 4 m above the ground to give a rounded crown.

The large tap roots and well developed lateral roots systems enable it to draw on ground water and to utilize the moisture held in surface soils after rains. C. *imberbe* is considered a savanna species or mixed woodland species, and occurs in a variety of habitats ranging from arid to moist savanna (Alias et al., 2003).

Figure 3.6: Pale yellow Combretum imberbe tree to the right of a Mopane tree (b) Combretum imberbe four-winged fruits.

3.6.2 Peltophorum Africanum

Common names: African Wattle, Omupalala

A semi deciduous shrub up to 4m high or a graceful tree with a spreading crown up to 12 m high with a spreading crown. Frequently branched from near the ground or 2 to 3 stemmed. It is usually found in northern Namibia, but most common in Karstveld. It is fast-growing, frost- and drought-resistant commonly occurring at medium to low altitudes, in wooded grassland and along marginal valleys.

Figure 3.7: Peltophorum Africanum pods (after Orwa et al., 2009).

3.6.3 Acacia hebeclada

Common name: candle pod acacia, candle thorn

Family: *Fabaceae*

Acacia hebeclada has two distinct forms the subspecies hebeclada is a small shrub growing up to 1.5 metre tall, whilst the subspecies *chobiensis* is a large, thicket-forming shrub or small tree growing up to 3 metres. Both forms branch from the ground, and occasionally form underground stolons. (www.ville-ge.com). It is found in dry savanna and grassland areas and on soil ranging from Kalahari sands to sandy alluvium soils, often associated with calcrete.

Figure 3.8: Acacia hebeclada shrub.

3.6.4 Vachalia erioloba / Acacia erioloba

Common names: Camel-thorn, *omuthiya*

Family: Fabaceae

Vachalia erioloba is the common and widely distributed woody species throughout the entire country. It is a semi-deciduous tree; its stature varies from a shrub to a very large tree with a spreading crown, depending upon water availability and depth. This species can grow up to 30 m high, trunk circumference up to 4 m. *Vachalia erioloba* prefers sandy soil, depressions and dry riverbeds. Tap roots can grow up to 60 m deep (Jennings 1974)

Figure 3.9: *Vachallia erioloba* tree.

3.6.5 Senegalia mellifera/ Acacia mellifera

Common names : Wait a bit thorn, black thorn, hook thorn

Acacia mellifera is a low, branched tree with a more or less spherical crown. It has a shallow but extensive root system radiating from the crown, allowing the plant to exploit soil moisture and nutrients from a large volume of soil. The roots rarely penetrate more than 1 m. *A. mellifera* is a commonly occurring shrub on rangelands throughout the savanna. *A. mellifera* is normally found on hard-surfaced, sandy soils and rocky hillsides. This species is drought-tolerant; it grows well on most soil types but prefers loamy soils with mean annual rainfall of 250-700 mm (Orwa et al., 2009).

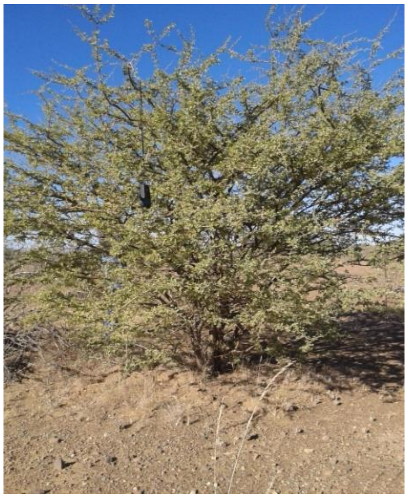


Figure 3.10: *Senegallia mellifera* shrub.

3.6.6 Boscia albitrunca

Common names: Shepherd tree, *Omunghudi*

Family: C*apparaceae*

Boscia albitrunca is als a protected species in Namibia. It is a stocky evergreen tree that may reach heights of 5-11 m , it usually has a well rounded crown . It prefers to grow on sandy, loamy and calcrete soils . Matured *B. albitrunca* trees has been found to be among the most drought torelant species (Alias et al., 2003). In the savanna ecosystem maximum rooting depth is 0.5 ± 0.1, however in the central Kalahari 68 m rooting depth was encountered (Obakeng, 2007)

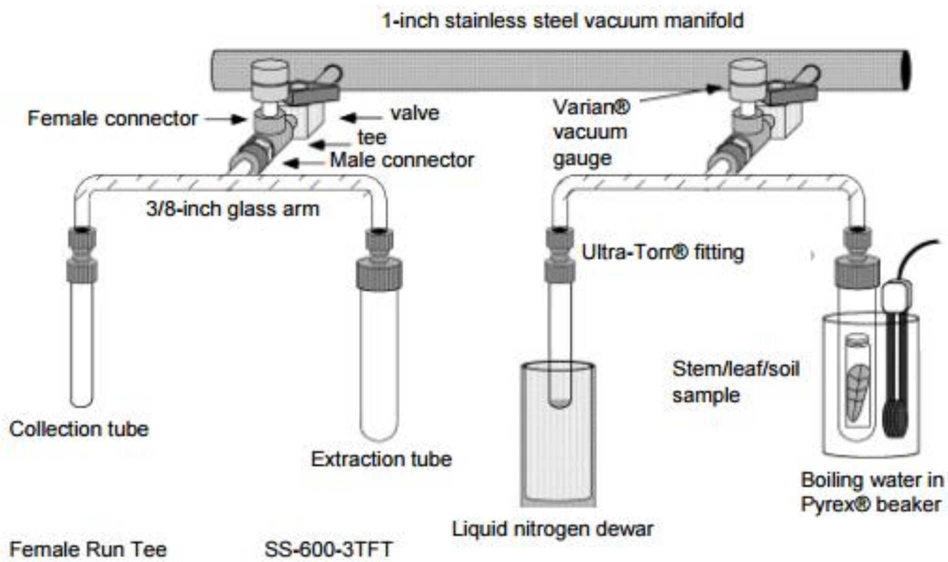
Figure 3.11: *Boscia Albitrunca* tree.

3.7 Analytical approaches

3.7.1 Xylem water extraction

Cryogenic vacuum distillation method was used to extract water from woody tissues. Extraction was performed at Bundesanstalt fuer Geowissenschaften und Rohstoffe (BGR), Geozentrum Hannover, Germany. A study by West et al. (2006) has shown that this method is simple, produce accurate and reliable results. Cryogenic distillation apparatus (Figure 3.11) consisted of six independent glass units all attached to 1- inch stainless stainless-steel vacuum manifold. Each unit consisted of 3/8-inch glass arm connected to the manifold via a Varian® 801 vacuum gauge and could be isolated from the manifold by a NUTRO® plug valve. Attached to either end of the 3/8-inch glass arm was a collection tube (½-inch Pyrex®) and an extraction tube (1-inch Pyrex®). All connections were made with appropriate sized Ultra-Torr® vacuum fittings or Swagelok ®, connected to a vacuum pump (Edward #5) (West et al., 2006).

The process requires samples to be frozen before extraction, frozen sample along with the vial were placed into the sample holder. The entire unit is pumped down to a pressure of approximately 60 m Torr while sample is immersed in liquid nitrogen to create a vacuum. Once the sample is under vacuum, it is warmed by placing the vial in boiling water. The collection tube is then immersed into liquid nitrogen to condense the moisture from the sample into the collection tube. The isotopic composition of water condensing in the tube follows a Rayleigh distillation curve; hence the water extraction process must proceed to completion to obtain an unfractionated water sample. The collection tube was then removed, sealed with Parafilm, allowed to thaw and retained for isotopic analysis (West et al., 2006; Yang et al., 2010).



Female Run Tee	SS-600-3TFT
Male Connector	SS-6-UT-1-4
Plug Valve	SS-6PAT
Port Connector	SS-601-PC
Female Connector	SS-600-7-2
Ultra-Torr fitting	**SS-8-UT-6-6**

Figure 3.12: Cryogenic extraction line (after West et al., 2006).

3.7.2 Analysis of hydrogen and oxygen isotopic ratios

Obtained water samples were analyzed for their isotopic composition using isotope ratio infrared spectrometer (L2120-i wavelength-scanned cavity ring-down spectrometer, Picarro Inc.) at the same laboratory. This device uses a Wavelength-Scanned Cavity Ringdown Spectroscopy (WS-CRDS) measure the absorption line features for three common water isotopologues: $^{1}H_2{}^{16}O$, $HD^{16}O$ and $^{1}H_2{}^{18}O$ (Bailey et al., 2015).

Infrared laser spectroscopy has gained popularity in the recent years due to its time efficiency since no extensive sample preparation is required. The analyzer has three components

(Figure3.12) a gas-phase instrument that measures the concentration and isotopic content of water in vapor form, a liquid evaporator that homogeneously vaporizes liquid water with little or no isotopic fractionation and an auto-sampler that injects liquid water samples into the evaporator. Vaporization enables the WS-CRDS cavity to be loaded with a higher vapor pressure to increasing the level of sensitivity and precision.

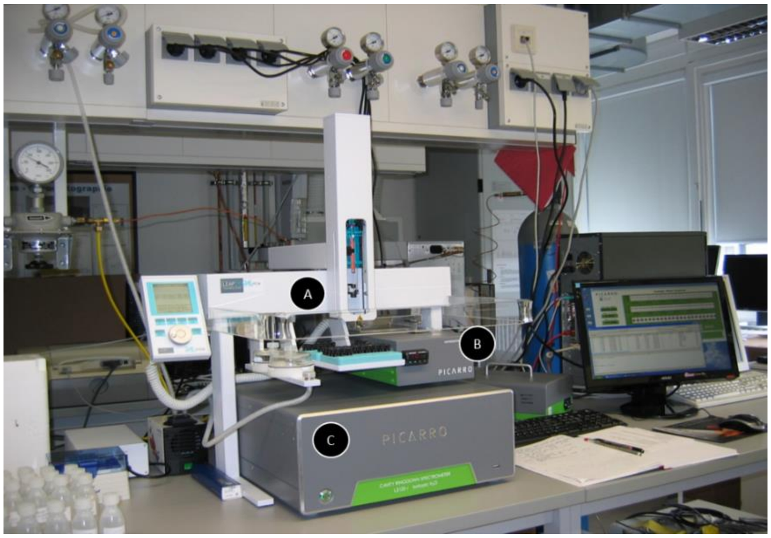


Figure 3.13: Major components of Isotope Ratio Infrared Spectrometer (L2120-i WS-CRDS) A: PAL auto-sampler, B: Picarro vaporizer, C: Picarro analyzer.

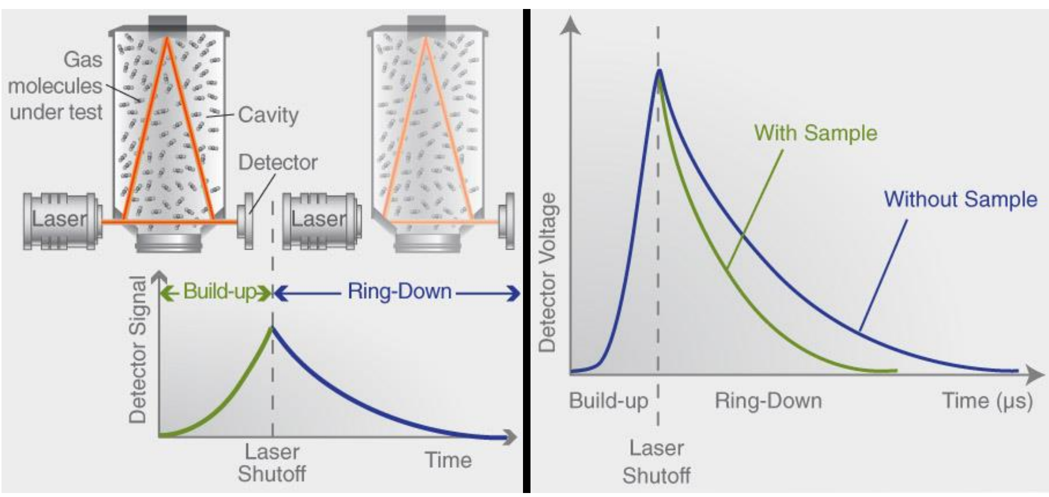


Figure 3.14: (a) Schematic of Picarro CRDS analyzer showing how a ring down measurement is carried out. (b) Demonstration on how optical loss is rendered into a time measurement (source: www.picarro.com).

In WS-CRDS, the beam from a single-frequency laser diode enters a cavity defined by two or more high reflectivity mirrors. When the laser is on, the cavity quickly fills with circulating laser light. A fast photo detector senses the small amount of light leaking through one of the mirrors to produce a signal that is directly proportional to the intensity in the cavity. When the photo detector signal reaches a threshold, the continuous wave laser is abruptly turned off. The energy decays from the cavity, through loss mechanisms, exponentially in time. This energy decay is measured, as a function of time, on the photodetector and is known as a ring down (www.picarro.com). The analyzer at the BGR laboratory has a precision of 0.8 ‰ for δD and 0.2 ‰ for $\delta^{18}O$.

Source water samples collected without cryogenic vacuum distillation (groundwater and surface water) were analyzed for $\delta^{18}O$ and $\delta^{2}H$ by a LGR DLT-100 Liquid Water Isotope Analyzer (Los Gatos Research, Inc., Mountain View, CA, USA) at the University of Namibia, Geology Department laboratory. International Atomic Energy Agency (IAEA) standard operating procedures were used. The analyzer has standard deviation of ±0.25‰ for $\delta^{18}O$ and ±1‰ for $\delta^{2}H$. The ratios of ^{18}O to ^{16}O and ^{2}H to ^{1}H were calculated relative to an international standard (VSMOW), Vienna Standard Mean Ocean Water and expressed in delta (δ) notation in per mil (‰).

Equation 3.1: $\delta^{18}O$ ‰ or $\delta^{2}H$ ‰ = $(R_{sample}/R_{standard} - 1)*1000$

Where R is the ratio of heavy to light isotope ($^{2}H/^{1}H$ or $^{18}O/^{16}O$).

3.7.3 Isotopic correction of xylem water

Results obtained from analysis were subjected to ChemCorrect™, Picarro's post-processing software package. It identifies and flags contamination from a broad range of organics, providing confidence in the accuracy of isotope ratios reported. However, organic contaminants in isotope analyses of xylem water with spectroanalyses and possible interferences are on-goingly discussed in the research community and more research is still needed to assess their final reliability.

3.8 Statistical analysis

All statistical analyses were performed using XLSTAT 2016. A linear model test was used deduce the relationship between $\delta^{18}O$ and $\delta^{2}H$ of groundwater and tree xylem water with reference to GMWL. It was also used to infer the relationship between Diameter at Breast Height (DBH) and groundwater isotopic composition as well as to test the relationship between isotopic compositions of sampled groundwater to groundwater database.

Analysis of variance (ANOVA) was used to assess variability of isotopic composition of groundwater and xylem waters. Such an approach was revealed useful to discriminate the importance of ecological factors influencing water uses. Posterior Turkey's test was used for multiple comparisons in order to determine the significant differences between local groundwater and xylem water. The *P*-values were considered statistically significant at the 0.05 level.

3.9 Tracing the isotopic composition of precipitation

Isotopic composition of groundwater in arid regions can be considerably modified from that of local precipitation and vice versa. The evaporation slope for $\delta^{18}O$ and $\delta^{2}H$ is a function of humidity and vary between 4 and 5. Therefore the characteristic trends imparted by evaporation can be useful in understanding mechanism of recharge as well as determining recharge rates, which can be as low as or lower than 1% of precipitation. Despite the strong evaporation in arid regions, it is possible that newly formed groundwater can have isotope contents close to the mean composition of precipitation (Clark and Fritz, 1997).

The isotopic composition of precipitation where groundwater originated was traced by calculating the intersection points of local groundwater evaporation lines with Global Meteoric Water Line (GMWL) the precipitation source value (Evaristo et al. 2015) using the equation below.

Equation 3.2: $$b = \delta^{2}H - (4.5 * \delta^{18}O)$$

Equation 3.3: $$\delta^{2}H \text{ intercept} = \delta^{2}H - m\,\delta^{18}O$$
$$= (\delta^{18}O * 8) + 10$$

Equation 3.4: $$\delta^{18}O \text{ intercept} = (\delta^{2}H \text{ intercept} - b)/a$$
$$= (b - 10)/3.5$$

Where *m*, *a* and *b* are the slope of evaporation line (4 to 5 for arid regions), the GMWL slope, and the GMWL intercept, respectively. The same equation was used trace the source of groundwater recharge at Guruchas - the only site where surface water was encountered presumably from recent rainfall.

CHAPTER 4

4. Results

4.1 Isotopic composition of water available for plant uptake

Groundwater Oxygen and Hydrogen isotope ratios analyzed throughout the study varied depending on location. These values were plotted together with isotope database compiled by Turewicz (2013) to characterize groundwater recharge. Groundwater samples from Guruchab, SA2-14 and Steinhausen displayed very high levels of enrichment in comparison to groundwater samples from other locations.

Guruchab sampled groundwater had $\delta^{18}O$ and δD composition of -4.08‰ and -30.5‰; it plotted below the GMWL along an evaporation line (Figure 4.1(a)), while groundwater database $\delta^{18}O$ and δD composition varied from -6.57‰ to -2.15‰ (mean: -4.30 ± 1.1‰) and -42.43‰ to -21.51‰ (mean: -31.35 ± 5.3‰). Steinhausen Sampled groundwater had $\delta^{18}O$ and δD composition of -5.04‰ and -38.8‰ (Figure 4.1(b)) slightly enriched than groundwater database which varied from -7.44‰ to -5.04‰ (mean -6.66 ± 1.10‰) and -53.20‰ to -38.85‰ (mean: -48.76 ± 6.72‰).

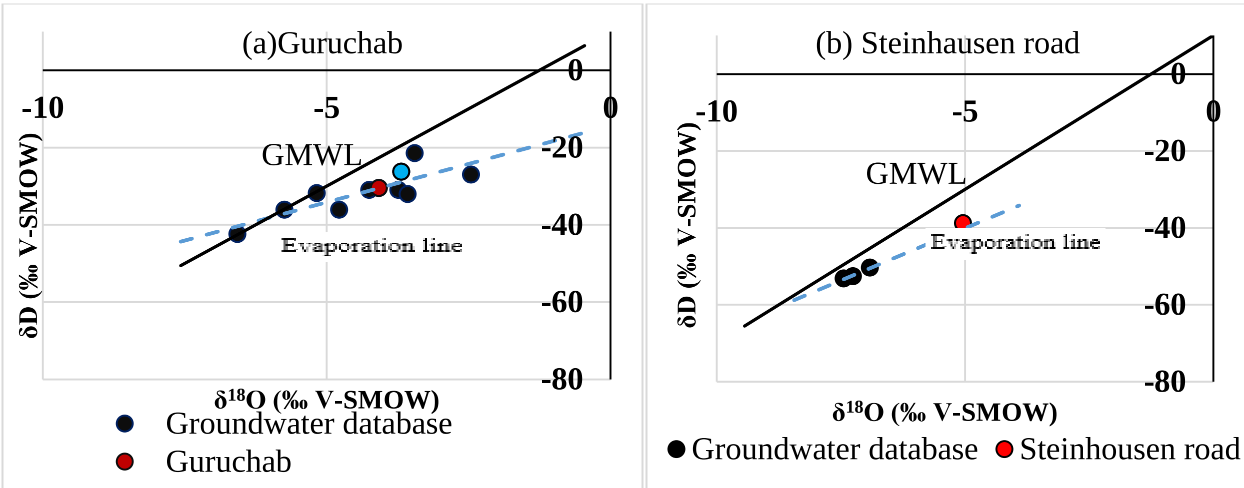


Figure 4.1: Groundwater $\delta^{18}O$ and δD composition for (a) Guruchab and (b) Steinhausen.

Ebenhazer sampled groundwater had $\delta^{18}O$ and δD composition of -7.22‰ and -53.6‰ (Figure 4.2 (a)). It was within the range of groundwater database which varied from -7.9‰ to -4.8‰ (mean -6.82 ± 0.8‰) and -56.0‰ to -41.0‰ (mean: -49.58 ± 3.9‰). Sampled groundwater from Stinkwater plotted along the GMWL and the groundwater database $\delta^{18}O$ and δD composition varied from -9.27‰ to -6.19‰ (mean -7.82 ± 1.5‰) and -60.72‰ to -42.49‰ (mean: -50.33 ± 8.5‰) (Figure 4.2(b)).

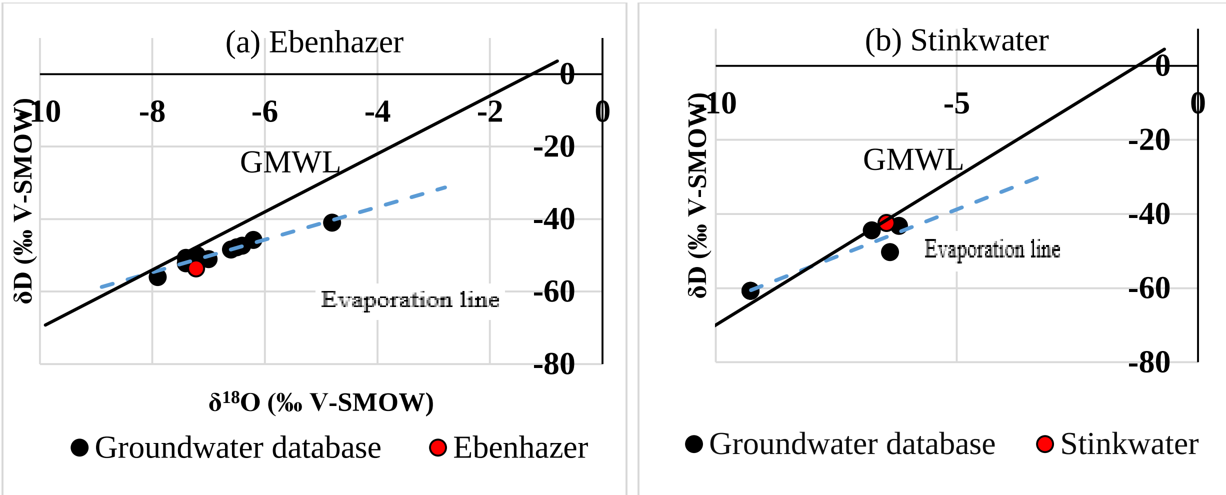


Figure 4.2: Groundwater $\delta^{18}O$ and δD composition for (a) Ebenhazer and (b) Stinkwater.

Warmbad sampled groundwater had $\delta^{18}O$ and δD composition of -5.69‰ and -88.5‰; it plotted above the GMWL presumably due to mixing with recent rainfall or a deviating of the LMWL from the GMWL (Figure 4.3(a)), while groundwater database composition varied from -6.79‰ to -2.15‰ (mean -5.17 ± 1.6‰) and -43.68‰ to -18.72‰ (mean: -34.57 ± 7.9‰). Madisa groundwater had the same $\delta^{18}O$ as Warmbad, but different deuterium excess, d excess = 2.24‰ and -42.45‰ for Madisa and Warmbad, respectively. Madisa sampled groundwater had $\delta^{18}O$ and δD composition of -5.53‰ and -42.0‰ (Figure 4.3(b)). It was within the range of groundwater database which varied from -9.70‰ to -3.73‰ (mean -5.67 ± 1.8‰) and -68.50‰ to -29.10‰ (mean: -40. 06 ± 12.1‰).

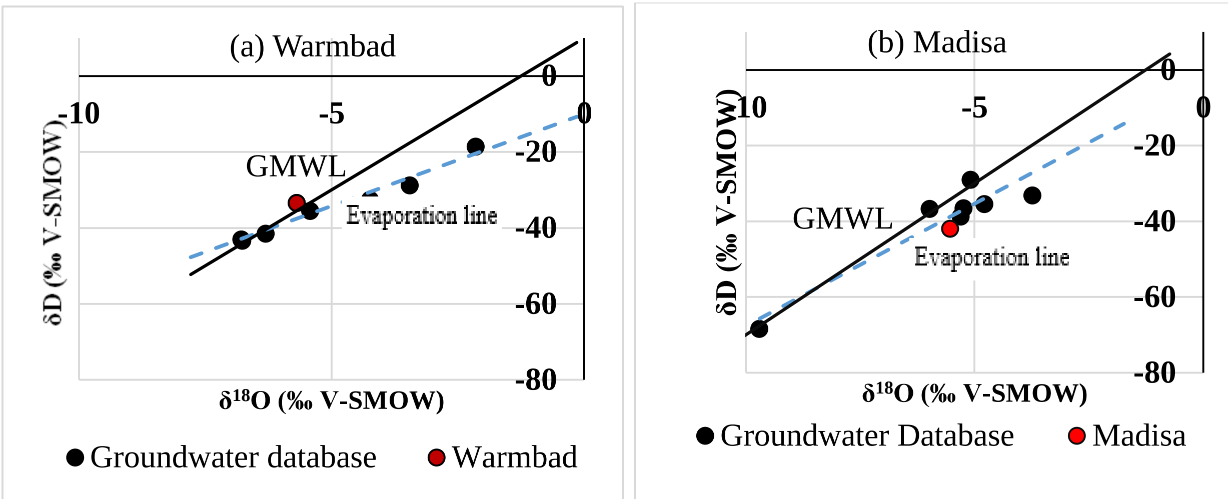


Figure 4.3: Groundwater $\delta^{18}O$ and δD composition for (a) Warmbad and (b) Madisa.

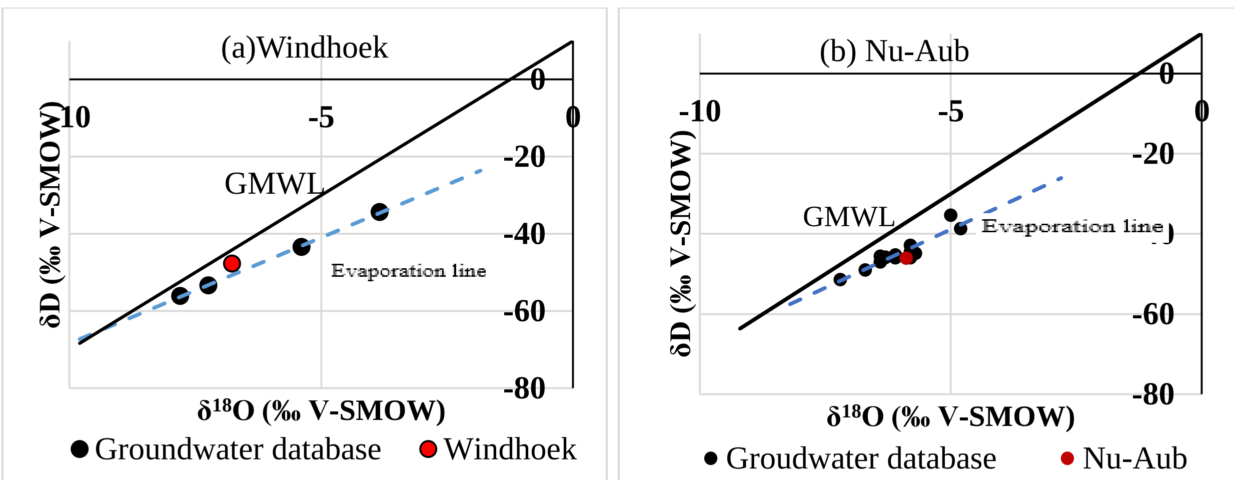


Figure 4.4: Groundwater $\delta^{18}O$ and δD composition at (a) Windhoek and (b) Nu-Aub.

Enyana and Fair- Constantia had the most depleted isotopic data. At Enyana sampled groundwater had $\delta^{18}O$ and δD composition of -8.11‰ and -59.2‰. Which was fitting perfectly in groundwater database of composition varying from -9.14‰ to -6.57‰ (mean -8.30 ± 0.78‰) and -66.5‰ to -49.11‰ (mean: -60.49 ± 5.3‰). Fair-Constantia sampled groundwater had $\delta^{18}O$ and δD composition of -7.60‰ and -53.6‰, while groundwater databases $\delta^{18}O$ and δD composition varied from -8.99‰ to -1.64‰ (mean -13.57 ± 4.6‰) and -63.97‰ to -24.55‰

(mean: -51.98 ± 9.4‰). Seisfontein groundwater database $\delta^{18}O$ and δD composition varied from -9.70‰ to -3.73‰ (mean -5.93 ± 1.88‰) and -68.5‰ to -29.1‰ (mean: -41.51 ± 13‰). Sampled groundwater had $\delta^{18}O$ and δD composition of -7.60‰ and -53.6‰.

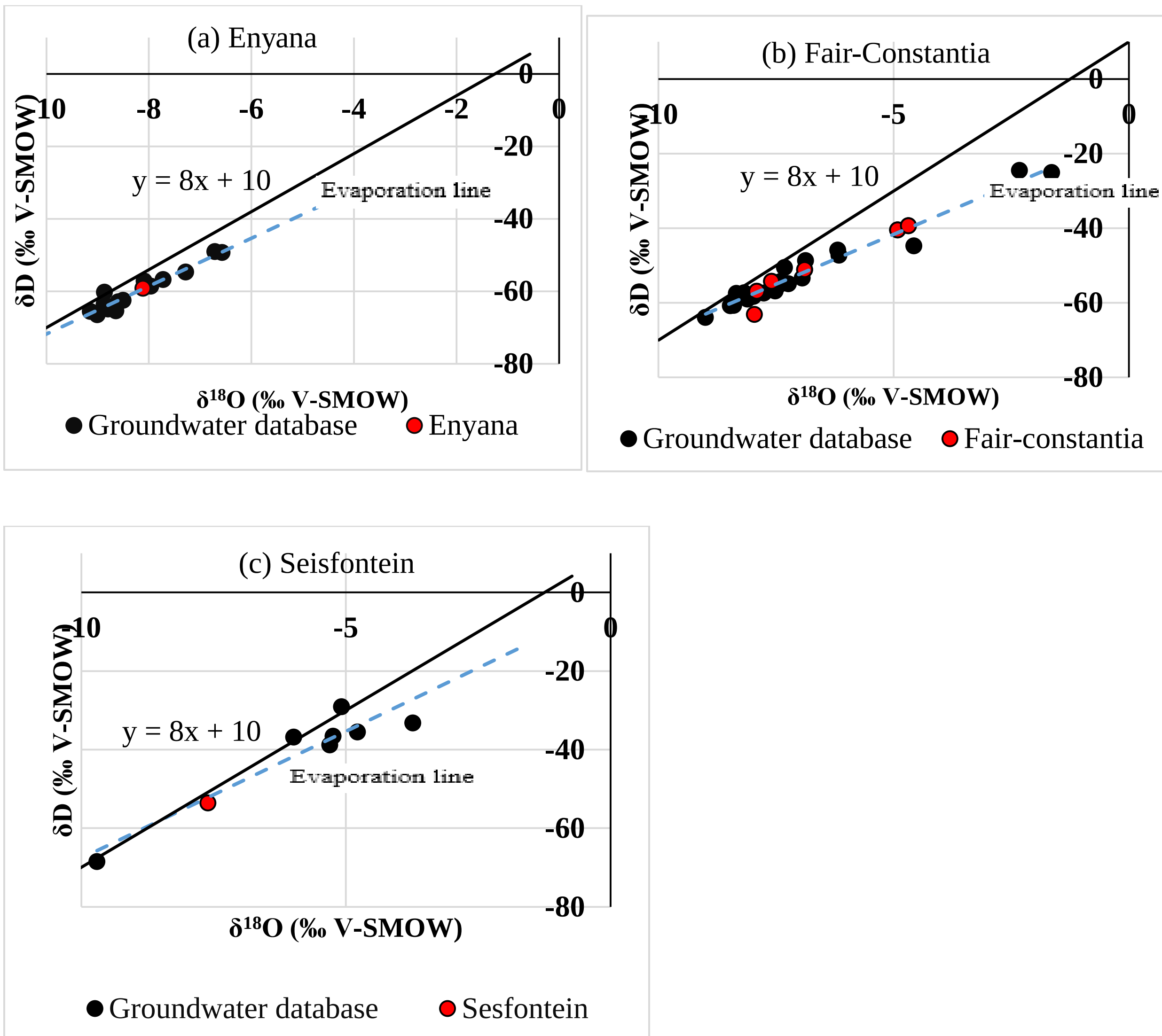


Figure 4.5: Groundwater $\delta^{18}O$ and δD composition for (a) Enyana, (b) Fair-Constantia and (c) Seisfontein.

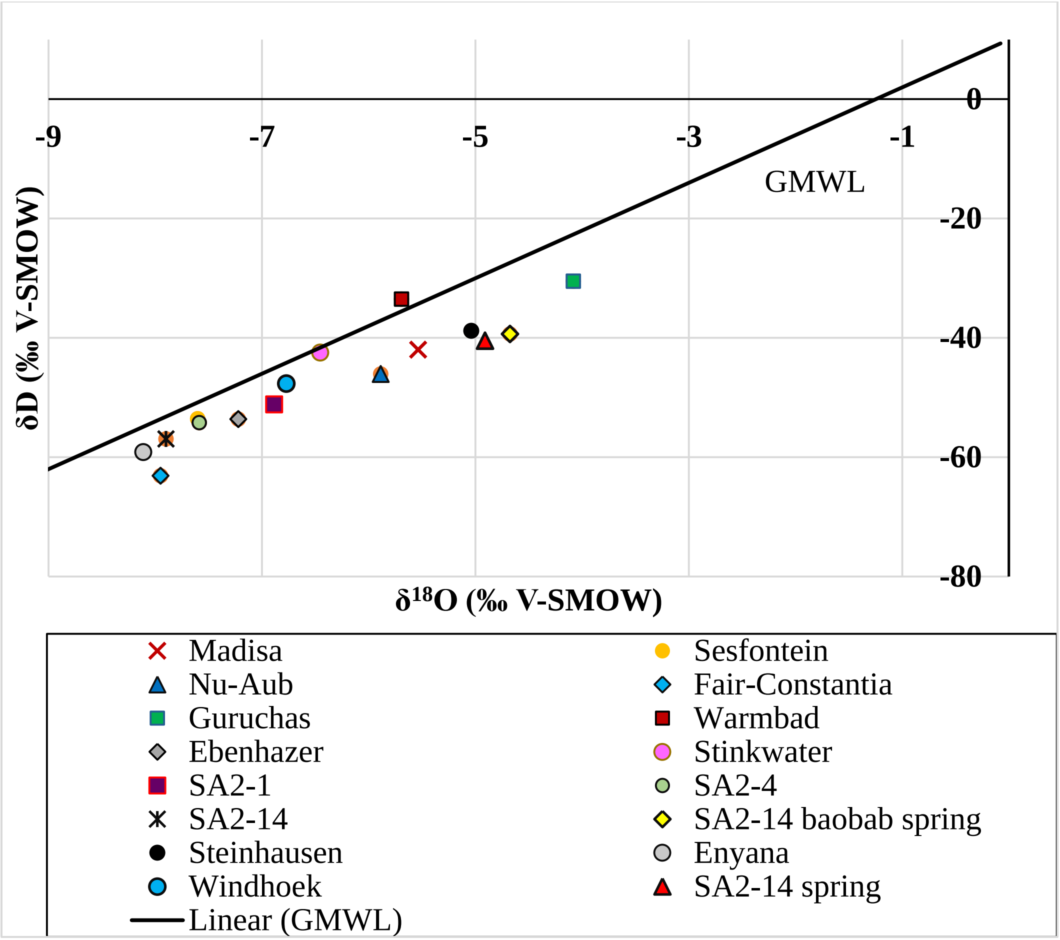


Figure 4.6: Groundwater $\delta^{18}O$ and δD composition of all study sites.

Groundwater $\delta^{18}O$ and δD composition of all collected samples varied from -8.11‰ to -4.08‰, (mean:-6.39 ± 1.3‰) and -63.15‰ to -30.51‰, (mean:-46.43 ± 10.3‰). None of the analyses in this study lie considerably off the meteoric water line; this implies that none of the samples have undergone substantial evaporation that would modify their oxygen and hydrogen isotopic composition. Samples plotting closer (Windhoek and Seisfontein) or on the GMWL line (Stinkwater) are likely to be recharged directly from local precipitation with little evaporation.

All groundwater samples fall below the Global Meteoric Water Line (GMWL), except for Warmbad. The deviation from the GMWL is due to evaporation process, typical of semi-arid to arid climatic conditions. Groundwater samples from the north part of the country were more depleted in heavy isotopes, while samples from the southern part were least depleted/ enriched in heavy isotopes.

Model calculation has shown that groundwater from Guruchab was recharged from precipitation with $\delta^{2}H$ and $\delta^{18}O$ values of -6.3‰ and -40.6‰, respectively. This shows that the standing water from Guruchab must has been around for quite some time to have attained such enriched composition of -0.07‰ and -11.8‰ for $\delta^{18}O$ and δD.

4.2 Isotopic composition of precipitation

Isotopic composition of precipitation where groundwater originated was traced by calculating the intersection points of local groundwater evaporation lines with GMWL.

Table 4.1: $\delta^{18}O$ and δD composition of groundwater, deuterium excess and isotopic composition of recalculated precipitation.

Site	**Groundwater $\delta^{18}O$ (‰)**	**Groundwater δD(‰)**	***d*-excess(‰)**	**Precipitation $\delta^{18}O$**	**Precipitation δD**
SA2-14	-4.68	-39.3	-1.9	-8.1	-54.7
Fair Constantia	-7.95	-63.1	0.4	-10.7	-75.4
Nu-Aub	-5.89	-46.1	1	-8.4	-57.6
Steinhausen	-5.04	-38.8	1.4	-7.5	-49.8
Guruchab	-4.08	-30.5	2.1	-6.3	-40.6

Table 4.2 continues.

Madisa	-5.53	-42	2.2	-7.7	-52
SA2-1	-6.88	-51.2	3.9	-8.6	-59
Ebenhazer	-7.22	-53.6	4.1	-8.9	-61.2
Enyana	-8.11	-59.2	5.7	-9.3	-64.7
SA2-14	-7.9	-56.9	6.2	-9	-61.8
SA2-4	-7.58	-54.2	6.4	-8.6	-58.8
Windhoek	-6.77	-47.7	6.5	-7.8	-52.3
Seisfontein	-7.6	-53.6	7.2	-8.4	-57.2
Stinkwater	-6.45	-42.5	9.1	-6.7	-43.6
Warmbad	-5.69	-33.5	12	Not calculated as sample plots above GMWL	

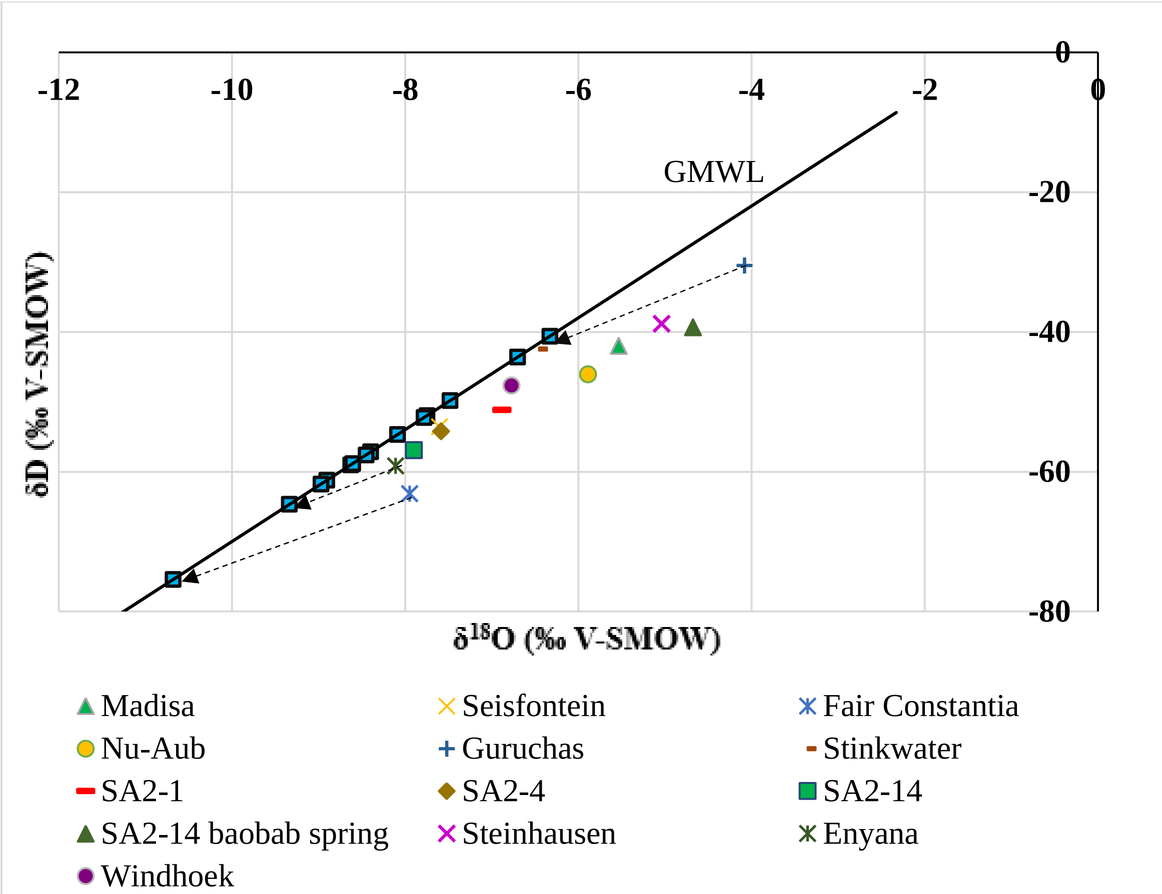


Figure 4.7: Groundwater (blue squares) and calculated source precipitation δD and $\delta^{18}O$ compositions with reference to GMWL. Samples from the north east (Fair Constantia and Enyana) have the most depleted source water. While samples from the southern part have more enriched source water.

4.3 Precipitation isotopic variation

4.3.1 Latitude effect

A strong negative correlation (R^2=0.64) existed between calculated $\delta^{18}O$ of precipitation and latitude and it is statistically insignificant (P>0.05). The observed gradient over the entire country was approximately -0.37‰ per degree latitude for $\delta^{18}O$.

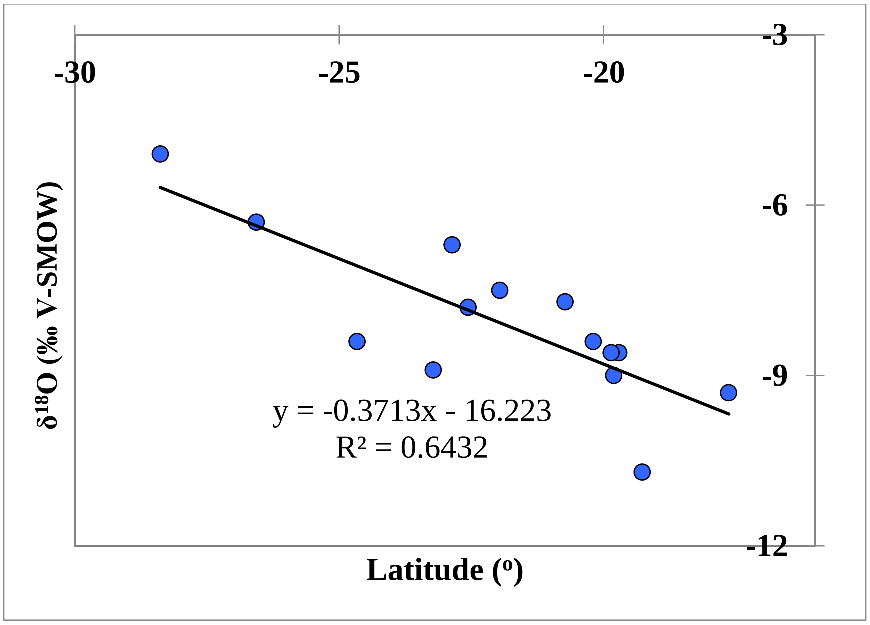


Figure 4.8: The relationship between latitude and precipitation $\delta^{18}O$ values of all the sampling points.

4.3.2 Longitude

The correlation between longitude and $\delta^{18}O$ composition of precipitation was very weak (R^2=0.016) and statistically insignificant (P>0.05). The observed longitude effect was approximately 0.09‰ $\delta^{18}O$ per degree longitude.

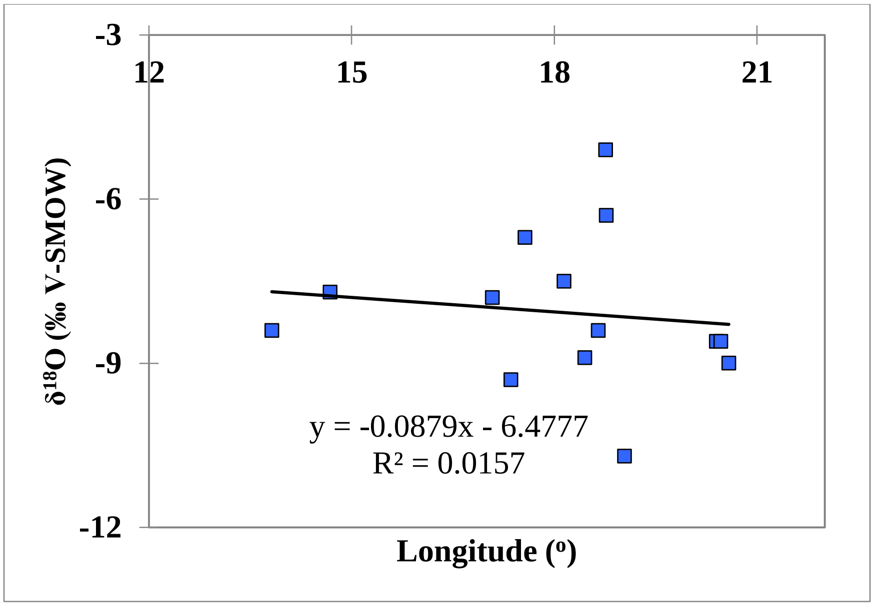


Figure 4.9: The relationship between longitude and precipitation $\delta^{18}O$ values of all the sampling points.

4.3.3 Distance from the coast

The correlation between distance from the coast and $\delta^{18}O$ composition of precipitation was negatively and weak (R^2=0.29) and statistically significant ($P<0.05$). A relationship between $\delta^{18}O$ in precipitation and its distance from the coast was found with an estimated depletion rate of -0.31 ‰ in precipitation per 100 km inland.

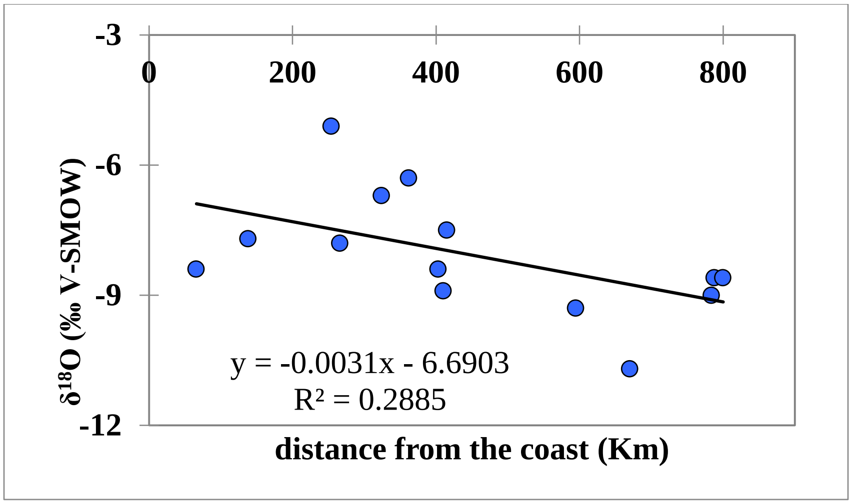


Figure 4.10 The relationship between distance from the coast and precipitation $\delta^{18}O$ values of all the sampling points.

4.3.4 Altitude effect

A very weak negative correlation (R^2=0.07) has been noted between $\delta^{18}O$ composition of precipitation and altitude, however the relationship was statistically insignificant (P>0.05). The estimated depletion rate of $\delta^{18}O$ in precipitation was -0.13 ‰ in precipitation per 100 m.

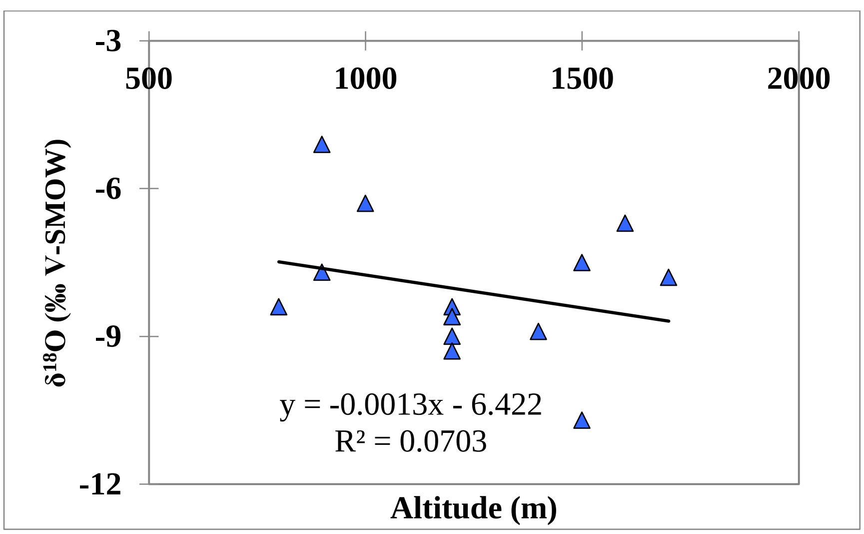


Figure 4.11: The relationship between altitude and precipitation $\delta^{18}O$ values of all the sampling points.

4.3.5 Amount effect

Rainfall $\delta^{18}O$ values are negatively moderately correlated to annual precipitation amount (R= -0.63). Moreover the relationship between the two is statistically significant at $P < 0.05$.

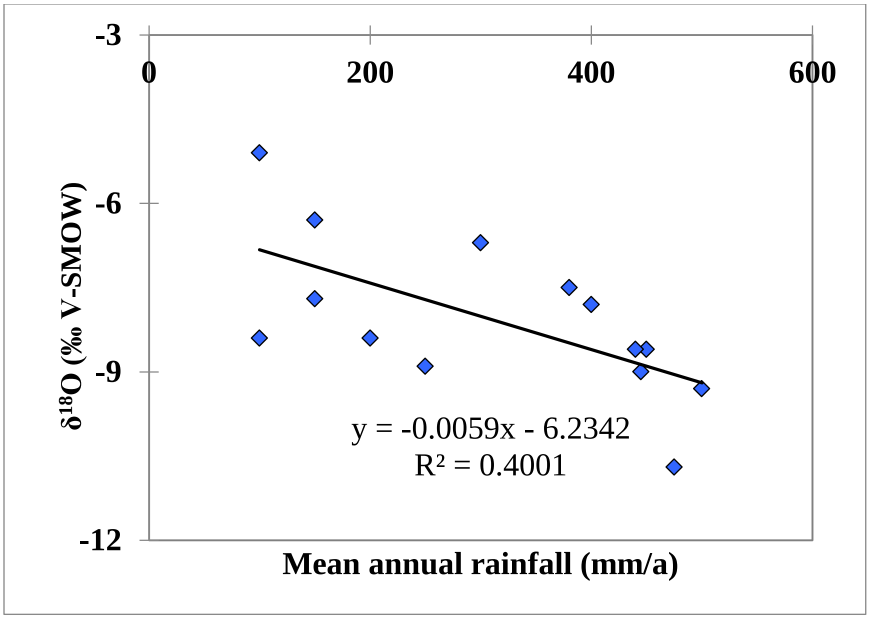
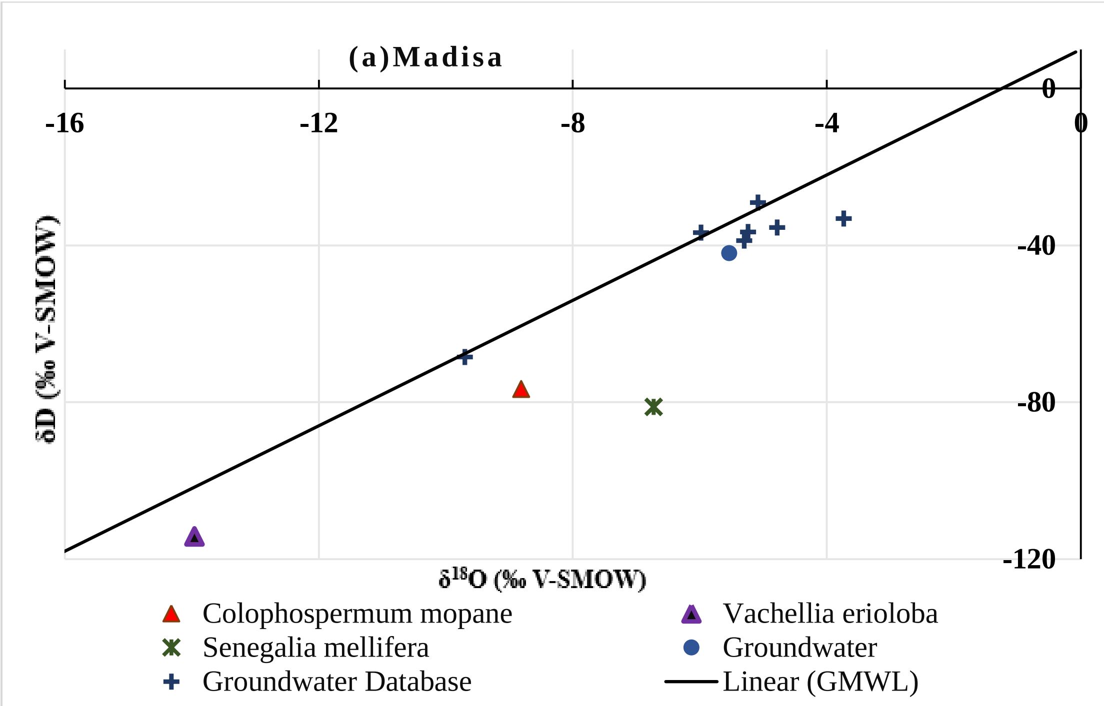
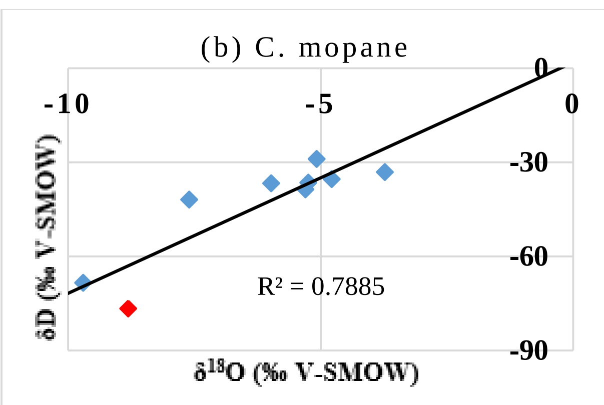


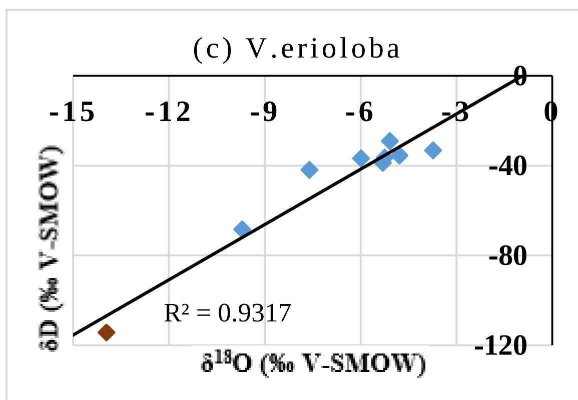
Figure 4.12 The relationship between annual average rainfall and precipitation $\delta^{18}O$ values of all the sampling points.

4.4 Isotopic composition of woody vegetation xylem water

4.4.1 Madisa







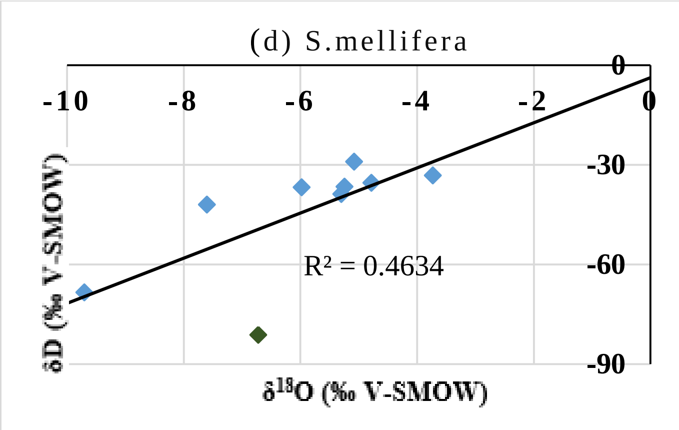


Figure 4.13: Woody vegetation xylem water and groundwater δD and δ^{18}O compositions with reference to GMWL. Linear correlation between groundwater and (b) *C. mopane*, (b) *V.erioloba*, (d) *S. mellifera* at Madisa.

At Madisa, the isotopic composition of the woody vegetation is more negative than groundwater. The δ^{18}O and δD value *of V. erioloba* xylem water was found to be -13.96‰ and -114.3‰, respectively. While, *C. mopane* xylem water δ^{18}O and δD values were -8.81‰ and -76.7‰, respectively. These values were lesser than those obtained from *S. mellifera which* were recorded as -6.72‰ and 81.2‰ for δ^{18}O and δD respectively. *S. mellifera* was transpiring water with slightly similar δ^{18}O composition as local groundwater but highly depleted in δD.

The plot of the xylem water together with groundwater indicate that *S. mellifera* was utilizing groundwater while *V. erioloba* and *C. mopane* were utilizing slightly depleted soil water probably recharged by heavy rainfall some months earlier.

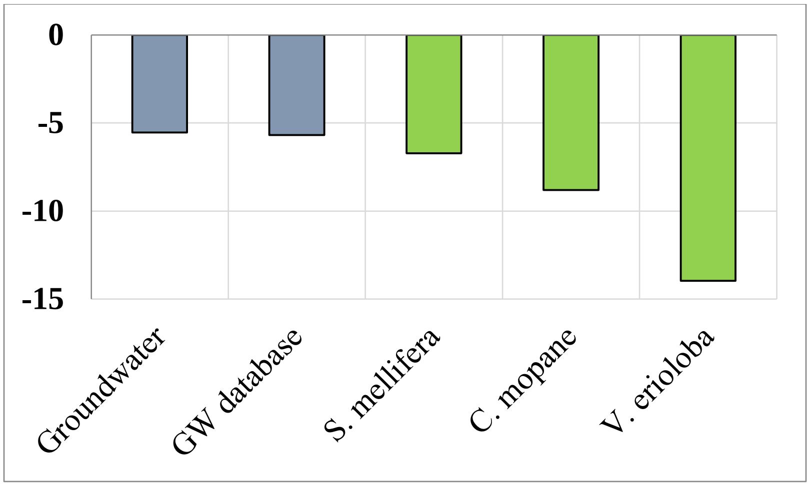


Figure 4.14: Mean $\delta^{18}O$ (‰) for woody vegetation and groundwater at Madisa.

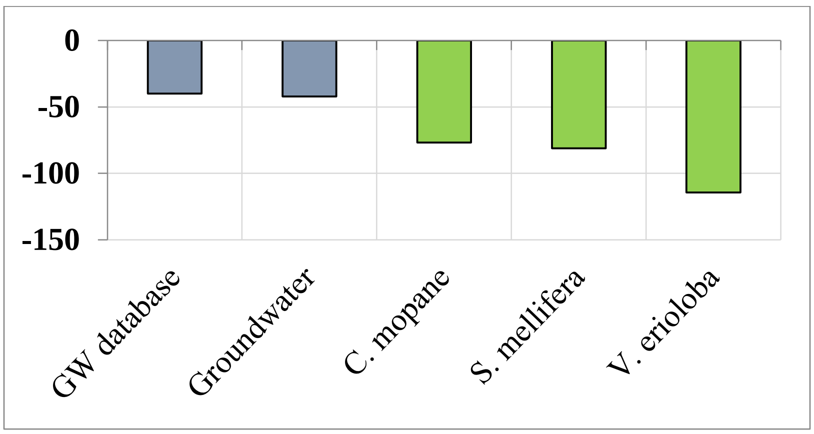
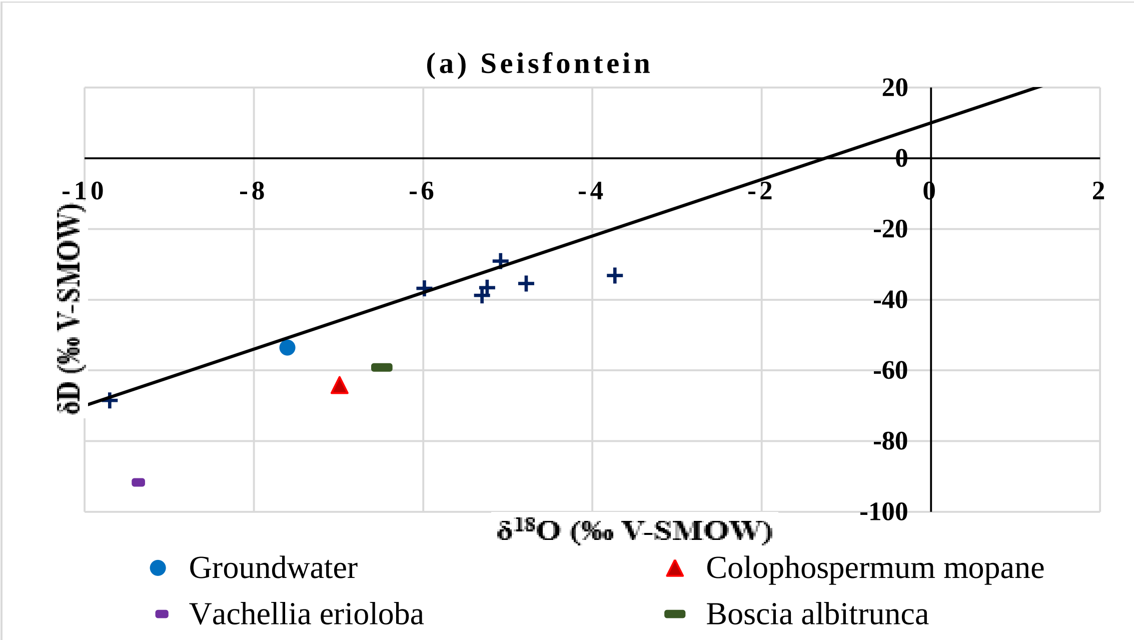
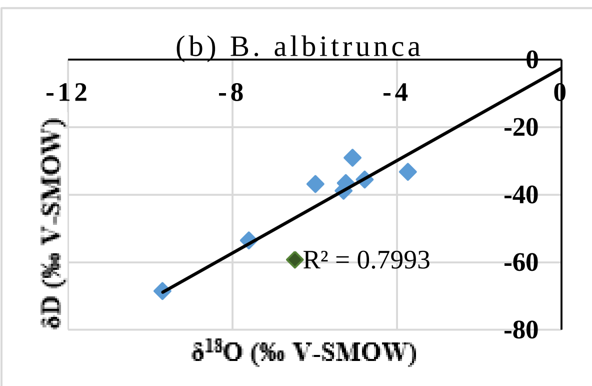
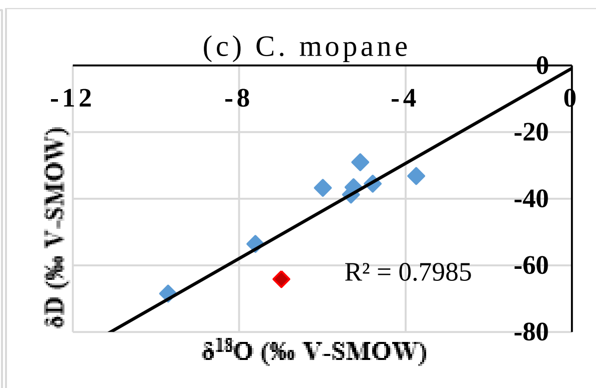


Figure 4.15: Mean $\delta^{2}H$ (‰) for woody vegetation and groundwater at Madisa.

4.4.2 Seisfontein







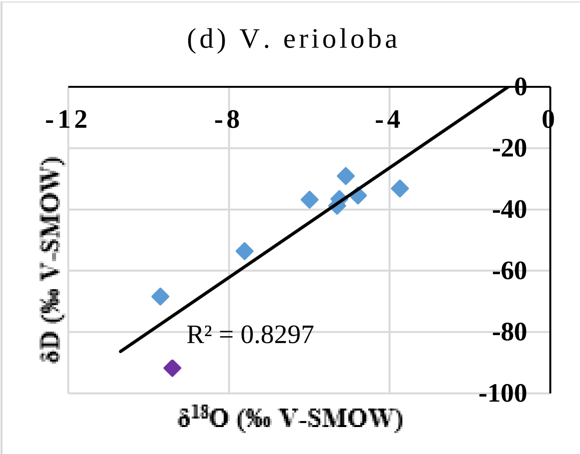


Figure 4.16: (a) Woody vegetation xylem water and groundwater δ^2H and δ^{18}O compositions with reference to GMWL. A biplot of δ^{18}O – δ^2H showing regression relationship between groundwater (b) *B. albitrunca*, (c) *C.mopane* and (d) *V. erioloba* at Seisfontein.

Groundwater plotted along the GMWL unlike woody species xylem water which all deviated from the GMWL. *C. mopane* and *B. albitrunca* xylem water had isotopic composition similar to groundwater. *C. mopane* xylem water δ^{18}O and δD composition was -6.99‰ and 64.2‰, respectively. This was slightly similar to *B. albitrunca*, which was 6.48‰ and 59.2‰. Meanwhile *V. erioloba* xylem water was the most depleted, isotopic composition was -9.41‰ and - 94.7‰, for δ^{18}O and δD respectively, but was still within the groundwater database range. From the analysis of δ^{18}O and δD data, all sampled species appear to have been using groundwater in the same range as groundwater database, but slightly depleted in δD.

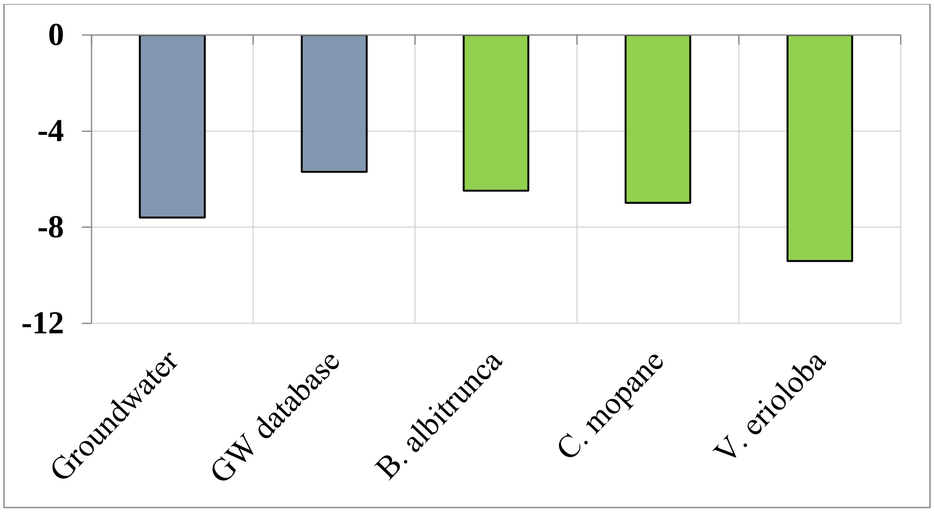


Figure 4.17: Mean $\delta^{18}O$ (‰) for woody vegetation and groundwater at Seisfontein.

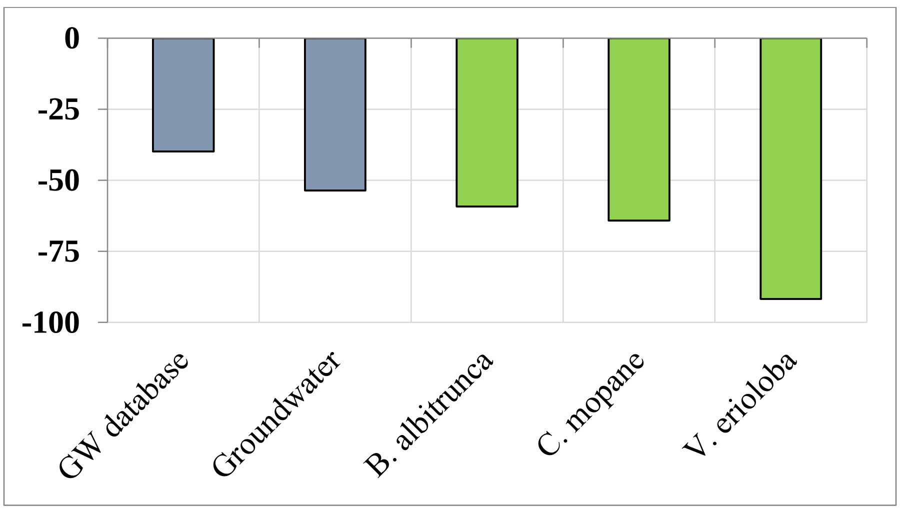
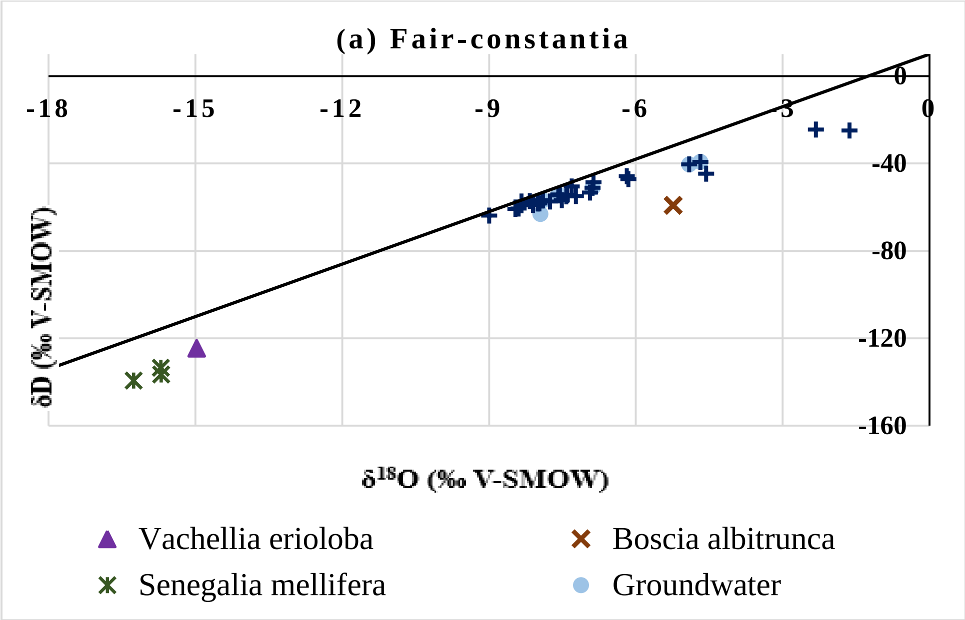
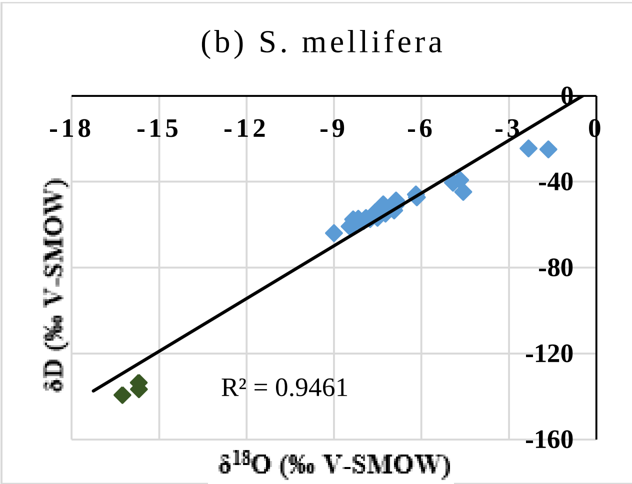
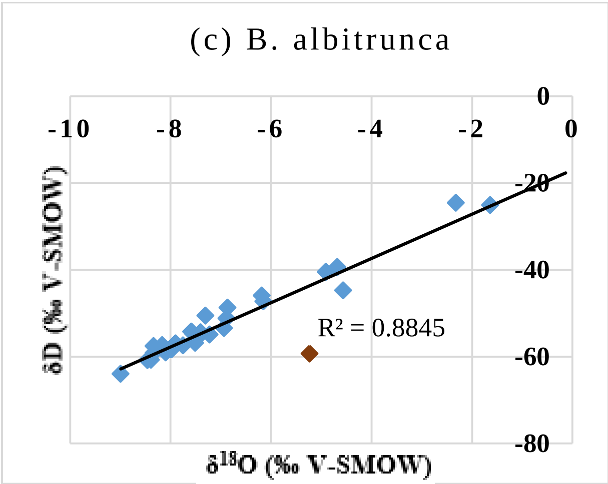


Figure 4.18: Mean $\delta^{2}H$ (‰) for woody vegetation and groundwater at Seisfontein.

4.4.3 Fair-Constantia







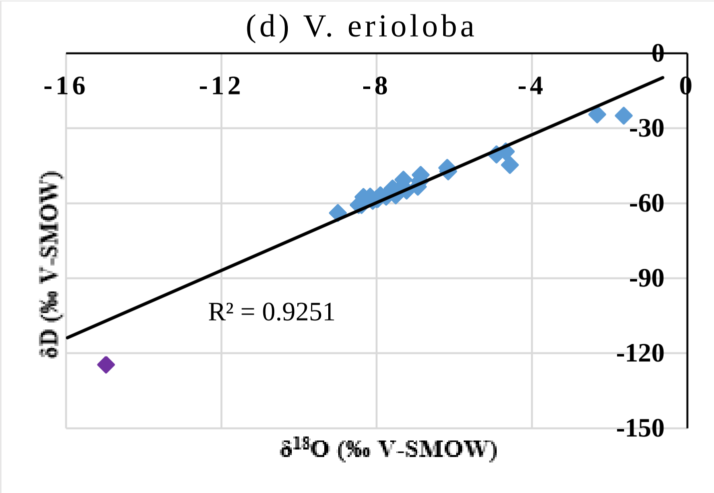


Figure 4.19: Figure 4.19 (a) Woody vegetation xylem water and groundwater δ2H and δ18O compositions with reference to GMWL. A biplot of $\delta^{18}O - \delta^{2}H$ showing regression relationship between groundwater and (b) *S.mellifera*, (c) *B.albitrunca* and (d) *V. erioloba* at Fair Constantia.

At this study site xylem water isotope composition for *S. mellifera* was the most depleted, followed by *V. erioloba*. Moreover *B. albitrunca* xylem isotope composition was similar to local groundwater. This confirms that *B. albitrunca* was utilizing groundwater while *V erioloba* and *S. mellifera* were utilizing soil water.

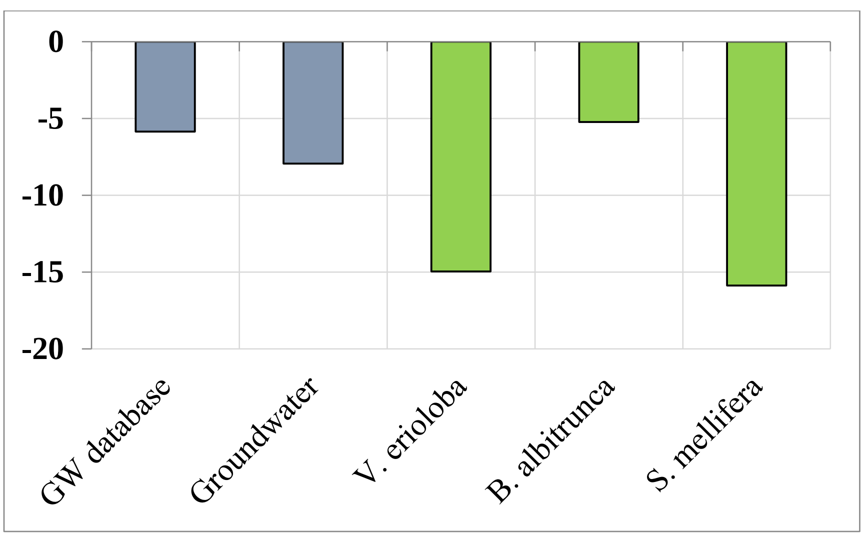


Figure 4.20: Mean $\delta^{18}O$ (‰) for woody vegetation and groundwater at Fair-Constantia.

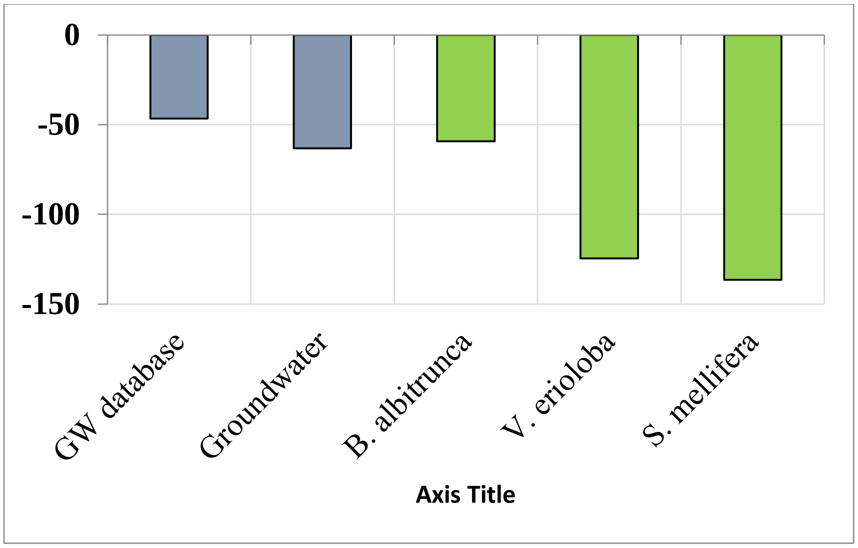


Figure 4.21: Mean δ^2H (‰) for woody vegetation and groundwater at Fair-Constantia.

4.4.4 Stinkwater

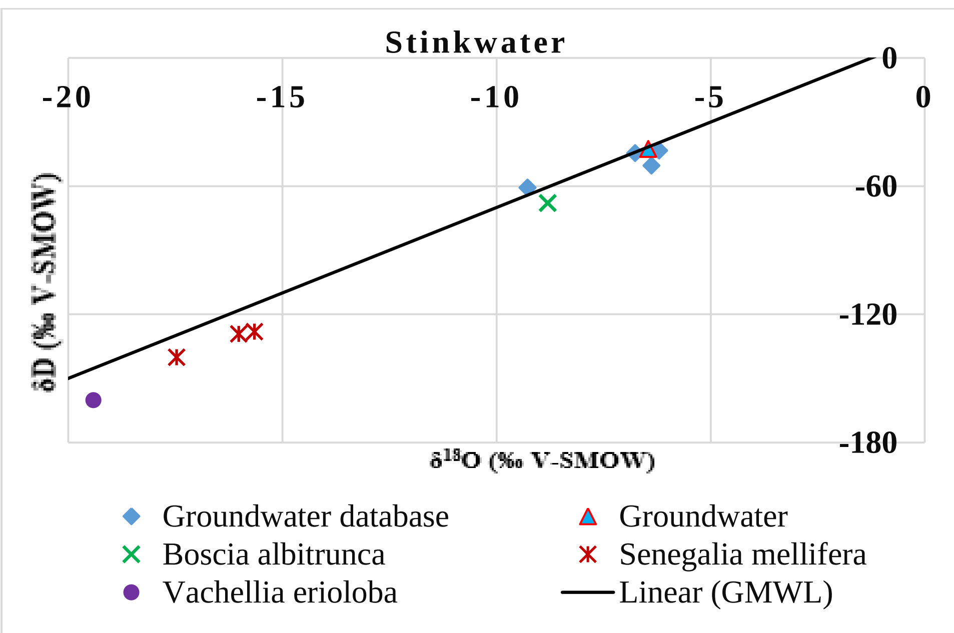


Figure 4.22 Woody vegetation xylem water and groundwater δ^2H and δ^{18}O compositions with reference to GMWL.

Groundwater $\delta^{18}O$ and δD composition was -6.45‰ and -42.5‰. *B.albitrunca* xylem water isotopic composition was similar to local groundwater. Meanwhile, *V. erioloba* and *S. mellifera* were utilizing water with a much depleted isotopic composition. These data implies that *B. albitrunca* was transpiring groundwater while *S. mellifera* and *V. erioloba* were utilizing soil water. All sampled woody vegetation woody vegetation had a linear regression with slope similar to GMWL

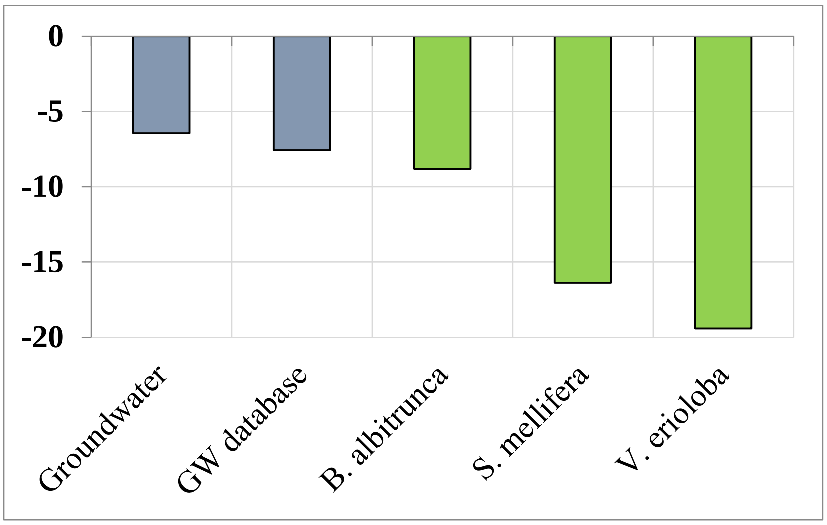


Figure 4.23 Mean $\delta^{18}O$ (‰) for woody vegetation and groundwater at Stinkwater.

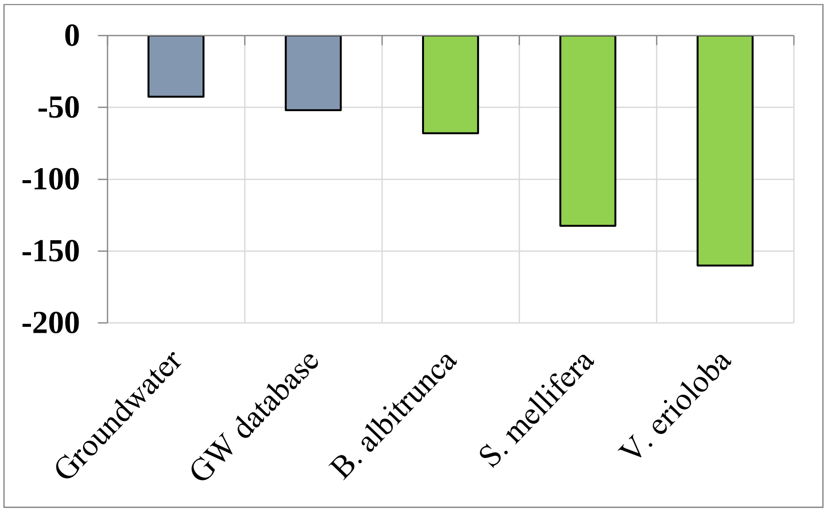
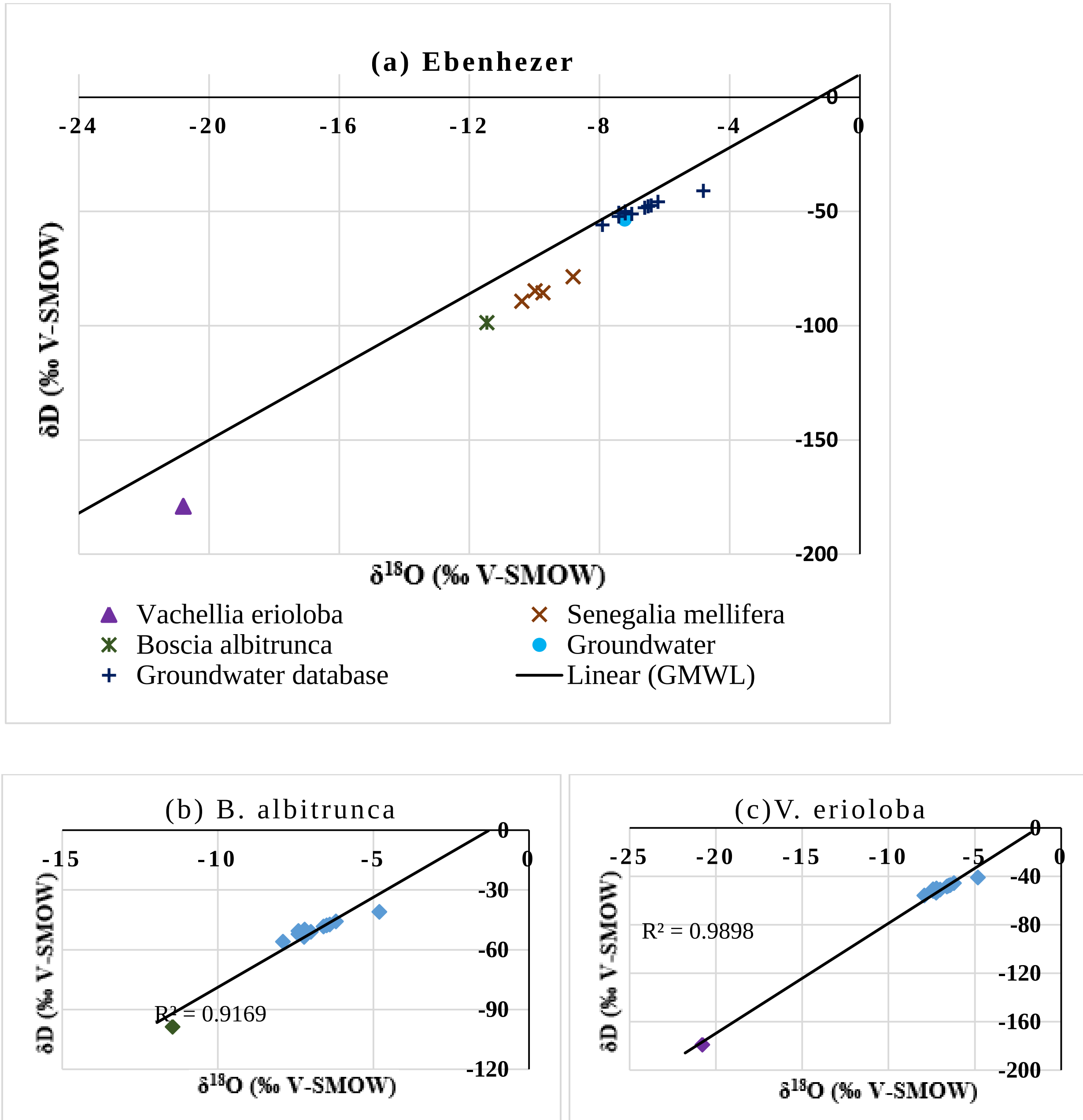


Figure 4.24: Mean δ^2H (‰) for woody vegetation and groundwater at Stinkwater.

4.4.5 Ebenhazer



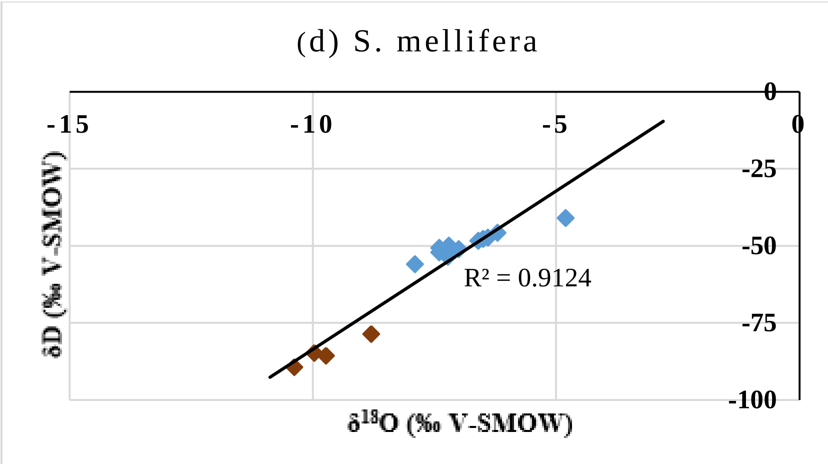


Figure 4.25: (a) Woody vegetation xylem water and groundwater δ^2H and δ^{18}O compositions with reference to GMWL. A biplot of δ^{18}O – δ^2H showing regression relationship between groundwater (b) B. *albitrunca*, (c) *V.erioloba* and (d) *S. mellifera.*

B. albitrunca and *S. mellifera* utilized water that was slightly depleted in δ^{18}O and δD in comparison to groundwater; both are using a mixture of groundwater and soil water. Their isotopic composition plotted close to local groundwater. Xylem water δ^{18}O and δD composition for *S. mellifera* varied from -10.38‰ to -8.8‰ (mean: -9.72 ± 0.7‰) and -89.36‰ to -78.61‰ (mean: -84.45 ± 19.7‰). *V. erioloba* transpired isotopically depleted soil water, the xylem water isotopic composition for *V. erioloba* was -20.78‰ and -179.0‰ for δ^{18}O and δD respectively.

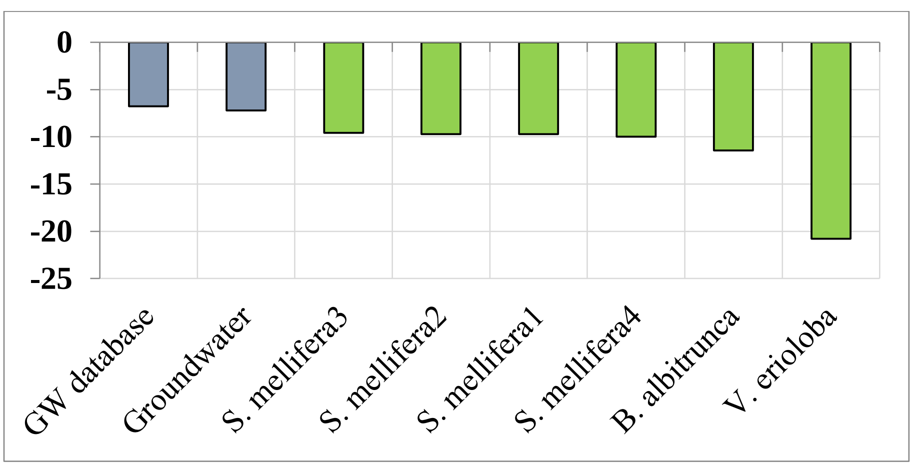


Figure 4.0-26 Mean δ^{18}O (‰) for woody vegetation and groundwater at Ebenhazer.

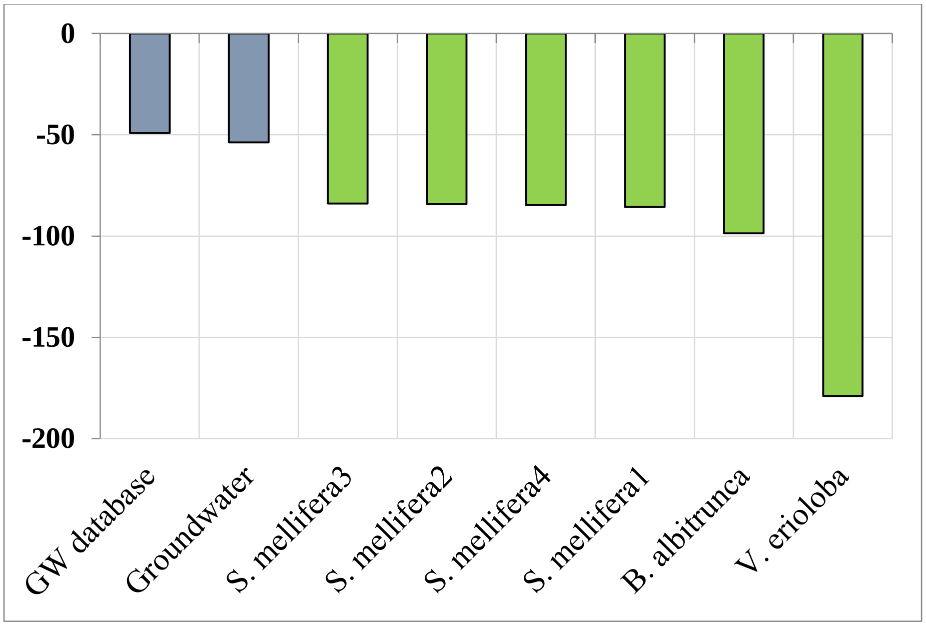
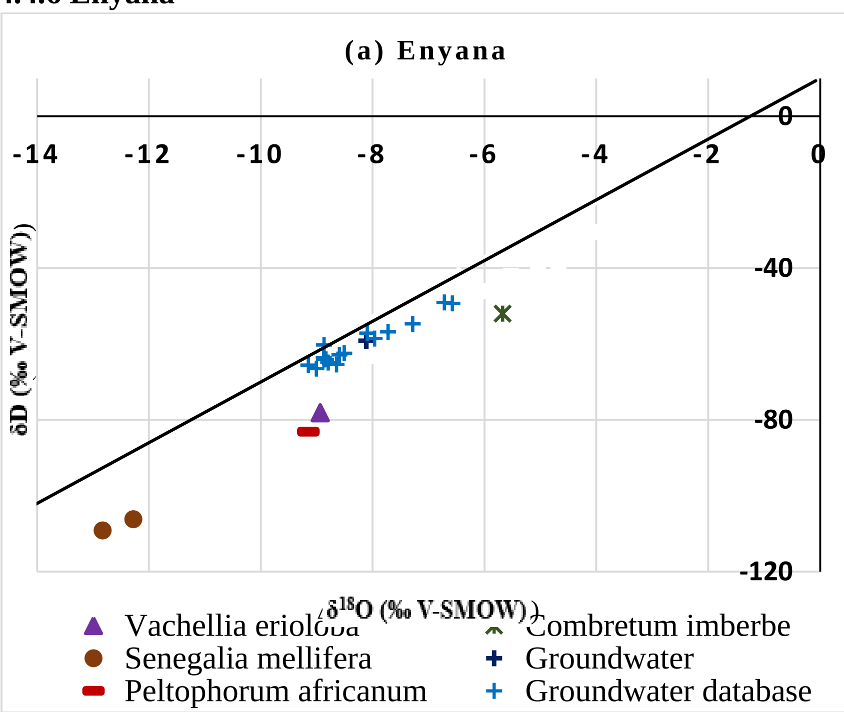


Figure 4.27 Mean δ^2H (‰) for woody vegetation and groundwater at Ebenhazer.

4.4.6 Enyana



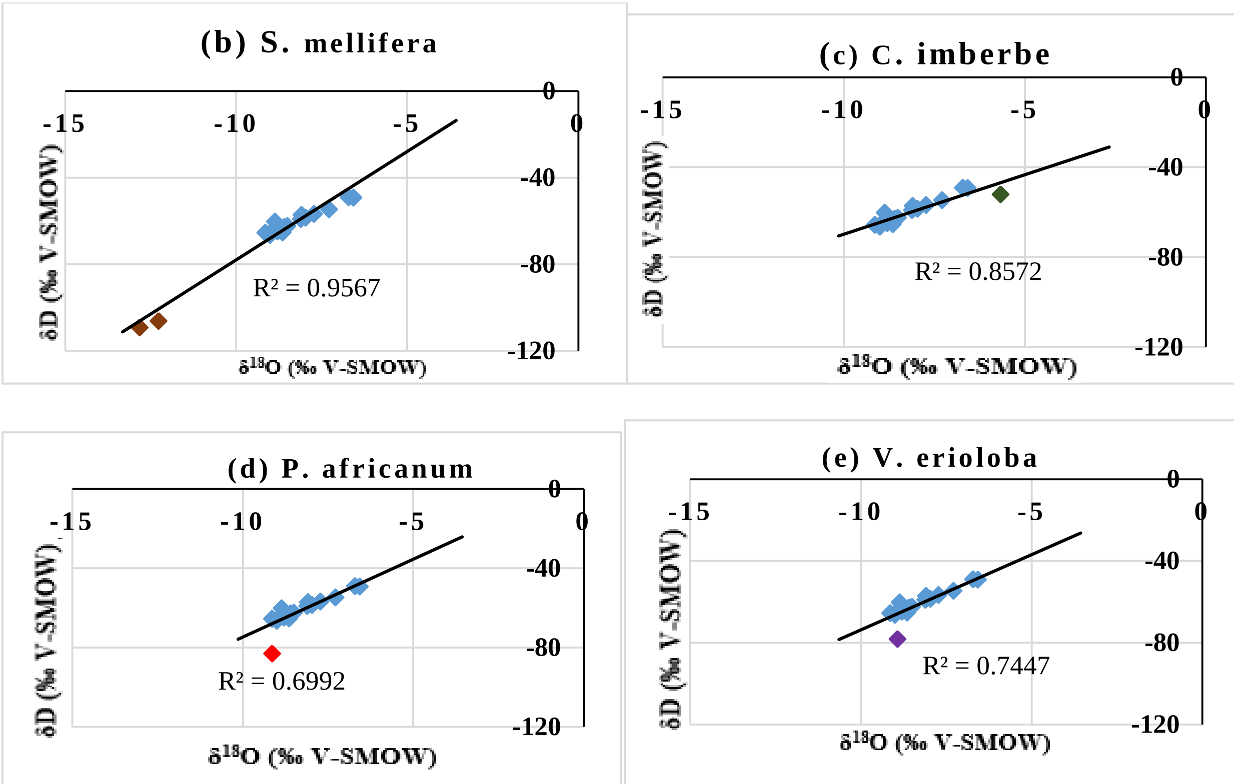


Figure 4.28: Woody vegetation xylem water and groundwater δ^2H and $\delta^{18}O$ compositions with reference to GMWL. A biplot of $\delta^{18}O - \delta^2H$ showing regression relationship between groundwater (b) *S. mellifera*, (c) *C. imberbe* and (d) *P. africanum* (e) *V.erioloba*.

P. africanum xylem water $\delta^{18}O$ and δD composition was -9.14‰ and −83.1‰, respectively. This was slightly similar to that of *V. erioloba*, -8.93‰ and -78.2‰. Unexpectedly *S. mellifera* had the most depleted values, ranged from -12.82‰ to -12.27‰ and from -109.2‰ to -106.2‰ respectively. From these findings it can be deduced that *P. africanum, C. imberbe* and *V. erioloba* in this area were using groundwater, while *S. mellifera* was utilizing soil water..

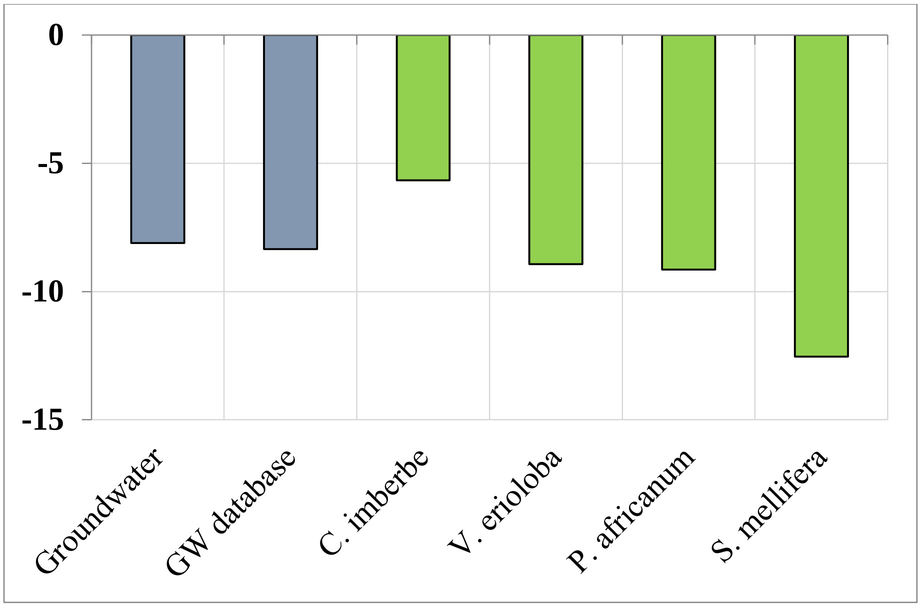


Figure 4.29: Mean $\delta^{18}O$ (‰) for woody vegetation and groundwater at Enyana.

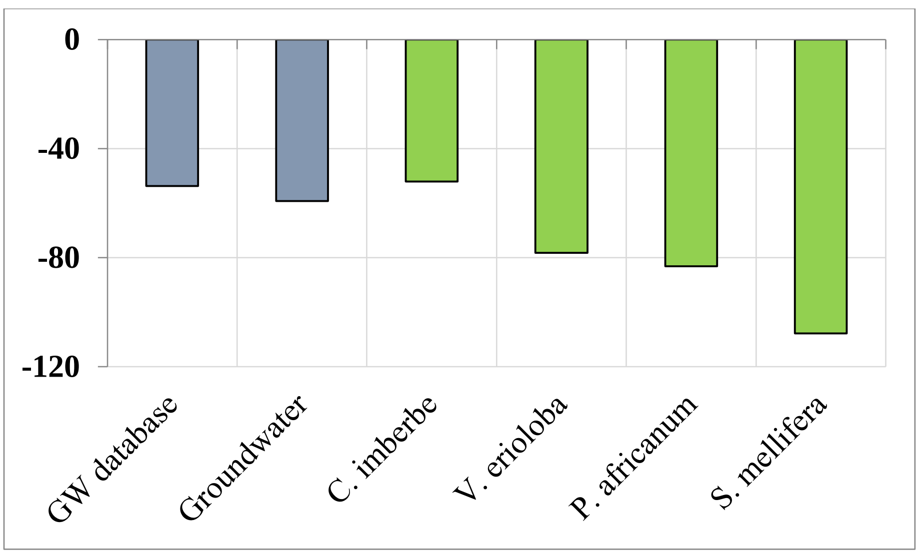
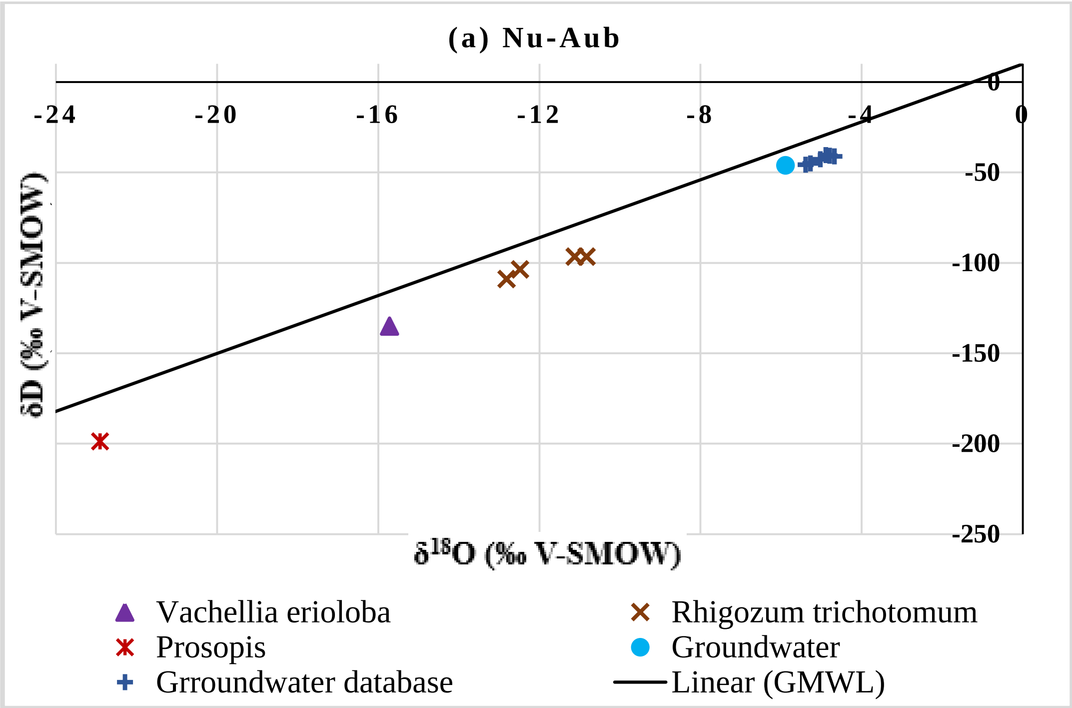
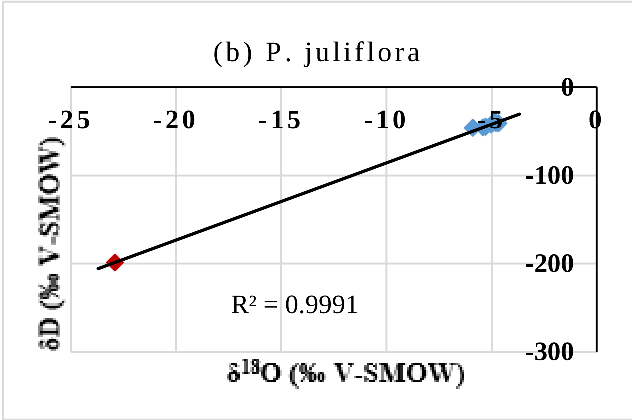
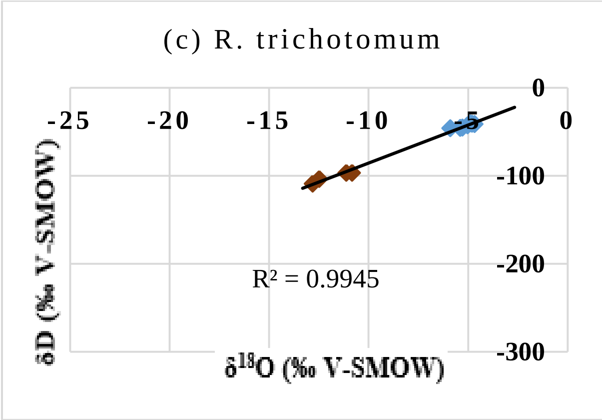


Figure 4.30: Mean $\delta^{2}H$ (‰) for woody vegetation and groundwater at Enyana.

4.4.7 Nu-Aub


(a) Nu-Aub
-24
-20
-16
-12
-8
-4
0
0
-50
-100
-150
-200
-250
δD (‰ V-SMOW)
δ18O (‰ V-SMOW)
Vachellia erioloba
Prosopis
Grroundwater database
Rhigozum trichotomum
Groundwater
Linear (GMWL)


(b) P. juliflora
-25
-20
-15
-10
-5
0
0
-100
-200
-300
R² = 0.9991
δD (‰ V-SMOW)
δ18O (‰ V-SMOW)


(c) R. trichotomum
-25
-20
-15
-10
-5
0
0
-100
-200
-300
R² = 0.9945
δD (‰ V-SMOW)
δ18O (‰ V-SMOW)

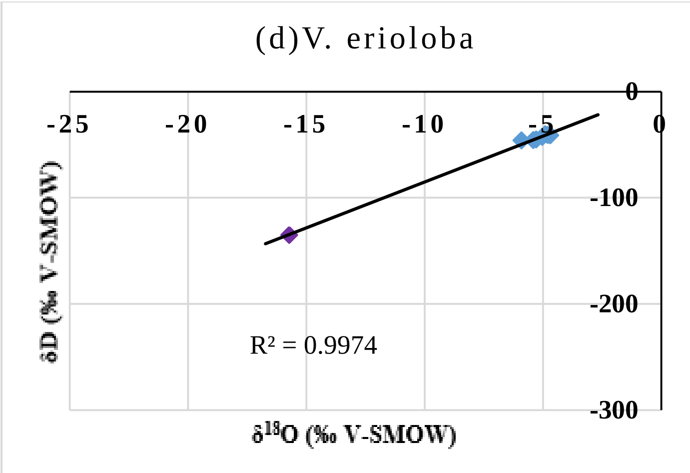


Figure 4.31(a) Woody vegetation xylem water and groundwater δ^2H and δ^{18}O compositions with reference to GMWL. A biplot of δ^{18}O – δ^2H showing regression relationship between groundwater (b) *P. juliflora* (c) *R. trichotomum* and (d) *V. erioloba.*

Isotopic compositions of waters from woody tissue of *P. juliflora* were more negative, followed by *V. erioloba* then *R. trichotomum*. *R. trichotomum* and *V. erioloba* were utilizing a mixture of soilwater and groundwater. While *P. juliflora* was absorbing predominantly soil water, its xylem water δD and δ^{18}O values were depleted with roughly 16‰ δ^{18}O and 150‰ δ^2H relative local groundwater.

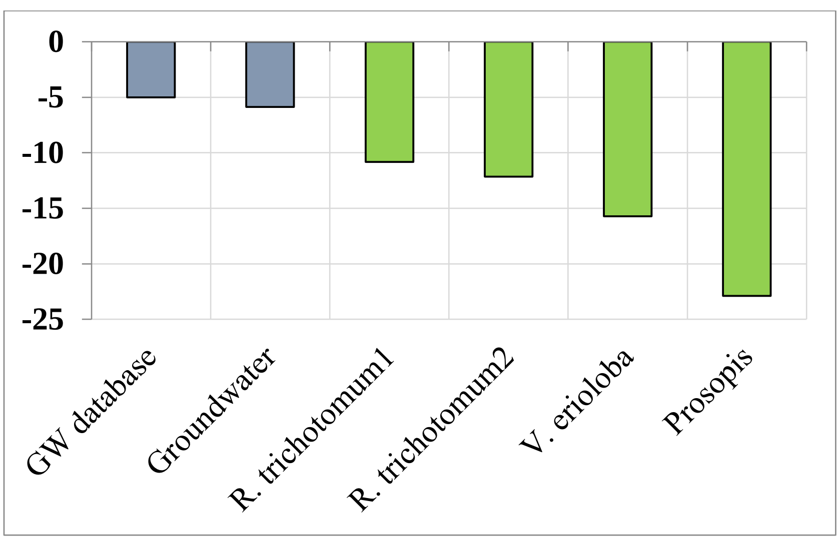


Figure 4.32: Mean $\delta^{18}O$ (‰) for woody vegetation and groundwater at Nu-Aub.

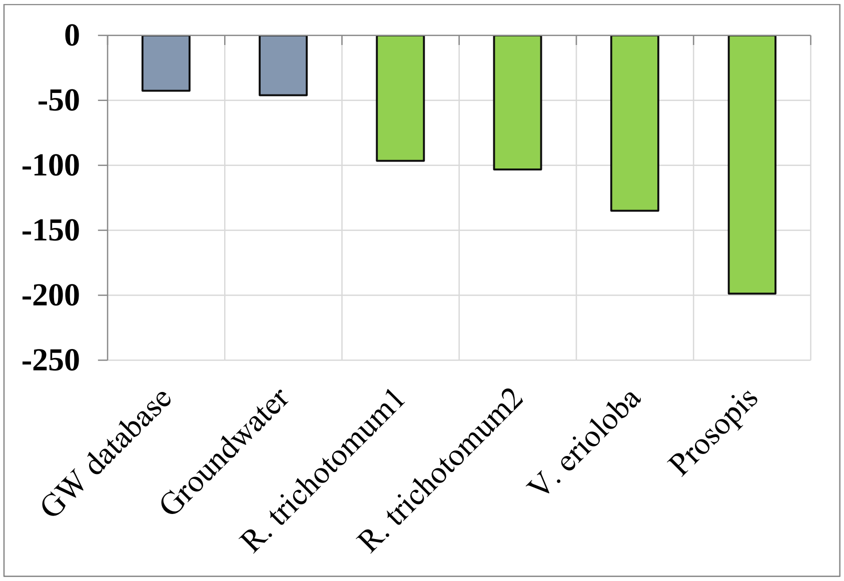
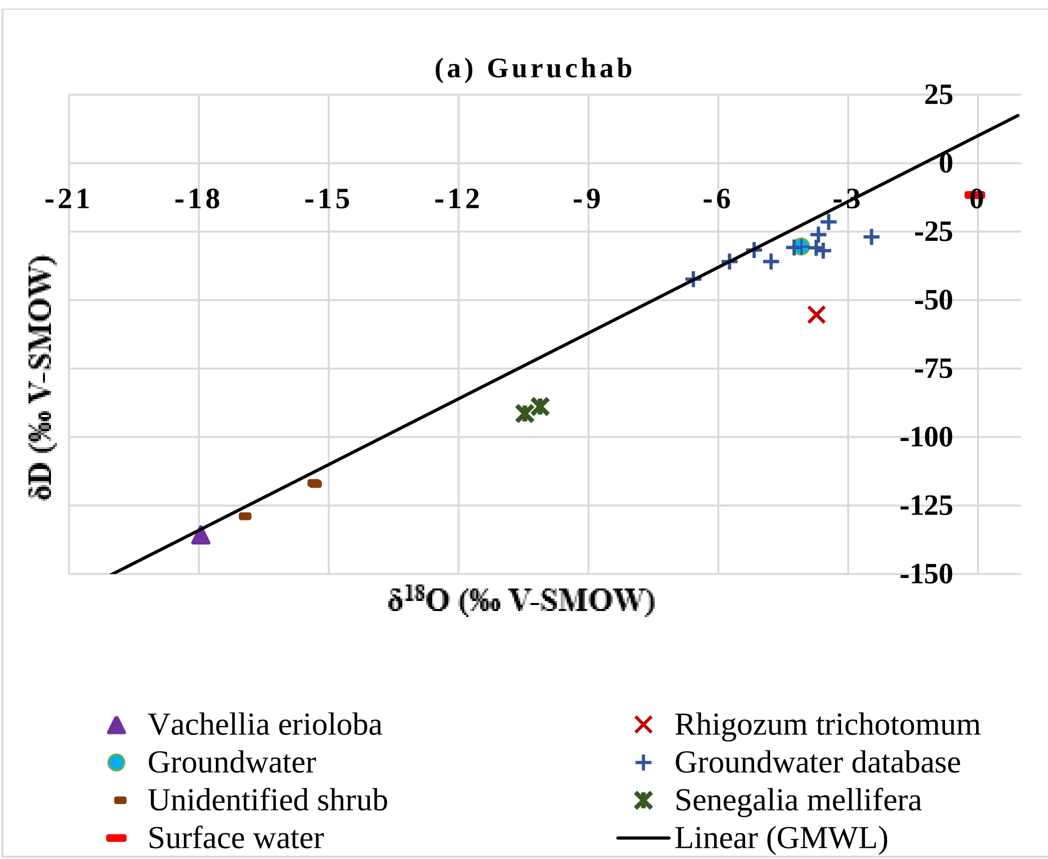


Figure 4.33: Mean $\delta^{2}H$ (‰) for woody vegetation and groundwater at Nu-Aub.

4.4.8 Guruchab



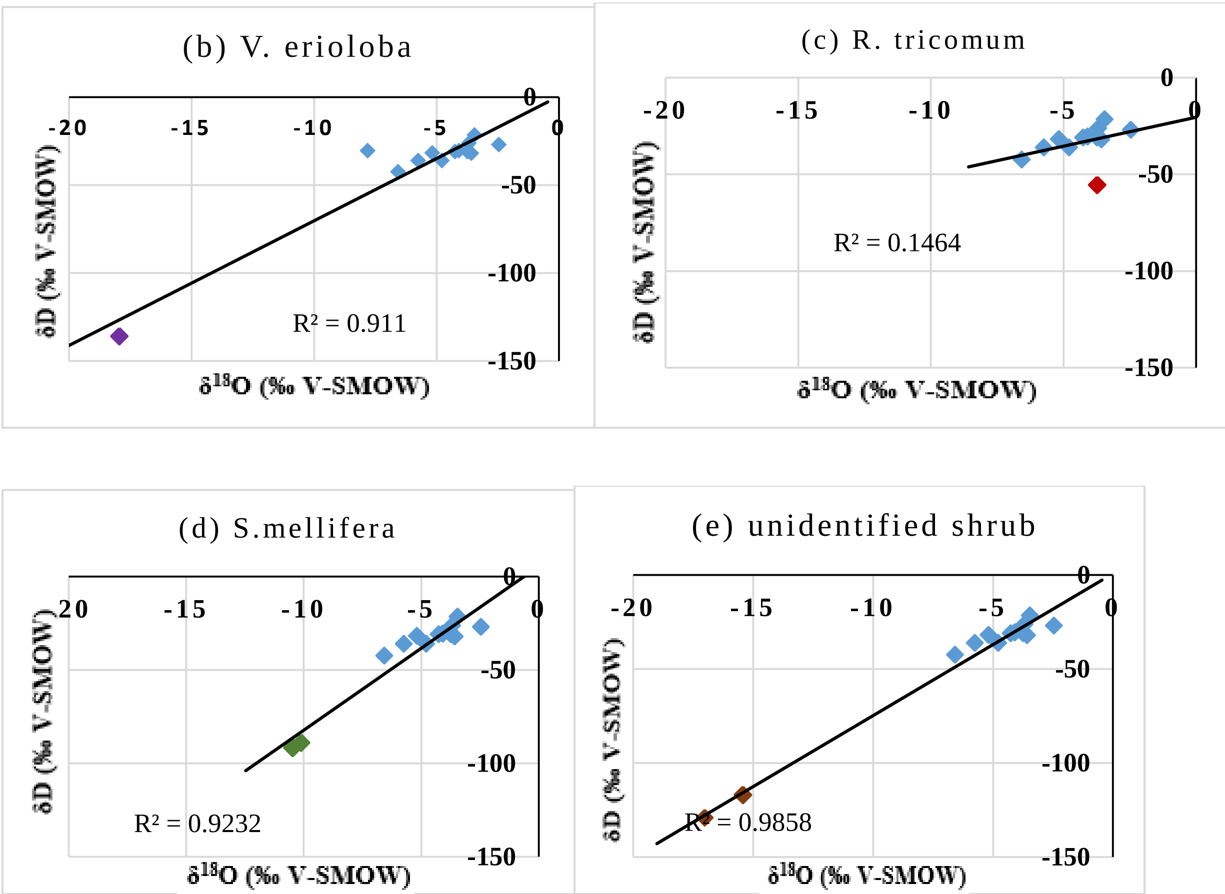


Figure 4.34: (a) Woody vegetation xylem water and groundwater δ^2H and δ^{18}O compositions with reference to GMWL. A biplot of δ^{18}O – δ^2H showing regression relationship between groundwater (b) *V. erioloba* (c) *R. trichotomum* and (d) *S.mellifera* and (e) unidentified shrub.

Woody tissue and surface water samples were collected along Guruchab stream, while groundwater was collected from a nearby farm about 100 m from the stream. Stream water appears to have undergone enrichment in δ^{18}O and δD, likely due to evaporation, however there was no significant difference in δ^{18}O and δD between surface water and groundwater.

The δ^{18}O and δD composition of xylem water from woody tissue of *R. trichotomum* was -3.73‰ and -55.5‰, closely matching the δ^{18}O value of groundwater -4.30‰, but slightly depleted in δD with 24.2‰ in comparison to local groundwater. *V. erioloba* xylem water δ^{18}O and δD composition was found to be -17.95‰ and -135.9‰, respectively which was more depleted than groundwater suggesting water uptake from a much depleted soil layer. These woody vegetations were utilizing soil water except for *R. trichotomum* which was utilizing groundwater.

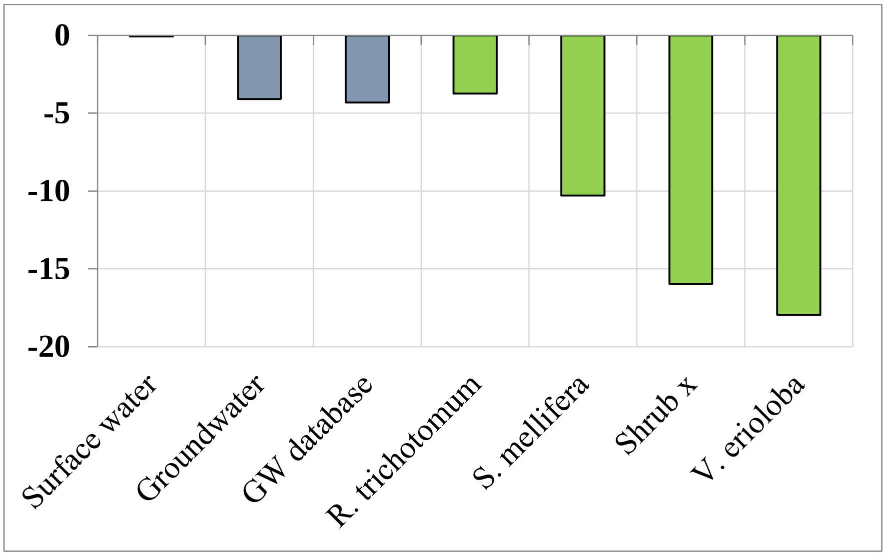


Figure 4.35 Mean $\delta^{18}O$ (‰) for woody vegetation and groundwater at Guruchab.

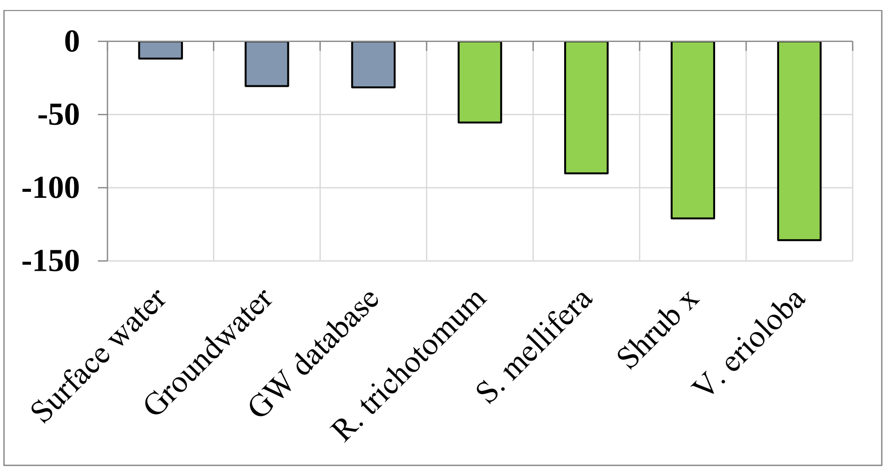


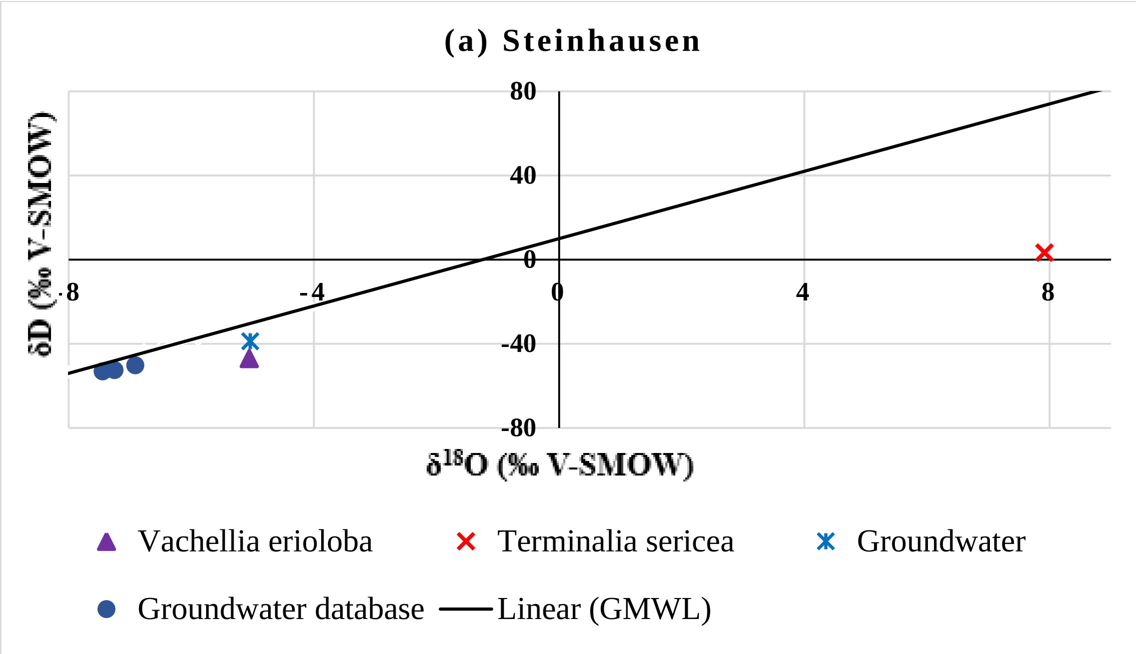
Figure 4.36 Mean $\delta^{2}H$ (‰) for woody vegetation and groundwater at Guruchab.

Given that there is an additional source of water and plant $\delta^{18}O$ and δD composition differed significantly from that of local groundwater. The fraction (f) of total plant xylem was calculated using a two-compartment linear mixing equation to determine the proportion plant xylem derived from the two sources, using the following equation derived by Snyder and Williams (2000).

Equation 5.1: $f = (\delta^{18}O_t - \delta^{18}O_{gw})/(\delta^{18}O_{sw} - \delta^{18}O_{gw})$

Where $\delta^{18}O_t$ is the mean $\delta^{18}O$ of tree xylem sap, $\delta^{18}O_{sw}$ is the measured $\delta^{18}O$ values of surface water and, $\delta^{18}O_{gw}$ is the measured $\delta^{18}O$ value of groundwater. It is a common assumption that streamside vegetation utilizes stream water which is easily accessible even to shallow roots. However this assumption was proven to be wrong after comparing the $\delta^{18}O$ and δD values of stream water, which was -0.07‰ and -11.8‰ respectively to highly depleted xylem water from all woody species. From the model *R. trichotomum* xylem water $\delta^{18}O$ composition indicated 91.26% contribution from groundwater and 8.74% surface water. The use of a two compartment model was fruitless for *S. mellifera* and *V. erioloba* because of the possible existence of a third source of plant water.

4.4.9 Steinhausen



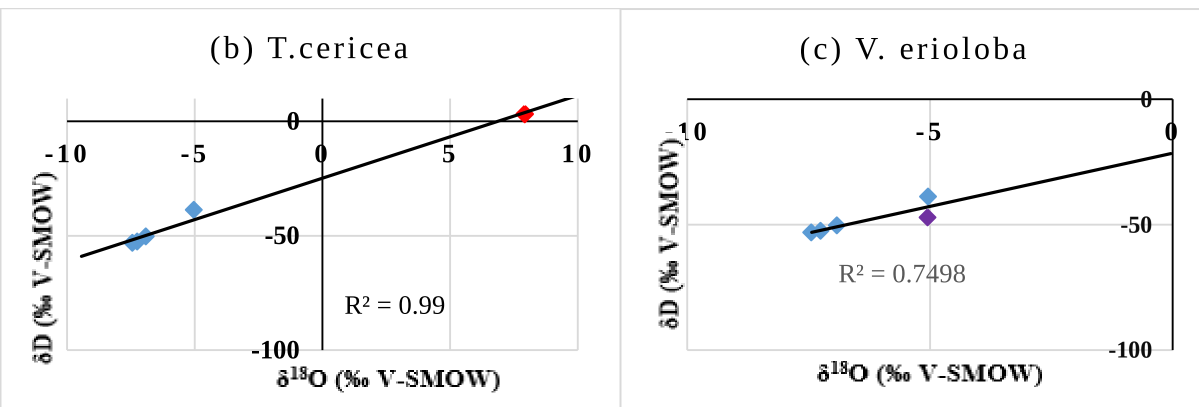


Figure 4.37: (a) Woody vegetation xylem water and groundwater δ^2H and δ^{18}O compositions with reference to GMWL. A biplot of δ18O – δ2H showing regression relationship between groundwater and (b) *T. cericea* (c) *V.erioloba* at Steinhousen.

T. sericea xylem water δ^{18}O and δD composition was 7.92‰ and 3.2‰, respectively. It plotted on the extreme right of Global Meteoric Water Line (GMWL), indicating utilization of water sources subject to evaporative isotopic enrichment (Williams and Ehleringer 2000). The infiltrating rainwater underwent some enrichment of the heavier isotopes prior to recharge and/or during the process of infiltration and percolation through the unsaturated zone to the saturated zone. There was no significance difference between *V. erioloba* and groundwater. Both *V. erioloba* and *T. sericea* were utilizing groundwater.

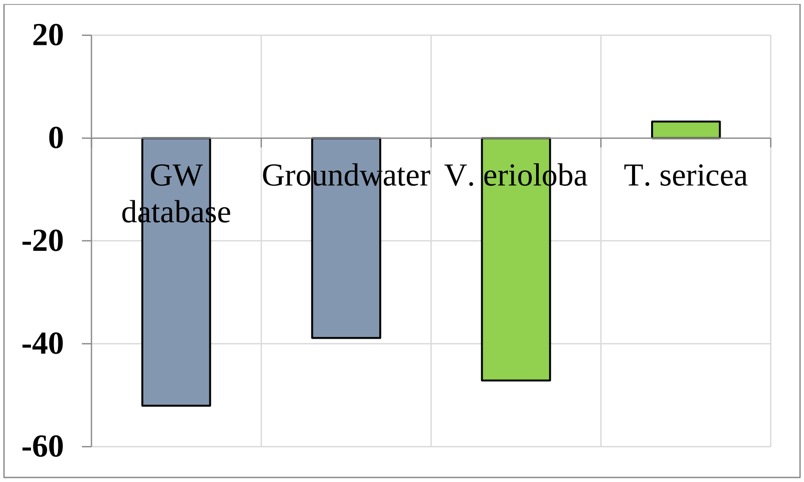


Figure 4.38 Mean δ^2H (‰) for woody vegetation and groundwater at Steinhausen.

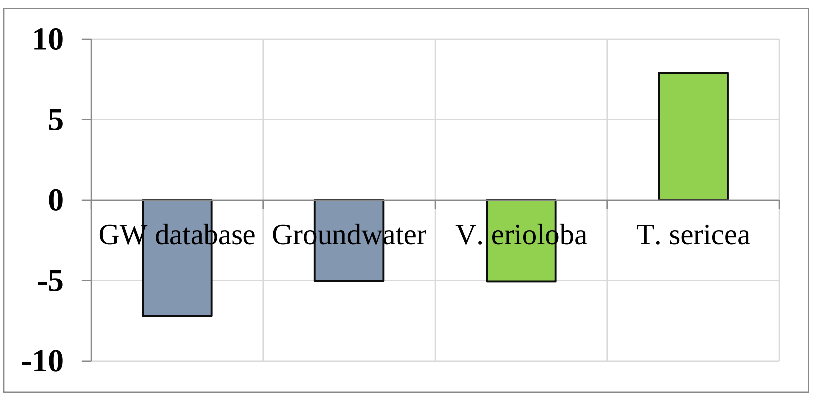


Figure 4.39 Mean δ^{18}O (‰) for woody vegetation and groundwater at Steinhausen.

4.4.10 Warmbad

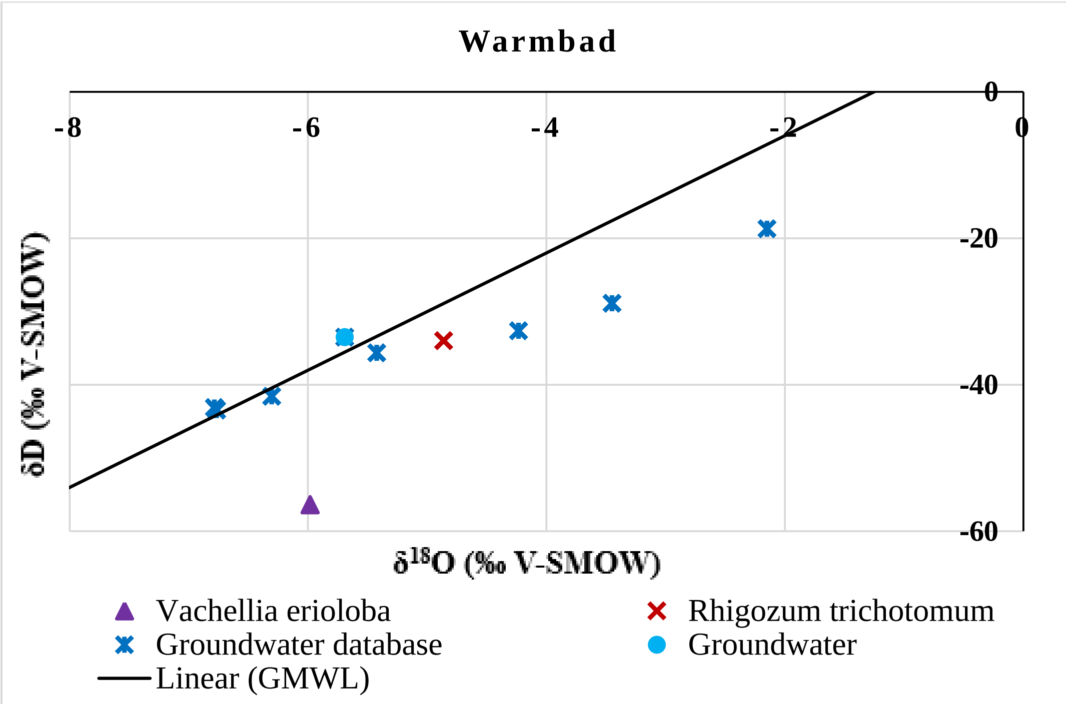


Figure 4.40: (a) Woody vegetation xylem water and groundwater δ^2H and δ^{18}O compositions with reference to GMWL at Warmbad.

V. erioloba was transpiring water with similar δ^{18}O as groundwater, but depleted with 20‰ in δ^2H. While *R. trichotomum* was transpiring groundwater with the same δ^{18}O as sampled groundwater, but somehow enriched in δ^2H. The similar behavior was observed in Guruchas where *R. trichotomum* was exposed to different water sources (stream water, soil water and groundwater), but chose to utilize only groundwater.

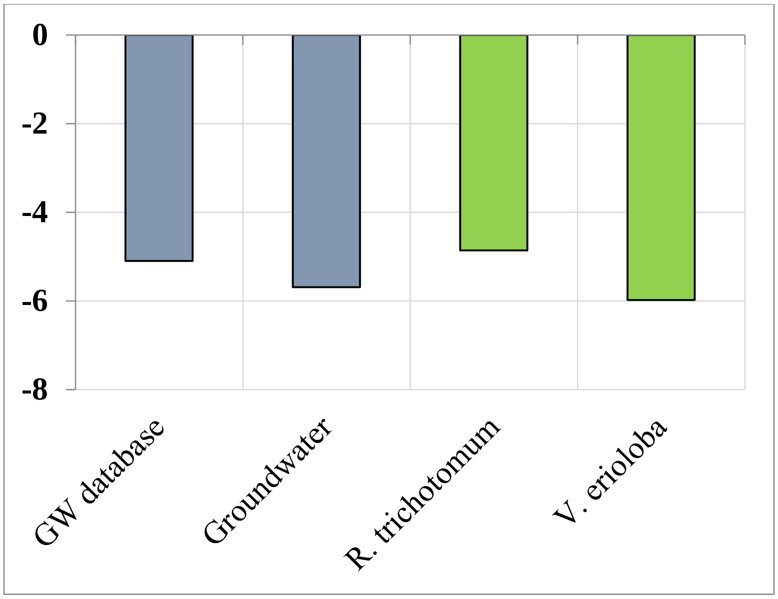


Figure 4.41: Mean δ18O (‰) for woody vegetation and groundwater at Warmbad.

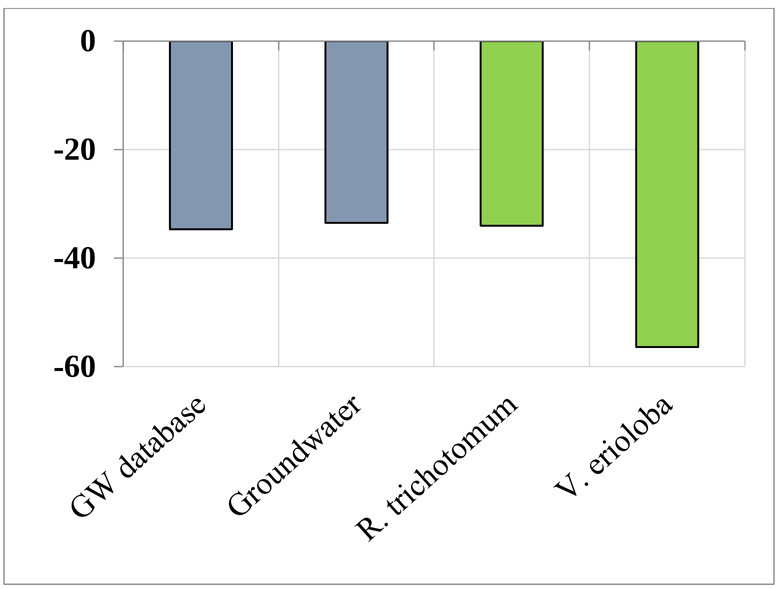
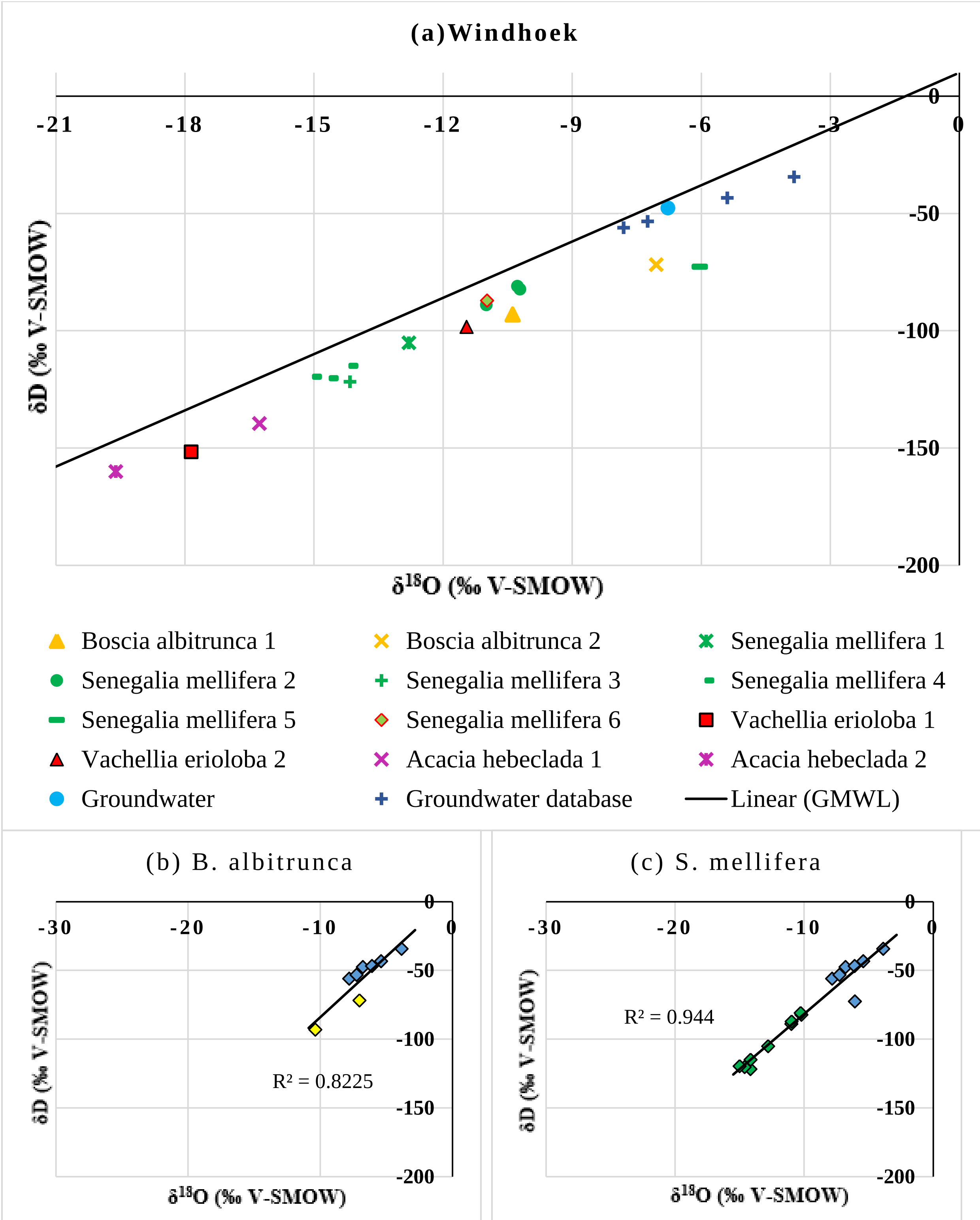


Figure 4.42: Mean δ^2H (‰) for woody vegetation and groundwater at Warmbad.

4.4.11 Windhoek



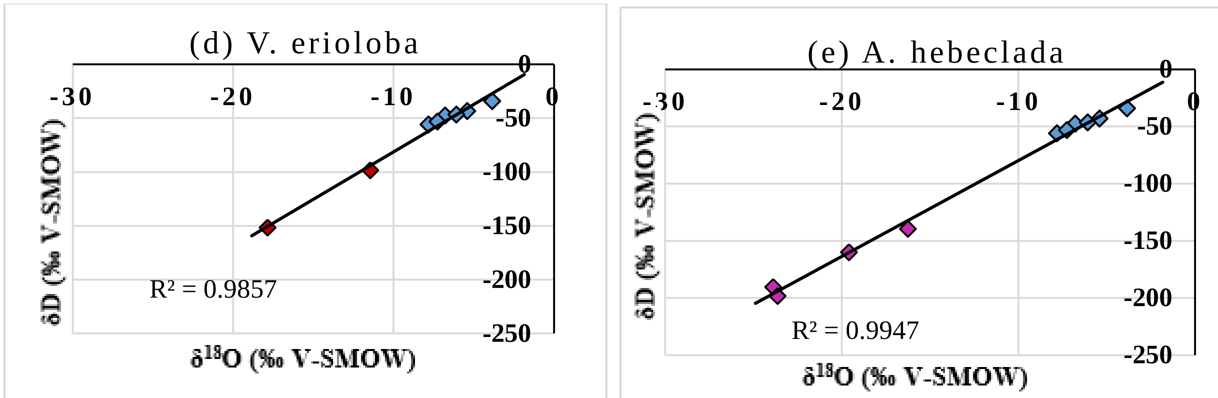


Figure 4.43: (a) Woody vegetation xylem water and groundwater δ2H and δ18O compositions with reference to GMWL. A biplot of δ18O – δ2H showing regression relationship between groundwater and (b) B. albitrunca (c) S. mellifera (d) V. erioloba (e) A. hebeclada.

Most woody species in this area were transpiring groundwater from a much depleted source, however *B. albitrunca* 2 and *S. mellifera* 5 were not following the same trend. These two trees had similar $\delta^{18}O$ values with groundwater but slightly depleted δD values. This shows that individual trees of the same species, in close proximity can sometimes transpire water from different sources. Among all the species in the study area *A. hebeclada* and larger *V. erioloba* trees were utilizing the most depleted groundwater source.

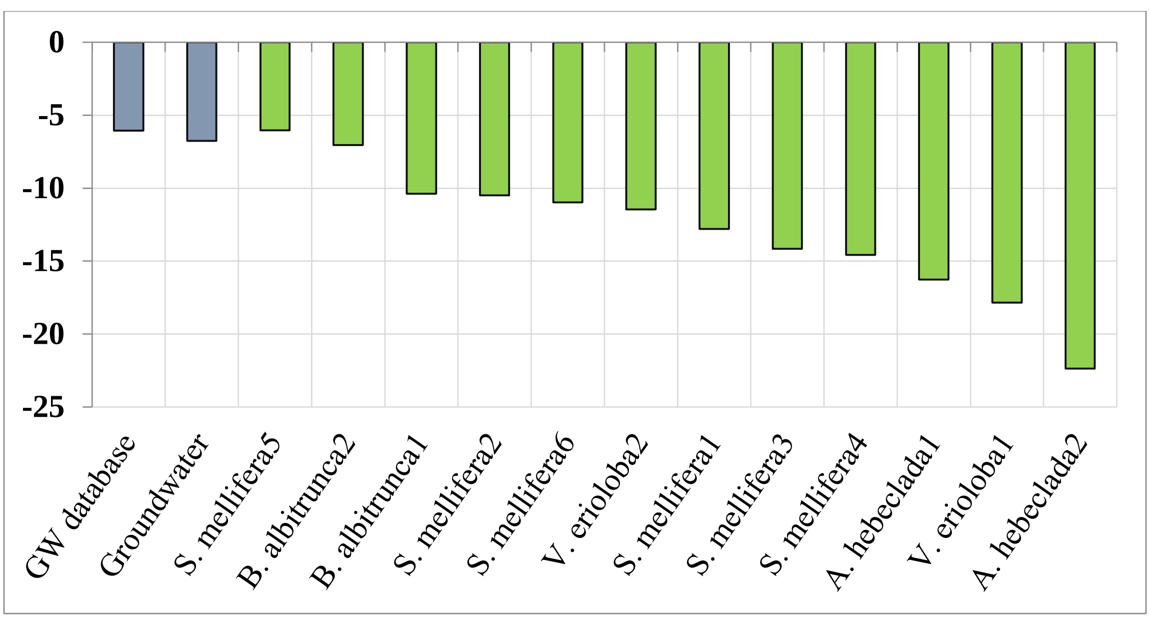


Figure 4. 44: Mean δ18O (‰) for woody vegetation and groundwater at Windhoek.

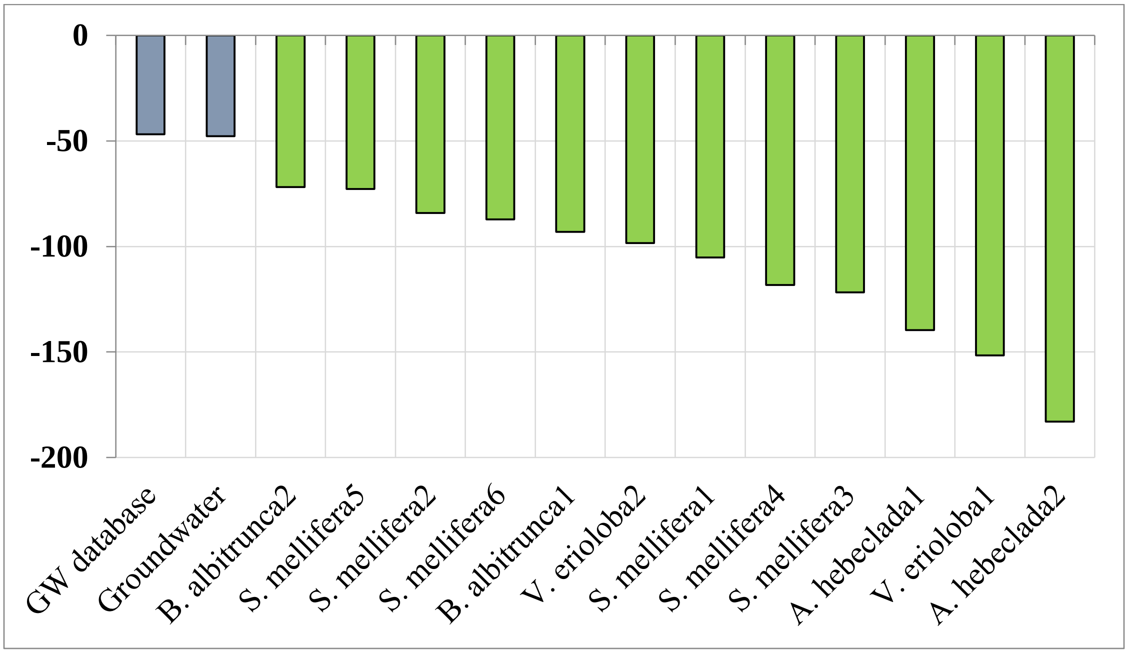


Figure 4.45: Mean δ^2H (‰) for woody vegetation and groundwater at Windhoek.

4.5 Relationship between plant water source and precipitation amount

Along the precipitation gradient, stable isotope analysis showed that there was no correlation between plant water source and precipitation amount.

Table 4.3 The relationship between plant water source (SW: soil water, G: groundwater) and average annual precipitation along the precipitation gradient.

			Woody vegetation species										
No	**Site**	**Precipitation [mm/a]**	**B.albitrunca**	**V. erioloba**	**S. mellifera**	**P. Mopane**	**R. trichotomum**	**T. sericea**	**Undifined/ shrub x**	**P. juliflora**	**A. hebeclada**	**C. imberbe**	**P. africanum**
1	Sesfontein	100	G	SW	both	gw							
2	Warmbad	100	G	gw									
3	Madisa	150	-	SW	both	gw							
4	Guruchab	150	G	SW	both	-							
5	Nu-Aub	200	both				both		SW	SW			
6	Ebenhazer	250	both	SW	both	-							
7	Stinkwater	300	G	SW	SW	-							
8	Steinhausen	380	-	G	-			G					
9	Windhoek	395	G	SW	G						SW		
10	Fair Constantia	475	G	SW	SW	-							
11	Enyana	500	G	G	both	SW						SW	G

4.6 Woody vegetation isotopic composition of all study sites

Throughout all the sampling sites there was a considerable variation in average isotope ratio of xylem water of different species examined, but there were still noticeable patterns regarding their main water source during the sampling period. Xylem water samples were all plotting below the global meteoric water line (GMWL) (Figure 4.44). Most xylem waters were found to be more depleted in δD than $\delta^{18}O$ relative to groundwater. Deviation of tree water from the GMWL varied not only from species to species but also from tree to tree.

B. albitrunca xylem water $\delta^{18}O$ and δD composition varied from -11.45‰ to -5.23‰ and -98.7‰ to 59.2‰ respectively. Meanwhile *P. africanum* xylem water $\delta^{18}O$ and δD composition was -9.14‰ and 83.1‰, respectively. *S. mellifera* was utilizing moderately depleted soil water and at some sampling sites a mixture of groundwater and soil water. Average $\delta^{18}O$ and δD values of *S. mellifera* were -8.23 ‰ and -75.0‰. *V. erioloba* transpired highly depleted soil water, at most sites except where *P. juliflora* or *A. hebeclada* were present. It had average $\delta^{18}O$ and δD values ranging from -20.78‰ to -4.86‰ and -179.0‰ to -34.0‰. *P. juliflora* and *A. hebeclada* utilize the most depleted soil water, average $\delta^{18}O$ and δD value of xylem water from *A. hebeclada* was -23.89‰ and -198.3‰. This was slightly similar to *P. juliflora*, which had xylem water composition of ` -22.9‰ and -198.8‰. *T. sericea* contained the most isotopically enriched water (Figure 4.45 and Figure 4.46).

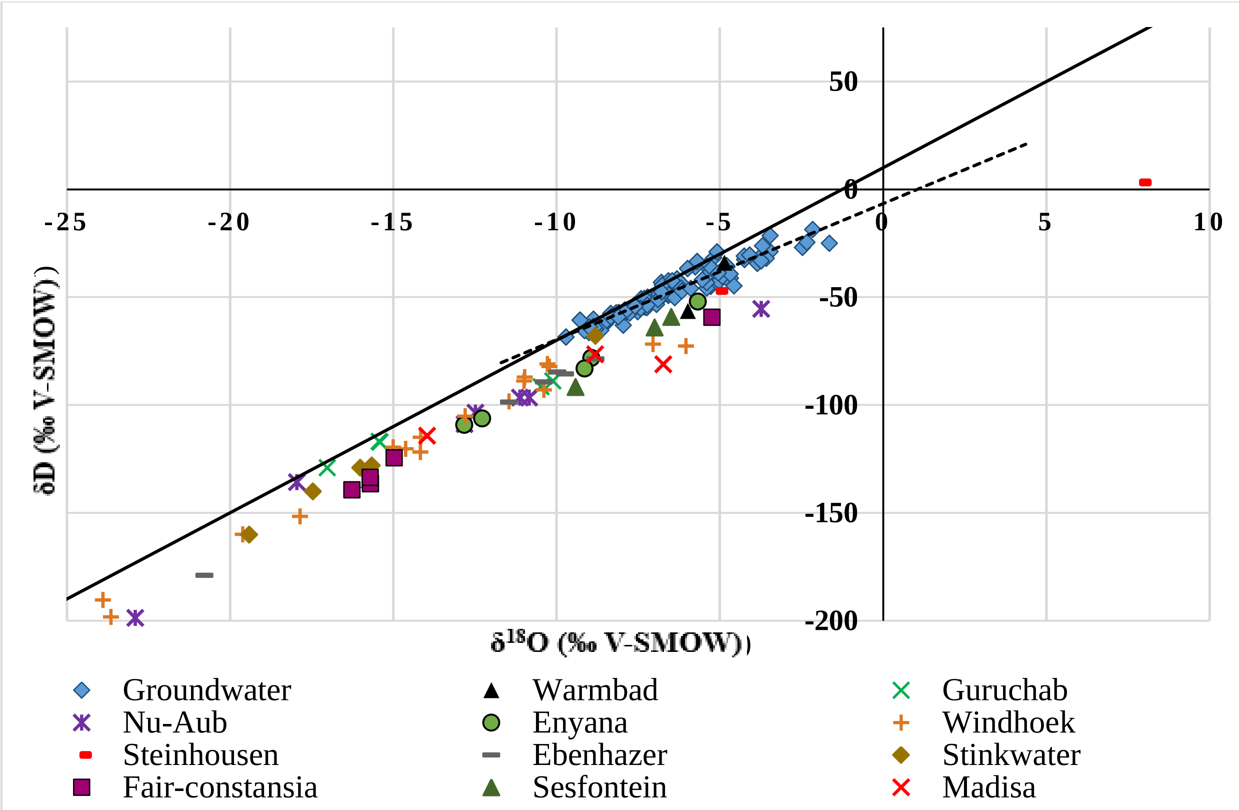


Figure 4.46 δ^{18}O and δ^{2}H values of groundwater and plant xylem water of all study sites

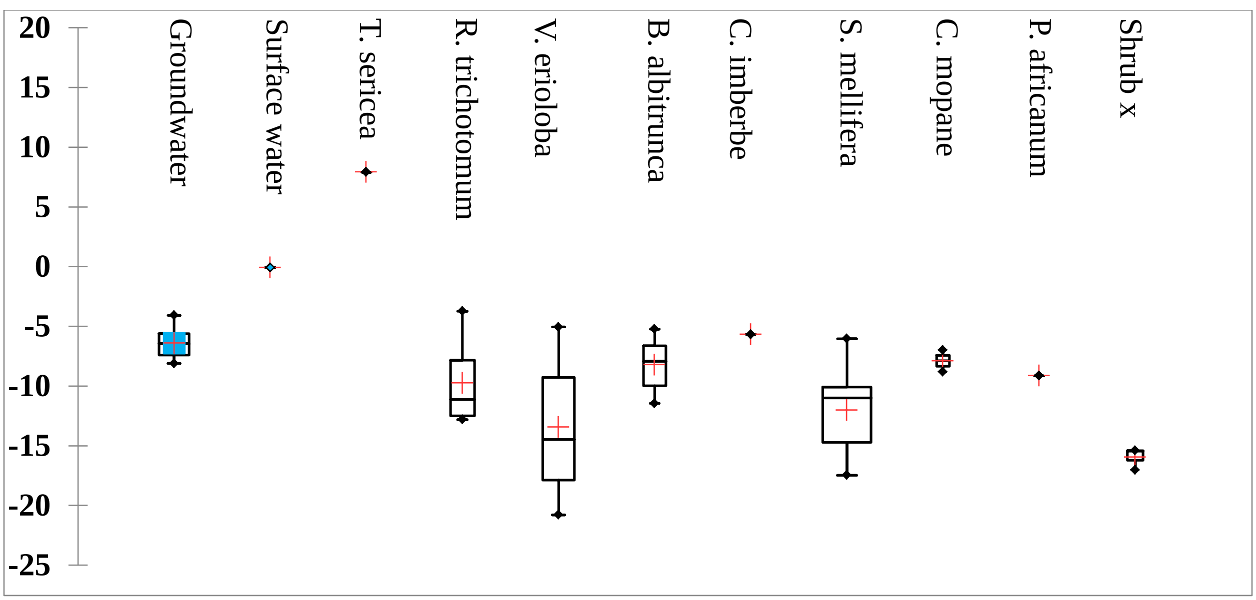


Figure 4.47: Boxplot of δ^{18}O values of groundwater and all sampled woody vegetation throughout the entire country. The median is shown by the horizontal line within each box.

Lines extending above and below and above each box mark the minimum and maximum of the ranked data.

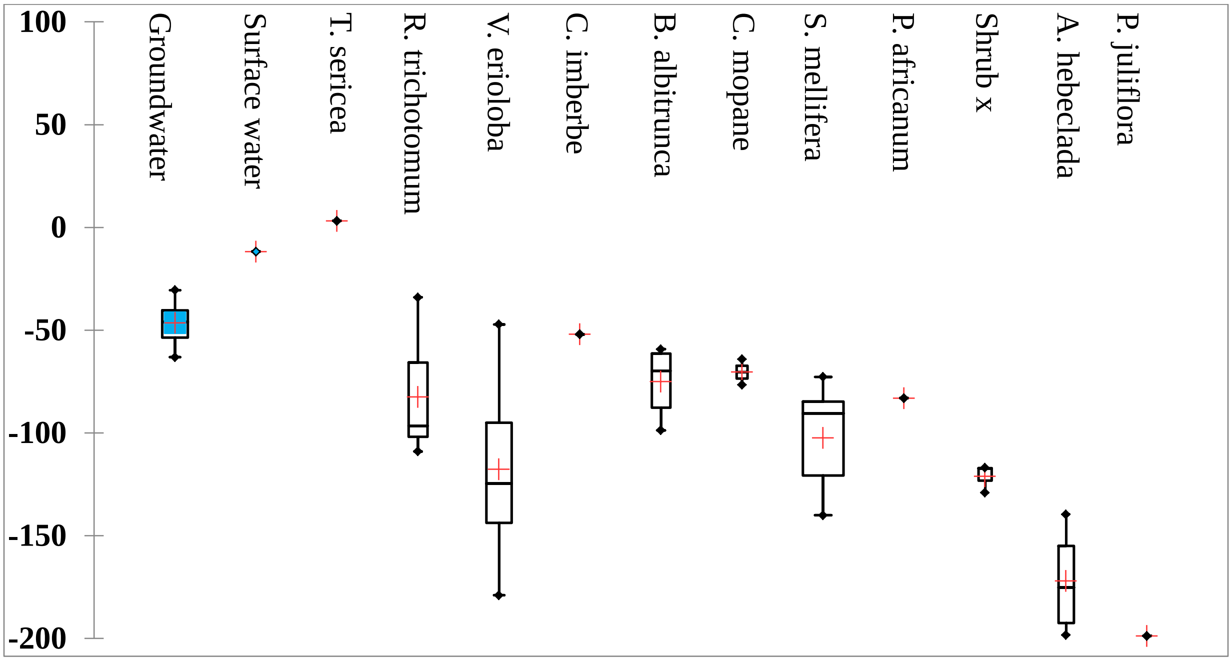


Figure 4.48: Boxplot of δD values of groundwater and all sampled woody throughout the entire country. The median is shown by the horizontal line within each box. Lines extending above and below and above each box mark the minimum and maximum of the ranked data.

4.7 Tree size and depth of water uptake

Water isotopes of $\delta^{18}O$ were used as estimation for depth of water uptake, with more negative (depleted) values signifying deeper water use. There was a weak, negative correlation between DBH versus xylem water $\delta^{18}O$ composition, and height versus xylem water $\delta^{18}O$ composition. However, no significant difference was observed between height and DBH ($P = 0.07$ for DBH and $P = 0.1$ for height).

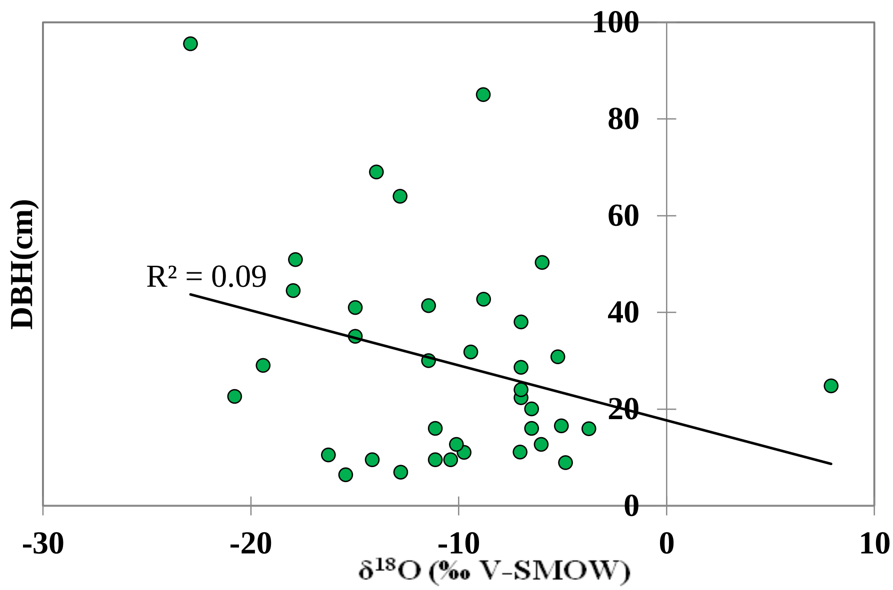


Figure 4.49: Relationship between $\delta^{18}O$ of xylem water and diameter at 1.4m of tree/shrub.

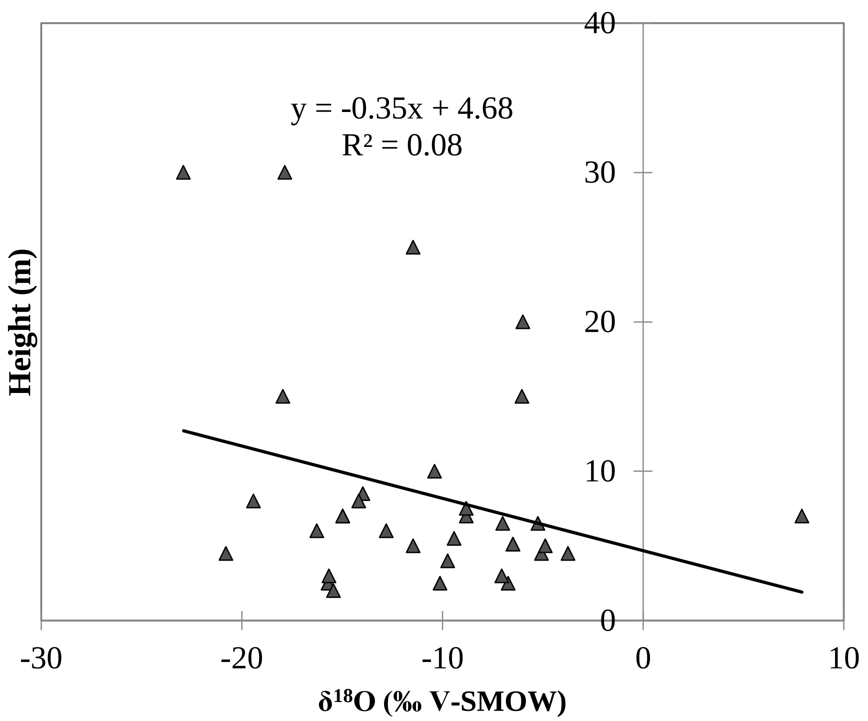


Figure 4.50: The relationship between $\delta^{18}O$ of xylem water and tree/shrub height.

CHAPTER 5

5. Interpretation and Discussion

5.1 Groundwater isotopic variation

Different recharge components can be identified through the stable isotope composition of groundwater, because evaporation during groundwater recharge leads to an increase in the proportion of the heavy isotopes D and ^{18}O. Rates of evaporation are determined by several factors, including temperature, solar radiation, humidity, wind speed and atmospheric pressure (Mendelsohn et al., 2002). According to Mendelsohn et al. (2002) the degree of water deficit- the difference between average annual rainfall and average rate of evaporation is highest in the south-east and gradually decrease towards the north east as a result of higher rainfall and less evaporation. Most groundwater samples plotted above the GMWL, which reflects the significant impact of evaporation.

The isotopic composition is depleted in the groundwater from Kalahari porous aquifers (Enyana and Fair-Constantia), while enriched in the fractured rock aquifers (Stienhausen, Madisa and Windhoek) these isotopically heavier groundwater samples may be attributed to the impact of evaporation before or during infiltration. Guruchas had the most enriched isotope values which correspond to the highest average annual evaporation rates of >3800 mm/year. Windhoek, Stinkwater and Ebenhazer had groundwater samples moderately depleted and moderate average annual evaporation rates 2100-2240 mm/year. Enyana and Fair-Constantia had the most depleted values and the least average annual evaporation rates 1820- 1960 mm/year and 2240-2380 mm/year respectively.

Rapid localized recharge in fractured rock aquifer versus slow infiltration in deep Kalahari sand cover had also played a major role in spatial variable isotopic composition. A noticeable proportion of the rain that falls on the sandy Kalahari surface evaporates and the groundwater in the Kalahari layers has a definite evaporation signal. Evaporation removes more of the lighter isotopes and, therefore, enriching groundwater with the heavier isotopes. This process may occur during rainfall through the atmosphere of lower humidity prior to infiltration or in the soil zone prior to deep infiltration or recharge to the deep groundwater system (Pelig-Ba, 2009). In semi-arid regions water might have rather long residence times in the top few meters of soil and therefore may be subject to partial evaporation.

Water that recharge rapidly may not be subjected to much evaporative enrichment but would tend to be more depleted in heavy isotope (Vogel et al., 1975). Isotopic value of soil water reflects direct input from precipitation or surface runoff, which can become isotopically enriched in the surface layers by evaporative water loss, and then depleted with depth in the soil profile (Coplen et al., 2000). Samples plotting on the GMWL, like Madisa, are regarded as recharging directly from local precipitation, through preferential flow paths. Moreover, groundwater from the Stampriet artesian aquifers has a very weak isotopic evaporation signal.

5.2 Isotopic variation in modeled precipitation

The isotopic composition of precipitation is dependent upon several factors including the isotopic composition of its vapor, fractionation that occurs as water evaporates into the air mass, precipitation formation processes, and air mass trajectory. Most of these factors are predominantly due to fractionation (McGuire and McDonnell, 2006). Four major causes of variation in precipitation stable isotope ratios are: altitude, latitude, distance from the oceanic vapour source area and amount of precipitation (Dansgaard, 1964). These factors are discussed below.

5.2.1 Continental effect

Continental effect is the observation that meteoric water is more depleted further from the source of the water vapor. Rainout reduces the heavy isotopic composition of an air mass as it travels inland. Isotopic composition of the condensing precipitation is more enriched than that of the remaining vapor due to due to isotopic fractionation during condensation. The ^{2}H and ^{18}O content decrease in precipitation with increasing distance from the coast due to rainout (Coplen et al., 2000; Kendall and McDonnell, 1998).

The observed continental effect was 3.1‰ depletion in $\delta^{18}O$ per km across Namibia. Highest $\delta^{18}O$ values were found in Guruchas (-6.3‰) and Warmbad (-5.1‰) due to close proximity with their water vapor source the Atlantic Ocean. Lowest values were found in Fair Constantia and Enyana where the rainout process has evolved to low residual vapor fractions since these sites are distant from their source, the Indian Ocean.

The average $\delta^{18}O$ isotopic gradients hwas greater than what have been measured in the Amazon basin and Europe, <1 ‰/1000 km and 2‰/1000 km respectively (Rozanski et al., 1993). As well as the Pacific Northwest, USA 12 ‰/1000 km (Welker, 2000) and Sierra Nevada, USA 50‰/1000 km (Ingraham and Taylor, 1991).

5.2.2 Latitude effect

Latitude effect is characterized by decrease in $\delta^{18}O$ and $\delta^{2}H$ values in precipitation with increasing latitude. These isotopic variations are caused by cooler temperatures that air masses encounter as they proceed from equatorial regions. On a whole-country scale, the precipitation $\delta^{18}O$ value depletes approximately 0.37‰ for every one degree southward in latitude. The latitude effect was quite noticeable in most samples for instance groundwater $\delta^{18}O$ composition at Enyana at latitude of -17.6° , was -8.1 ‰, while Warmbad, latitude -28.4°, groundwater $\delta^{18}O$ value were -5.69‰. The latitude effect results from increased evolution of the air mass due to increased isotopic fractionation at the cooler temperature of condensation in a manner similar to that responsible for the elevation effect (Kendall and McDonnell, 1998).

The observed latitude effect is lower than the effect observed for coastal and continental stations in Europe and the USA, i.e. 0.6‰/degree of latitude (Mook, 2001) which might be due to an overprint by other effects and/or influenced by higher temperatures in the study area.

5.2.3 Altitude effect

Elevation effect is the observation that the stable isotopic compositions of meteoric water are more depleted at higher elevation. The lowering of temperature with increasing elevation leads to enhanced condensation and therefore to a progressive depletion in heavy isotopes of precipitation. In this study isotopic data on precipitation did not show a clear trend with altitude.

The altitude effect was poorly correlated due to different precipitation sources and nature of low elevation gradient. The $\delta^{18}O$ values of precipitation decreases at 0.13‰ per 100 m rise in altitude. Heavy isotope content of precipitation does not decrease always in the same manner with the altitude (Gonfiantini et al., 2001). This was observed in the results, for example Fair Constantia, elevation 1500 m above sea level had the most depleted $\delta^{18}O$ values -10.7‰ than Windhoek (-7.1‰) which has highest elevation approximately 1700 m above sea level.

The observed altitude effects are consistent with altitude effects found on continental Africa e.g. for Mount Cameroon (-0.156‰) (Gonfiantini et al., 2001) but smaller than for Mount Kenya (-0.27‰) (Tongiorgi, 1970). However, the observed altitude effect in this study is consistent with the general magnitude of the altitude effect, i.e. between -0.1 up to -0.6‰/100 m worldwide (Vogel et al., 1975).

5.2.4 Amount effect

Amount effect is described as a negative correlation between $\delta^{18}O$ and the amount of monthly precipitation (Dansgaard, 1964). It is a consequence of a Raleigh condensation and rainout process of atmospheric vapor. Enyana and Fair Constantia had the highest average annual rainfall corresponding to the most depleted $\delta^{18}O$ values. Sites with summer rainfall had depleted $\delta^{18}O$ values than winter rainfall this is because they are originated from Intertropical Convergence Zone (ITCZ) and rain at these sites is a later stage product. Precipitation isotopic values decrease with increasing monthly or annual mean precipitation, thus higher rainfall amount tend to have isotopic composition that are more depleted in ^{2}H and ^{18}O than more frequent lighter precipitation events (Coplen et al., 2000).

5.3 Water uptake by plants

In arid and semi-arid-regions water used by vegetation may only be available from the very top soil layer (0-50cm), directly derived from recent rainfall or from the groundwater (Brunel et al., 1991). In this study the δD and $\delta^{18}O$ data indicated that *B. albitrunca*, *C. mopane* and *C. imberbe, R. trichotomum and T. sericea* were mainly using groundwater.

It was hypothesized that the encroacher species *R. trichotomum* and *S. mellifera* were utilizing soil water and this gives them an advantage over non-encroachers. However, isotopic ratios of xylem sap indicated that *R. trichomum* predominantly utilized groundwater while *S. mellifera* utilized a mixture of groundwater and available soil water that was more negative than groundwater. The water uptake pattern of these species is highly attributed to their rooting system. *S. mellifera* has relatively shallow, but extensive rooting system (maximum rooting depth ±4.5m) (Canadell et al., 1996), while *R. trichotomum* have a well-developed root system up to three times wider than the height of the plant (Union, 2010).

Dawson and Ehleringer (1998) reported that encroacher species were able to access both shallow and deeper water sources whereas the original pasture vegetation only accessed deep water. These encroaching plants affect aquifers by directly extracting groundwater from saturated strata and by reducing the proportion of rainfall that is recharged. Much of the groundwater is situated at depths where it is unlikely for shallow-rooted woody species such as *S. mellifera* to reach. It is assumed that these plants were utilizing water drawn by deep rooted species such as *B. albitrunca* and *V. erioloba* from the groundwater aquifer, transported upward in the root system into a drier upper soil layer which is at a lower water potential, a phenomenon known as hydraulic lift (Horton and Hart, 1998). The shallow root system of these vegetation and hydraulic lifting was the reason why it was able to access stored soil water instead of groundwater throughout the dry season.

Hydraulically lifted water source allows small trees to continue transpiration when they normally would not. The physical basis behind hydraulic lift is best explained in terms of various components of water potential in the root zone. In areas where transpiration and evaporation are removing soil moisture from shallow surface soils, the total water potentials will decrease or become more negative. Water from deeper soil layers with less negative water potentials will then move upward towards the surface to replenish this lost water (Landmeyer, 2011).

T. sericea, a shallow rooted tree that prefers growing on very sandy soils had the most isotopically enriched xylem water. One explanation for the more enriched xylem water would be that the source water was a large shallow reservoir where accelerated evaporative isotopic enrichment took place. Isotopic ratios for groundwater in “closed basins” are typically more enriched than the meteoric water that feeds them. Meanwhile, *C. mopane* was transpiring a mixture of groundwater and soil water. *C. mopane* has an extensive root system with large proportion of the roots concentrated to shallow depth where they actively compete with shallow rooted herbaceous plants by intercepting most of the available soil water (Christian, 2010).

The $\delta^{18}O$ and δD data further showed that plants with deep roots such as *B .albitrunca*, *V. erioloba* and *P. juliflora* accessed isotopically depleted soil water and groundwater. Apart from deep roots, these trees also have extensive lateral root development that enables them to take advantage of sparse precipitation. Studies by February and Schachtschneider and February

(2013) have shown that *V. erioloba* and *P. juliflora* compete for the same water and this have negative impact on available water, species diversity and ecosystem function through the decline in viability of *V. erioloba*.

Observed $\delta^{18}O$ and δD compositions of *P. africanum, T. sericea, S. mellifera, A. hebeclada, R. trichotomum* and *P. juliflora* showed evidence of transpiring water from an isotopically separate pool from groundwater or stream water. According to Evaristo et al. (2015) this phenomenon is known as “Eco-hydrological Compartmentalization” whereby the isotopic composition of water that supply plant transpiration differs from that of waters that supply groundwater and streamflow. This is because, soil water that supplies plant transpiration is isolated from the water that recharges groundwater and replenishes streamflow.

The large amount of variation observed in woody vegetation $\delta^{2}H$ and $\delta^{18}O$ compositions suggests that trees were using water from a reliable water source, but it may indicate that trees are using old stored soil water from past percolation rainfall or irrigation events. However, more commonly it is caused by phase changes such as condensation events when water vapor in the soil airspace/ matrix reaches its dew-point as the soil becomes cooler with depth (Kendall and McDonnell, 1998). These erratic values could also be due to cryogen vacuum distillation method used to extract xylem water.

CHAPTER 6

6. Conclusions

The study's main objective was to identify plant water source of woody vegetation in Namibian Savanna aquifers along a precipitation gradient. This principal assumption underlying this study is that water is not isotopically fractionated when taken up by the plant (Dawson and Ehleringer 1998) and plant tissues are expected to carry the same isotopic composition as the source water. The stable isotope studies here have proven to be an effective method in determining plant water source. Results have shown that deep rooted species such as *V. erioloba*, *P. juliflora* and *A. hebeclacada* mostly transpired the mostly depleted soil water recharged from heavy rainfall. In large rainfall events, precipitation can complement deep soil moisture and function as a reservoir such that plants can consume this portion of water in the next period when plants experience drought stress (Huang and Zhang, 2015). While shallow rooted species such as *C. mopane* and *S. mellifera* utilized a mixture of soil water and groundwater hydraulically lifted by deep rooted trees.

In contrast to the study's original hypothesis that woody vegetation of the Savanna ecosystem utilizes groundwater in dry areas and soil water in wetter areas, it has been found that woody savanna vegetation generally rely on soil water, groundwater or both for transpiration. Plant water source vary from specie to specie and it is not influenced by precipitation amount or tree size. Savanna woody vegetation in Namibia uptakes groundwater and soil water in a hierarchical manner at different depths in order to ward off competition between species. Based on these findings, in areas where large amount of water are to be extracted for water supply, monitoring of groundwater levels is necessary to avoid negative impact on woody vegetation especially of protected species. Woody vegetation requires water for consumptive use as well as for biophysical processes.

The water source utilization of these plants is consistent with the two layer theory developed by Walter (1971). This theory states that woody and herbaceous plants are able to coexist in savanna because they utilize water from different soil depths. Woody plants have a larger proportion of roots in deeper layers taking considerably more soil water. These plants have evolved dimorphic roots that absorb shallow soil water in rainy season and deep soil water in arid seasons (Yang et al., 2010).

The observed spatial variability in $\delta^{18}O$ and $\delta^{2}H$ values of xylem water in woody tissues at different sampling sites along the precipitation gradient are attributed mainly to latitude and amount effect in the source water, i.e. precipitation that becomes surface water, soil water or groundwater and is later taken up by the vegetation. Groundwater samples plotted below the GMWL and thus indicate the effects of evaporation attributed to high temperatures, low relative humidity, and slow infiltration rates through the top soil layers. Nevertherless groundwater samples plot approximately along the GMWL, this pattern suggest groundwater to follow the local precipitaion input signal (Evaristo et al., 2015). Overall the tree xylem $\delta^{18}O$ and δD composition showed evidence of a stronger evaporative signal compared to groundwater.

Plant xylem water showed evidence of originating from an isotopically separate pool from groundwater and it may indicate that trees are using deep soil water from an earlier season or year. The observed in $\delta^{18}O$ and δD compositions in xylem water of all sampled woody vegetation suggests that they were using water from a reliable source, which points to groundwater or deep soil water rather than shallow soil water or surface water as the main source of water supporting transpiration.

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Appendix

Table A.1: Data used in this study: site, species, xylem water isotopic composition, diameter at breast& height (1.4 m) and crown diameter.

Sample ID	**Site**	**Species**	$\delta^{18}O$ **(‰)**	$\delta^{2}H$ **(‰)**	**DBH(cm)**	**Height (m)**	**Crown Diameter (m)**
CK-1	Madisa	*C. mopane*	-8.81	-76.7	85	7	
CK-2	Madisa	*V. erioloba*	-13.96	-114.3	69	8.5	
CK-3	Madisa	*S. mellifera*	-6.72	-81.2	Multi-stemed	2.5	
CK-4	Seisfontein	*V. erioloba*	-9.41	-91.7	31.8	5.5	
CK-5	Seisfontein	*C. mopane*	-6.99	-64.2	24,28.6& 38	6.5	
CK-6	Seisfontein	*B. albitrunca*	-6.48	-59.2	16& 20	5.1	
CK-7	Fair Constantia	*V. erioloba*	-14.97	-124.6	41 & 35	7	
CK-8	Fair Constantia	*B. albitrunca*	-5.23	-59.3	30.8	6.5	
CK-9	Fair Constantia	*S. mellifera*	-15.69	-136.6	Multi-stemed	2.5	
CK-10	Stinkwater	*V. erioloba*	-19.41	-160.1	29	8	
CK-11	Stinkwater	*S. mellifera*	-15.65	-128.1	Multi-stemed	3	
		S. mellifera	-17.46	-140.1			
		S. mellifera	-16.01	-129.1			
CK-12	Stinkwater	*B. albitrunca*	-8.80	-67.9	42.7	7.5	
CK-13	Ebenhazer	*V. erioloba*	-20.78	-179.0	22.6	4.5	
CK-14	Ebenhazer	*S. mellifera*	-9.73	-85.7	11	4	
	Ebenhazer	*S. mellifera*	-10.38	-89.4			
		S. mellifera	-8.80	-78.6			
		S. mellifera	-9.97	-84.8			
CK-15	Ebenhazer	*B. albitrunca*	-11.45	-98.7	30	5	
CK-16	Steinhausen	*V. erioloba*	-5.05	-47.2	16.5	4.5	
CK-17	Steinhausen	*T. sericea*	7.92	3.2	24.8	7	
CK-18	Windhoek	*B. albitrunca*	-10.38	-93.1	7, 7.6 &10.8	10	6 by 6
CK-19	Windhoek	*B. albitrunca*	-7.04	-71.8	9.5, 13&12	3	7 by 7
CK-20	Windhoek	*S. mellifera*	-12.79	-105.2	6, 6.3 &5.7	6	4.3 by 4.4
CK-21	Windhoek	*S. mellifera*	-10.21	-82.3			
		S. mellifera	-10.99	-89.0			
		S. mellifera	-10.27	-81.0			

CK-22	Windhoek	*S. mellifera*	-14.16	-121.8	10, 6.4 &7.6	8	5.7 by 6.1
CK-23	Windhoek	*S. mellifera*	-14.61	-120.3			
		S. mellifera	-14.15	-115.0			
		S. mellifera	-15.00	-119.7			
CK-24	Windhoek	*S. mellifera*	-6.03	-72.7	11, 9.5&8	15	7 by 5
CK-25	Windhoek	*S. mellifera*	-10.97	-87.2			
CK-26	Windhoek	*V. erioloba*	-17.85	-151.7	50.9	30	11.5 by9.8
CK-27	Windhoek	*V. erioloba*	-11.45	-98.4	41.4	25	9 by 8
CK-28	Windhoek	*A. hebeclada*	-16.26	-139.6	9.5, 10 &11	6	6 by 6.5
CK-29	Windhoek	*A. hebeclada*	-23.89	-190.5			
		A. hebeclada	-23.64	-198.3			
		A. hebeclada	-19.60	-160.0			
CK-30	Enyana	*V. erioloba*	-8.93	-78.2			
CK-31	Enyana	*C. imberbe*	-5.67	-52.1			
CK-32	Enyana	*P. africanum*	-9.14	-83.1			
CK-33	Enyana	*S. mellifera*	-12.82	-109.2			
		S. mellifera	-12.27	-106.2			
CK-34	Nu Aub	*P. juliflora*	-22.90	-198.8	95.5	30	
CK-35	Nu Aub	*R. trichotomum*	-10.83	-96.6			
CK-36	Nu Aub	*R. trichotomum*	-12.81	-109.0		4.5	5 by 5
		R. trichotomum	-11.12	-96.7	9.5 & 16		
		R. trichotomum	-12.48	-103.6			
CK-37	Nu Aub	*V. erioloba*	-15.72	-135.0	64	20	13 by 12
CK-38	Guruchab	*V. erioloba*	-17.95	-135.9	44.5	10	15 by 12
CK-39	Guruchab	*R. trichotomum*	-3.73	-55.5	15.9	4.5	3 by 3.
		S. mellifera	-10.11	-88.9	12.7	2.5	
		S. mellifera	-10.47	-91.6		2	3 by 4
CK-41	Guruchab	*Unidentified shrub*	-15.43	-116.9	6.4	2	1 by 1
		Unidentified shrub	-15.40	-117.3	6.4	2	1 by 1
		P. juliflora	-17.02	-129.1	95	30	20 by 18
CK-42	Warmbad	*V. erioloba*	-5.98	-56.4	50.3	20	11 by 10
CK-43	Warmbad	*R. trichotomum*	-4.86	-34.0	8.9, 6, 4 & 9.5	5	4 by 4
CK-44	Ebenhazer	*S. mellifera*	-10.38	-89.4			

		S. mellifera	-8.80	-78.6			
		S. mellifera	-9.97	-84.8			

Table A.2: Groundwater isotopic composition.

Site	δ^{18}O**(‰)d18O**	δ^{2}H**(‰)d2H**
Madisa	-5.53	-42,.0
Sesfontein	-7.60	-53.6
Fair Constantia	-7.95	-63.1
Nu-Aub	-5.89	-46.1
Guruchas	-4.08	-30.5
Warmbad	-5.69	-33.5
Ebenhazer	-7.22	-53.6
Stinkwater	-6.45	-42.5
SA2-1	-6.88	-51.2
SA2-4	-7.58	-54.2
SA2-14	-7.90	-56.9
Steinhausen	-5.04	-38.8
Enyana	-8.11	-59.2
Windhoek	-6.77	-47.7