Approaches to the Study of Water Resources in North-Central Namibia

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A water balance analysis utilizing NDVI data for three case studies

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List of Abbreviations and Acronyms

DEA – Directorate of Environmental Affairs
DRD – Directorate of Rural Development
DRFN – Desert Research Foundation of Namibia
DWA – Department of Water Affairs
GCM – General Circulation Model
FAO – Food and Agriculture Organization of the United Nations
IIASA – Institute for Applied Systems Analysis(Austria)
MAWRD – Ministry of Agriculture, Water and Rural Development
MET – Ministry of Environment and Tourism
MRC – Multi-Disciplinary Research Center (social sciences division of UNAM)
NASA – National Aeronautics and Space Administration (US)
NDVI – Normalized Difference Vegetation Image
NEPRU – Namibian Economic and Policy Research Unit
NNEP – Northern Namibian Environmental Project
NOAA – National Oceanic and Atmospheric Association (US)
NRSC – National Remote Sensing Center
PET – Potential Evapo-Transpiration
SADC – Southern African Development Community *(consisting of: Angola, Botswana, Democratic Republic of Congo, Lesotho, Malawi, Mauritius, Mozambique, Namibia, South Africa, Swaziland, Tanzania, and Zimbabwe.)*
SWA – South West Africa
SWAPO – South West African People's Organization
UNAM – University of Namibia
UNDP – United Nations Development Program

Chapter 1: Introduction

Namibia is the driest country in sub-Saharan Africa, with seasonal rainfall averaging between 90 and 600 mm each year. The North-Central communal lands make up the four regions Ohangwena, Oshana, Omusati, and Oshikoto. These regions hold more than half of the country's population, while comprising only about 1/10 of its area. Mainly supported by a subsistence agriculture system, the economics and way of life are very sensitive to changes in the environment. Fears of desertification have been raised due to changes in land cover and rainfall over the past two decades.

This study is meant as a first step towards the identification of changes in the overall water balance for north-central Namibia and possible causes for these changes. For this first step, various approaches towards studying the general water balance were examined using Ondangwa, Oshakati, and Oshikuku as case studies. These areas were chosen as characteristic samples of their regions in which water security is critical and relevant for the time scale under consideration.

1.1 Geography & History

Namibia is located on the west coast of Southern Africa between the Orange River in the south and the Kunene and Okavango rivers in the north. The first visit of Europeans to what is now Namibia, came in the mid-19th century by German missionaries. They called the area *German South West Africa*.

The main thrusts of exploration in this part of the world were mineral resources and political maneuvering among the various European nations. The Germans took over lands and affected the cultures of the various African groups in the region (mainly the Herero and Nama in the central and southern parts of Namibia). In the first years of this century, the German colonial government attempted what they described as the extermination of the Herero people. This was the first instance of attempted genocide in the 20th century. The Nama and Herero formed an alliance in resistance to the Germans during the Nama Wars of 1903-1908. After World War II, the country was placed under the jurisdiction of the British by the League of Nations, and the name was shortened to *South West Africa*. The British, in turn, gave this authority to South Africa, then a British

Colony. South West Africa was governed as a colony by the South African government until a long resistance by the South West African People's Organization (SWAPO) led to independence in 1990. Thus, only in the past 10 years have the people of Namibia had real control over their own country and the policies that affect their lives.

The study area in north-central Namibia (see figure 1) is traditionally called Owamboland, named after the main communal tribal group. In 1990, the area was divided into the four political regions of Oshikoto, Ohangwena, Oshana, and Omusati (commonly called the four-O's).

Figure 1.1: Namibia, with the Owambo shaded. (from MET, 1999)

These north-central communal lands have been extremely important throughout Namibia's history. When the Herero and Nama tribes were fighting the German colonialists in the central and southern areas before World War I, Owamboland housed many of the refugees. And during the resistance against South Africa colonial rule, SWAPO was based in Owamboland. This contributed to the importance of Owambo culture as a symbol of Namibia.

1.2 Population

More than half of the Namibia's entire population currently lives in the four O's, and in the past this number has been estimated to be closer to 70%. And yet, the regions collectively represent less than 10% of the country's total area. Namibia's population is estimated at 1.6 million, with over half of the citizens living in the four-O's.

Population estimates are always difficult in developing countries as death, birth and migration records are often lacking. These estimates are particularly hard in northern Namibia due to the largely unregulated crossover with Angola. At various times during the ongoing Angolan civil war (since 1975), refugees have come into Namibia in great numbers. In addition, the Namibia-Angola border that stretches between the Kunene and Okavango Rivers is largely arbitrary, cutting through traditional tribal areas. And the border is, for the most part, just a line on a map.

This concentration of people in the north-central regions is due mainly to the higher availability of water and arable land than in other parts of the country. The land in these areas has a higher carrying capacity than areas to the west and south. Within the four-O's, the central portion is the most densely populated.

Another factor in the high population density is the restriction placed on the movement of agriculture by the veterinary 'Red Line.' This was a law that disallowed the exporting of meat from north of the 19^{th} parallel, officially to prevent the spread of disease in cattle. But this restriction served to control the movement of the Owambo by keeping them from expanding their agriculture. Thus, Owamboland was separated from the economic movements of agriculture in the rest of the country, and therefore maintained its communal subsistence agricultural system. This happened while most of Namibia's agriculture turned commercial.

1.3 Ways of life

Traditionally, the way of life in Owamboland is a based on a silvo-pastoral agriculture system. They rely on crops such as sorghum, mahangu, and to a much less extent maize. Composite data for area planted to crops is shown in figure 1.2. Livestock include cattle, sheep, goats, donkeys, pigs, and poultry figure 1.3.

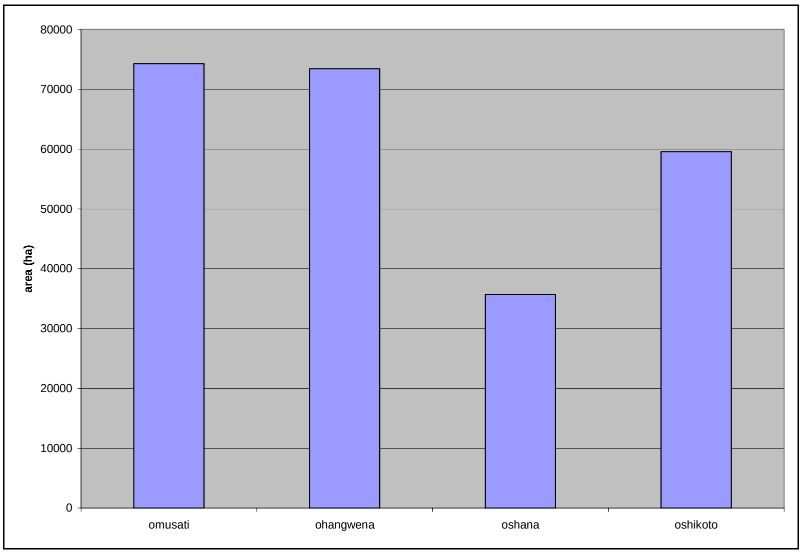


Figure 1.2: Area planted to cereals (mahangu, sorghum, maize) by region (MAWRD)

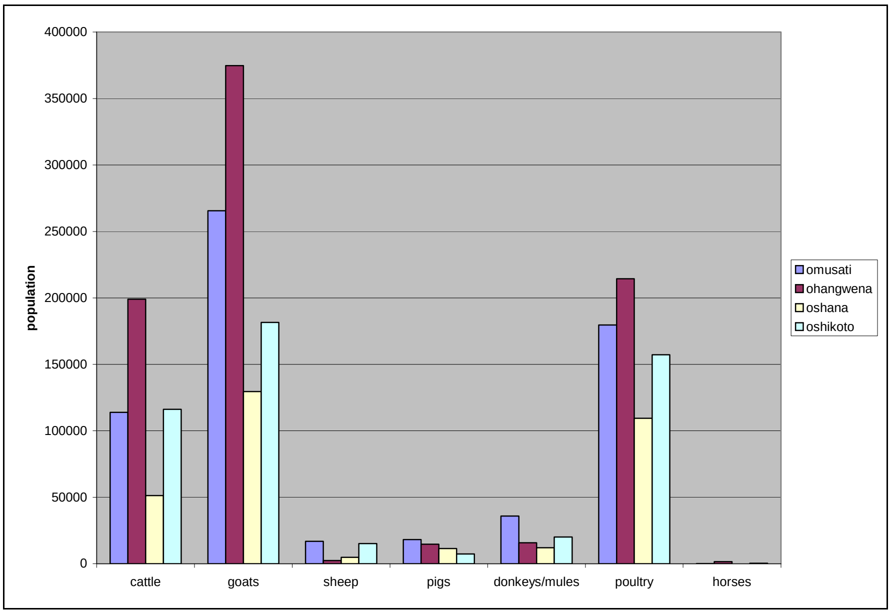


Figure 1.3: Composite livestock populations for the four-O's

Essential to this system is diversity. The agricultural products, stores, and livestock can be seen as commodities. Given that the climate in Namibia is uncertain and often harsh, diversity in these commodities provides some insurance against variability in the resources. For example, depending on the nature of the rainy season, different types of crops will have varying production. And similarly, some types of livestock can weather water and food shortages better than others. This necessity of diversity indicates that commercial agriculture would not work well in the north-central Namibia. That is, success in a commercial economic system requires specialization. In addition, other parts of the country where this specialization is attempted require large amounts of water to be supplied for irrigation. Such large-scale irrigation in Owamboland would very likely quickly degrade the soil and groundwater quality due to high evaporation rates.

So these factors have led to the maintaining of traditional agricultural practices in north-central Namibia. This is a general statement that naturally has exceptions, but is correct in the context of agricultural changes that have occurred in the rest of the country. Since independence in 1990, more and more families in Owambo receive money from relatives working in the cities. In addition, many Owambo now hold public sector jobs in Windhoek, which changes the economic dynamic of Owamboland slightly. These are recent developments, but still need to be considered when looking at long-term regional goals and strategies.

The most densely populated portion of north central Namibia is unique in that it is dominated by an oshana surface water system. Oshanas are wide, flat waterways that flow only during the rainy season. Cuvelai is the name for the rainfall basin that begins in the Sierra Encoco mountains in Angola. Owamboland is very flat in general, forcing the Cuvelai into a delta formation as water comes down from Angola towards the Etosha Pan, located just to the south of the Oshana region. Water only reaches Etosha through the oshana system during years of exceptional rainfall in both northern Namibia and southern Angola. These flood events are called *efundja* and they happen on the order of once every ten years. It is generally thought that these floods are the result of excess water flowing down into the Cuvelai from Angola. However, it has been shown that they also require large amounts of local rainfall.

So, much of Owamboland's water originates in Angola. This means that the region receives more water than what actually falls as rain. It also brings international politics directly into the water resource scheme. This can be seen more directly with the damming of the Kunene River described in chapter 3.

Chapter 2: Climate

The southern African climate varies greatly across the region. Tropical conditions exist in the Congo and parts of Angola. On the eastern side, Zimbabwe has fertile agriculture land and Mozambique is subject to both devastating floods and droughts. Namibia, on the west coast, has an arid to semi-arid to sub-tropical climate. The north-central areas are considered to be semi-arid.

Northern Namibia lies at the juncture between the Inter-Tropical Convergence Zone (ITCZ) and the Mid-latitude High Pressure Zone (MHPZ). This juncture runs diagonally across the region, and fluctuates with annual changes in global atmospheric patterns. The southern boundary of the ITCZ is affected by the Zaire Air Boundary (ZAB), and therefore has a wide north-south range. This range is generally considered to be between 10 S-16 S at 20 E. This forces the boundary, and therefore low pressure systems over the northern to north-eastern sections of Namibia during the rainy season. So the study area in the north-central region only sees the very edge of the border. So local fluctuations in air patterns can have an impact on which areas see the low pressure systems of the ITCZ. These fluctuations are considered to be a major factor in the variability of rainfall in the region. (Moorsom et al, 1995)

2.1 Rainfall

Rainfall in Namibia is seasonal and variable. Annual average precipitation ranges from 50mm in the desert portions of the south west, to 600mm in the Caprivi. But even these averages don’t come close to giving the whole story.

All of the weather systems come from the Indian Ocean. And much of the moisture is gone once the weather systems reach Namibia, on the Atlantic side. Namibia’s coastal areas do see some weather systems coming off of the Atlantic, but the Benguela current sweeps up from the Antarctic stealing most of the moisture before it reaches the land. So the coast only gets the remnants of these systems in the form of fog. Fog can also come from localized convection currents.

2.2 Temperature

Temperature in Namibia exhibits large spatial variability as do most other climatic and geophysical parameters. The lowest temperatures usually occur in July, with the most extreme values dropping to less than 2˚C in the central to south-eastern regions. In the study area, temperatures do not generally drop below 5-6˚C. Maximum temperatures usually occur in February, and reach extremes of more than 40˚C in the south-central regions. Maximums in the study area generally fall in the 36-38˚C range. (Tarr, 1998)

2.3 Evaporation and Evapotranspiration

Evaporation is a major problem for Namibia throughout the year. It reaches its peak in September and October when temperatures begin to rise towards the beginning of summer and there is still very little cloud cover to impede radiation from the sun. Annual totals range between 3000 mm in some coastal areas to 4000 mm in the southeast to 2500 mm in the Caprivi. North-Central areas see total of evaporation in the 2600-3000-mm range. These are potential evaporation values based on the temperature and cloud cover at various times during the year, and therefore provide general estimates. The estimates indicate that, for example, an open body of water in North-Central Namibia could lose 2500-3000 mm of water to evaporation each year.

Evapotranspiration (ET) is a measure of water lost to the atmosphere from the surface through evaporation from the soil and plant transpiration. Thus, it is very closely related to evaporation and temperature. And as a measure of the demands placed on the soil water resources, Potential Evapotraspiration (PET) is used to describe the evapotranspiration of a reference vegetation cover. PET is a central component to water balance studies, and it described rigorously in [chapter 6]. In terms of climate change, a 1˚C change in annual temperature can cause the annual PET value to change by 5.25%±1.55 (Tarr, 1998).

2.4 Desertification/Drought

Southern Africa is subject to a high frequency of natural disasters. These are divided mainly into droughts and floods. Most of the people of sub-Saharan Africa live very close to the land. This means that they depend directly on natural resources for their subsistence, and are therefore very sensitive to changes in the availability of those resources. The combination of extreme and variable weather with this resource sensitivity results in unique devastation that requires outside aid. And since such a large number people are affected, the economic influence of these events is significant.

Periods of low rainfall have affected southern Africa as a region throughout history. In the 20th century, sub-Saharan Africa has seen general drought conditions during the following seasons 1946-47, 1965-66, 1972-73, 1982-83, 1986-88, 1991-92, and 1994-95. The frequency of drought-like conditions seems to be increasing over the past half-century. But this apparent increase needs to be quantified, and possible anthropogenic and natural causes must be evaluated. (Chenje and Johnson)

In Namibia, a drought can be expected every 12-15 years, although the historical records show this trend to vary greatly. Also, a drought can have very different effects in different regions. For example, the 1992/1993 drought had enormous impact on Ondangwa and central Owamboland because the lack of water occurred in the most critical part of the growing season. Sustained, multi-year low rainfall is generally required to impact the entire country. (Moorsom, 1995)

2.5 Trends

Due to the high variability of the climate in Northern Namibia, long term trends are difficult to discern. The long-term distributions for each month do seem to show a gradual decrease in rainfall. This trend is due mainly to the lack of rainfall in recent years.

The long-term (1915-1996) mean annual rainfall for all of Namibia is 272 mm. Only 2 of the years from 1981-1996 have had rainfall totals above the long-term mean. (Tarr, 1998) And 9 of the 14 below average years have deviations greater than 45 mm below the mean. This is a 17% departure from the 82 year average. These are volumetric averaged values for all of Namibia, so the degree of variation in annual rainfall is very high.

Surface temperature is a very common indicator of climate change. And these values do seem to show a gradual increase in the past 50 years. From 1950-1997, mean surface temperatures for Windhoek have increased 0.023 C/year. (Tarr, 1998) This gives a total increase of 1.1 C, or a 2.0 F increase over the past 48 years. While this is a striking trend, it remains to be shown that greenhouse gases are the cause in Namibia. Certainly, large-scale climate change has been accepted as a major current global problem. And these changes have been linked in many places to increased greenhouse gas emissions. For example, in the U.S. rise in surface temperatures has been directly correlated to increased carbon dioxide levels in the atmosphere. Given the magnitude of the worldwide trends, it is likely that further study of large-scale climate change in Namibia will list similar causes.

Chapter 3: The Problem Of Water

In the previous chapter, it was shown that Namibia's climate is highly unpredictable, and can be very harsh at times. In addition, the people depend directly on the land for their subsistence. The combination of these two factors leads to a situation in which the continued well-being of the population in general is not guaranteed.

A main question is whether or not the region is becoming increasingly susceptible to climate variations and therefore increasing the effects of drought. This was looked at after the 1992-93 drought that affected the entire country, with the most significant effects seen in the north central communal lands. The question can be examined in terms of each individual's susceptibility, and has been tied to many factors including sources of income, economic level, water use, and land use (Moorsom, 1995). It would be very useful to trace the changes in drought susceptibility through these factors to whatever extent possible with the available data. This would be an extremely useful as an indicator of the overall changes in the region and way of life as I look at the specific climatic and engineered changes that have occurred.

The delicate balance between society and the environment must be understood very well and closely monitored for the system to be able to cope with changes that occur in either the environment or the community.

3.1 History of water in Owambo

Water has always been scarce in Namibia. The traditional agriculture practices allow for people and livestock move to where the water is. For example, large livestock were often moved to cattle posts during the dry months. This provided water for the herd as well as allowing the pastures used during the wet season to recover. The implementation of engineered water resources into this type of system has the potential for causing problems for the carrying capacity of the land. When a permanent water source is available, large stock do not need to be taken to cattle posts for water. Instead, the herds graze on the same areas of land for the entire year. This can lead to over-grazing and degradation of the land.

The “Owamboland Water Supply Scheme” was the first official program to engineer the water resources of north-central Namibia. The motivation was to improve the water security for South African military stations set up near the border with Angola. It was introduced by Wipplinger and Stengel in the late 1950’s and involved a system of dams, canals, and pipelines with two main purposes. The first was to tap the perennial rivers to the north and west as both a source of freshwater and hydroelectric power. The Kunene River originates in the Sierra Encoco mountains in Angola along with the Cuvelai oshanas and the Okavango River. It forms the western portion of Namibia’s border with Angola.

As a result of this program, the main source of freshwater is the Calueque dam in Angola. Construction on the dam began in the 1970’s but has never been completed because of the civil war that started in the late 1970’s and continues in Angola today. The Kunene’s hydroelectric power scheme is located at the Ruacana falls, which are on the Namibian border. This system includes a pipeline that is designed as a backup to supplement the supply from Angola in times of water shortage.

The second purpose of the water supply scheme was to collect the rainfall and flow from oshanas into canals and either excavated or pumped storage dams. This water could then be used for watering livestock or for irrigation. Later, as towns began to build up to serve the military in the area, the dams came to supply these slightly urban areas.

Owamboland’s groundwater resources have not been very heavily studied, although they have traditionally been the main source of water for the farms in this region. A main obstacle to water supply in the four-O’s is the quality of the groundwater. Traditionally shallow hand dug wells have supplied water to farms and villages. These were often dug in or near ephemeral waterways, as these areas are groundwater discharge points and are easily excavated during the dry season. But below the shallow perched freshwater aquifer, the groundwater becomes either brackish or saline. The perched aquifer is only a sustainable source of freshwater in areas of higher elevation. In general, areas higher than 1150 m above sea level have access to decent quality fresh water from this perched aquifer. In the lower elevations wells come too close to the salt horizon, and wells become useless after a shorter time. Deeper freshwater horizons have been found in various drillings across the region. But the expense associated with these deep boreholes cannot be justified at this point for the rural water supply they would be supplementing.

There have been studies looking into the mixing of groundwater reserves with the freshwater piped in from the Kunene river. But it was found that salinity is not the only problem, and there are more harmful contaminants in much of the groundwater. Still, boreholes and wells do serve much of Owamboland as it is too expensive for subsistence and small scale farmers to bring in piped water from the more concentrated areas. And artesian conditions exist in the far south east around Oshivelo.

Since independence in 1990, the Department of Water Affairs has further developed the engineered water systems in the region. This has included an expansion of the pipeline network as well as helping individual farms drill new boreholes and protect existing wells. Initially, all supplied water was subsidized by the government. In 1998, all of Namibia's bulk water supply (urban supply) was transferred to NamWater, a company that uses government infrastructure while attempting cost-recovery for water production. These attempts have been met with much protest, many communities simply refusing to pay for something that used to be free. The rural water supply remains the responsibility of the Ministry of Agriculture, Water and Rural Development.

3.2 Present issues

Some major issues regarding water supply in Owamboland are land degradation, population growth, and urbanization. As the social and economic dynamics of the region change, it is necessary to understand and possibly adjust the necessary management of the scarce water resources.

The state of the land seems like a natural element to study in a region where the people depend directly on the land and its resources. But as with rainfall, since the availability of resources is naturally highly variable, measuring long term trends is difficult. The changes in vegetation cover, agricultural production, and soil characteristics (composition, fertility, moisture content) must be continually monitored to gain a better understanding of the state of the land.

As described in the previous section, the implementation of permanent water sources can have detrimental effects on the land. The traditional agriculture system was deliberately flexible to deal with the lack of water in a given area. Adjusting the water supply necessarily changes the resources that form the foundation of the agriculture-based communities. So, in areas where over-grazing is suspected or known to be harming the land, the underlying causes must be examined. It is possible that the engineering of the resource base has shifted the foundation of the community.

The population growth rate in northern Namibia is estimated at 3% per year. This growth has already greatly increased the population density in the central areas causing some urbanization. Areas that are considered urban in the four-O's are simply non-farming areas. There are only a few tarred roads in the region, and the 'urban' areas lack much infrastructure.

Also mentioned in the previous section, the issues surrounding attempted cost-recovery of supplied water will get more complicated as the population continues to increase. More people means more water need to be supplied. Further urbanization will require more complex and expensive engineered systems, which will increase the need for cost-recovery even more. In addition, the environmental strain that greater population density causes will very likely disrupt the water resources situation.

Chapter 4: Water Balance

As mentioned in the introduction, the purpose of this thesis is to examine approaches to the study of water resources in North-Central Namibia. An overall goal of hydrologic analyses is a well-defined and accurate description of the fate of water in the system. A water balance incorporates the various inputs and outputs of water to the system, and is useful for identifying the relative importance of each one. And, tracing the water balance over time shows trends in each variable. Then the impacts and causes of the trends can then be evaluated.

The results and analysis of the water balance depend on the time scale used. This time scale is usually limited by the availability of data. In the case of Northern Namibia, data is the determining factor in the resolution of any analysis since only monthly rainfall data is available for the relevant time period. Data availability is described in the next section.

The method for this water balance analysis is to determine the changes in overall storage seen within each month for the three case studies: Okatana, Oniipa, and Ombalantu. In each case study the system is defined as the soil column beneath the given surface region. The main exchange of water in this system is with the atmosphere. Storage is defined here as the amount of water in the soil column at any given time. Surface water is assumed to be at steady state. That is, the amount that comes in is equal to the amount that leaves the study area. Even though the study areas are small, this is a very big assumption, and needs to be thoroughly evaluated as the water balance is further developed. Given the probable major impact of this assumption, this water balance analysis can only be a first step in understanding the true situation.

The definition of storage used in this study is meant to give and indication of the state of the land with respect to its ability to support the ecosystem that depends on it. The well-defined rainy season in southern Africa creates a situation in which the available water must be used with the knowledge that there will be virtually no rain from April to September. So in theory, the changes in storage for the months during the rainy season will be positive, and those during the remainder of the year will be negative.

4.1 Methodology

The water balance is based on the equations:

$$\Delta S = Q_S + Q_B + Q_R + Q_G - Q_{ETcrop} - Q_U \qquad (1)$$

with,

$$Q_{ETcrop} = PET \times k_c \qquad (2)$$

and,

$$Q_U = R_H N_H + R_S N_S + R_L N_L \qquad (3)$$

Table 4.1: Water balance parameter definition

Variable	Meaning
ΔS	Change in overall storage for the given time period
Q_S	Volume of surface water used in the given time period
Q_B	Volume of water supplied by the Ministry of Agriculture, Water and Rural Development and/or NamWater in the given time period
Q_R	Volume of rainfall over the time period
Q_G	Volume of water extracted from the ground by wells or boreholes during the time period
Q_{ETcrop}	The volume of water required by the land cover during the time period
PET	Volume of water required a reference crop during the time period
k_c	Crop coefficient
Q_U	Volume of water required by humans and livestock during the time period
R	Rate of water intake for the given element (H = human, S = small livestock, L = large livestock) over the time period
N	Population of the given element

The various parameters are in volumetric form to be able to use demand and supply in a form that makes sense. Rainfall and evapotranspiration are usually given in depth units rather than volume. So when these parameters stand alone, or are compared with values from other studies, depth units will be used.

4.1.1 Data[1]

With water data, it is easiest to divide the data in a way that preserves continuity. That is, it is desirable to have all the data for a single rainy season described continuously in a single 'water year.' This practice is used by the US Geological Survey begins its 'water year' in October. In the case of Namibia, the rainy season starts around October

[1] A list of data sources with contact information is listed in Appendix A

and ends in April. So climatic data for a year begins in May and ends in April of the next year. Thus, a typical yearly data set is given as, for example, 1997/98. Another factor that enters in here is the growing season, which in north-central Namibia typically lasts for around 100 days from December through the beginning of March.

Rainfall data is available in monthly and daily formats. The monthly data has a higher spatial resolution, and longer history. However, the spatial resolution is limited. Specifically, there are 20 monthly, and 5 daily rainfall data stations for all of Ohangwena, Oshikoto, Oshana, and Omusati regions. This provides good long term averages for each region as a whole. But any smaller region that is being looked at must have a rainfall station within a reasonable distance to provide accurate information.

Surface water data is estimated. The information available consists of the amount of water that was collected in dams, or how full the dam was at a given time. Also, very general estimates of average flow are available. So, this parameter is highly variable. Another option is to use qualitative reports on flows in the ephemeral rivers. These are not extensive, and would only give an idea of the order of magnitude. A promising note about this lack of data is that much of the water seeps into the ground, and is then part of the quantifiable volume extracted from the groundwater.

Land cover data comes from two sources. First, the Normalized Difference Vegetation Index (NDVI) satellite imagery from AVHRR NOAA data can be used to estimate the percentage of land cover in terms of a vegetation index (see Figure 4.1). This data is available at the very high resolution of 0.01 degrees (1x1.1 km) for the period March 1993 – April 1999. One degree resolution data is available from 1981, but is only useful for global scale evaluations. The NDVI is described in detail in section 4.1.5.

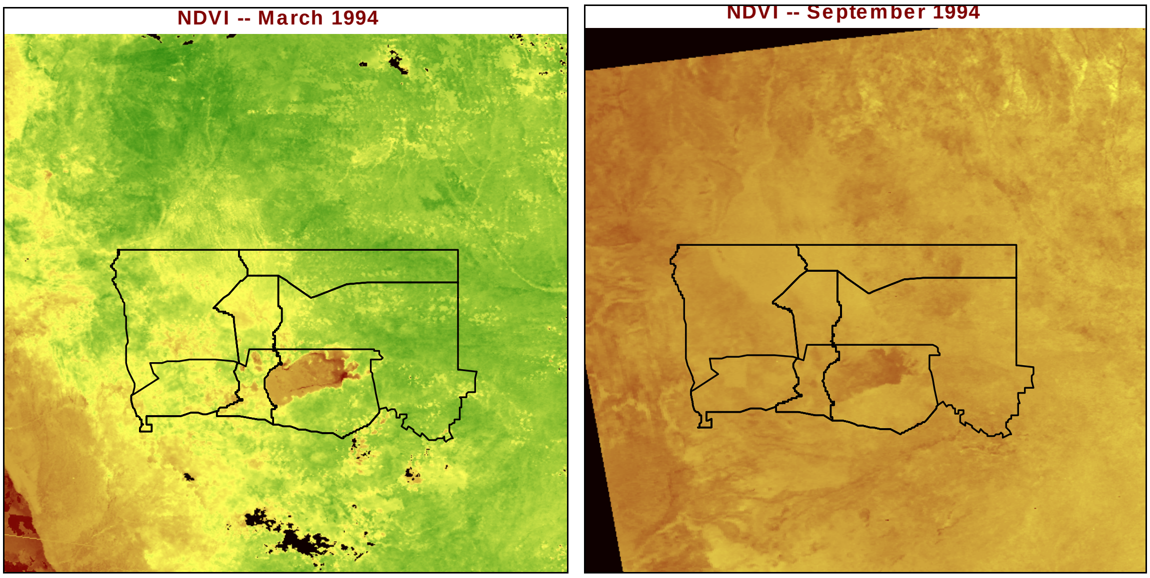


Figure 4.1:NDVI images of northern Namibia, March 1994 and September 1994. The Four-O's and Etosha are highlighted. Higher NDVI values have been colored green to indicate vegetation. The values range down from green through shades of tan, with the darkest tan indicating no vegetation.

Second, the annual survey of agriculture (Central Bureau of Statistics, 1-2) provides basic tables and analysis of composite data for each of the four-O's. In terms of land cover, each survey gives the area of land planted to specific crops for each region. This is only useful for a large-scale water balance, or comparison with the smaller study areas.

Population data used in quantifying the demand term in the water balance comes from a number of sources. Human population information is available from survey data and general extrapolations from generalized models. The GIS database compiled by the DEA contains household population data at a very high resolution. Livestock population data comes from some surveys, reports, and the annual agriculture surveys. Again, the agriculture survey gives only composite data for each region.

Another type of data used in this analysis has to do with characterizing the interaction of people and water. The OMITI database developed by Emanuel Kreike at Princeton University contains survey data collected in 1993 for 400 farms across the four-O's. The main focus of the survey is on tree use and availability. But there is also a section that covers water availability and ownership. This gives generalized information on the water source as well as distance to the water source for both humans and animals during the wet season and dry season. This type of data can be used to expand on the analysis in this thesis towards the overall goal of understanding the relationship between people and water. The OMITI database provides a very valuable baseline for this future study.

4.1.2 Evapotranspiration

The evapotranspiration term in the water balance is the amount of water that is lost to the atmosphere due to evaporation from the soil and transpiration from the plants. Water lost by transpiration is carried from the soil through the plants roots to the leaves where it enters the atmosphere from the surface of the plant. Evapotranspiration has been heavily studied worldwide because of its importance to the water balance in general, and specifically to agriculture. Many different algorithms for calculating this term have been developed and shown to be useful to varying degrees in different situations.

In the 1970's the Food and Agriculture Organization (FAO) attempted to standardize the methods for calculating ET by thoroughly examining the various methods and giving recommendations for different situations. Table 4.2 lists the methods examined and the data requirements for each.

Table 4.2: ET calculation method and its data requirements. (from Doorenbos & Pruitt, 1977)

Method	Temperature	Humidity	Wind	Sunshine	Radiation	Evaporation	Environ
Blaney-Criddle	*	0	0	0			0
Radiation	*	0	0	*	(*)		0
Penman	*	*	*	*	(*)		0
Pan evaporation		0	0			*	*

* = measured data 0 = estimated data (*) = non-essential data

The 1977 revised edition (FAO Irrigation and Drainage Paper #24, commonly called FAO 24) of this effort (Doorenbos & Pruitt, 1977) has been used and recognized as the worldwide standard for ET calculations (Moorsom et al, 1994). From this procedure, the present study of northern Namibia would be limited to the Blaney-Criddle method.

However, since the 1977 edition, advancements have been made in technology that led to a revision of FAO 24 in 1990 (Smith, 1992, 1996). This revision endorses a new Penman-Monteith method that provides mechanisms for estimation when there is a lack of climatic data. It also gives the performance of 20 calculation methods in both humid and arid environments compared to actual measurements. The Penman-Monteith method performed the best overall. The Blaney-Criddle method from FAO 24 is shown to be very accurate in arid environments, but fairly weak in humid ones (Table 4.3).

Table 4.3: Performace of ET calculation methods (Smith et al, 1996)

	Humid			Arid		
	Rank	**Over Estimate**	**Standard Error**	**Rank**	**Over Estimate**	**Standard Error**
Penman-Monteith	1	+ 4%	0.32	1	- 1%	0.49
Blaney-Criddle	9	+16%	0.79	9	0%	0.76

So for this analysis of northern Namibia, both the Penman-Monteith and Blaney-Criddle calculation methods are used and the results are compared in section 4.3.3. These results should come close to each other as the study area is a semi-arid environment. But the Penman-Monteith results should be taken as more accurate since it is the procedure endorsed by the FAO. A specific difference to look for in the results is in the transition months. The FAO 24 procedure says that the Blaney-Criddle method could be more inaccurate for mid-latitude locations during transition months. For northern Namibia this means November, December, April, and May. The specific calculation procedures for the two methods used in this analysis are outlined below.

Blaney-Criddle Method in the FAO procedure (Doorenbos & Pruitt, 1977):

$$PET = c[p(0.46 \times T + 8)] \times t_{days} \tag{4}$$

with,

c = adjustment for day and night variations
p = mean daily percentage of total annual daytime hours
T = mean daily temperature in ˚C
t_{days} = number of days in the time period

Penman-Monteith method in the FAO procedure (Smith, et al, 1996):

$$PET = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} \cdot U_2 \cdot (e_a - e_d)}{\Delta + \gamma(1 + 0.34 \cdot U_2)} \times t_{days} \qquad (5)$$

with,

R_n = net radiation at the crop surface [MJ m^{-2} d^{-1}]
G = soil heat flux [MJ m^{-2} d^{-1}]
T = average air temperature [C]
U_2 = wind speed measured at 2m height [m s^{-2}]
(ea-ed) = difference between the saturation vapor pressure at mean air temperature and the mean actual vapor pressure of the air
Δ = slope of the vapour pressure curve [kPa C^{-1}]
γ = psychrometric constant [kPa C^{-1}]
900 = conversion factor
t_{days} = number of days in the time period

Both methods use data as well as tables to calculate the PET in units of [mm/time period]. This must be converted to a volume for use in the water balance.

4.1.3 Rainfall

Rainfall is the main input of water in this water balance system. Effective rainfall is a percentage of the actual rainfall. It is set to 75% of the actual rainfall for this water balance study (after Moorsom et al, 1995). It is recognized that this is as a conservative estimate for the rainfall term, and will be analyzed as such.

4.1.4 The Normalized Difference Vegetation Index

The use of satellite imagery for mapping and monitoring vegetation has been explored since the 1960's. The basic idea is that certain frequencies in the signal sent out by the satellite are absorbed by vegetation, and others are reflected. The Advanced Very High Resolution Radiometer (AVHRR) is used on various NOAA satellites. The spectral characteristics of satellites are summarized in Table 4.4.

Table 4.4:Spectral band widths (micometers) of the AVHRR. (Kidwell, 1998)

Channel	TIROS-N	NOAA-6,-8,-10	NOAA-7,-9,-11,-12,-14	NOAA-13	IFOV (mr)
1	0.55-0.90	0.55-0.68	0.55-0.68	0.55-0.68	1.39
2	0.725-1.10	0.725-1.10	0.725-1.10	0.725-1.0	1.41
3	3.55-3.93	3.55-3.93	3.55-3.93	3.55-3.93	1.51
4	10.5-11.5	10.5-11.5	10.3-11.3	10.3-11.3	1.41
5	Ch. 4 repeated	Ch. 4 repeated	11.5-12.5	11.4-12.4	1.30

The Normalized Difference Vegetation Index (NDVI) is a unitless measure of the degree to which these signals are either absorbed or reflected. It compares the reflectances of a near infrared (NIR) frequency (channel 2) with a red frequency (channel 1) through a ratio transform (Equation 6). "The first AVHRR channel is in a part of the spectrum where chlorophyll causes considerable absorption of incoming radiation, and the second channel is in a spectral region where spongy mesophyll leaf structure leads to considerable reflectance." (AVHRR, 1998)

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad (6)$$

Since it is normalized, the NDVI ranges from –1 to 1. The typical range is from –0.200 to 0.730. It has been shown that the NDVI exhibits non-linearity with respect to the NIR and Red ranges. But it becomes fairly linear in the range of interest, 0 to 0.6.(Eklundh, 1996)

For storage purposes, the NDVI data is scaled to the GIMMS 8-bit NDVI value, called DN. The original NDVI value is recovered through the equation:

$$NDVI = \frac{DN - 82}{256} \qquad (7)$$

Sample NDVI image shown in figure 4.1.

4.1.5 NDVI and Land Cover

For this study, NDVI is assumed to have a good correlation with vegetation. This is not a poor assumption according to previous studies. Eklundh, 1996, gives a very good review of the body of research on NDVI and vegetation cover (Eklundh) The nature of the NDVI indicates that it is a measure of the ‘greenness’ of a given area.

The correlation between NDVI and land cover is essential for the evapotranspiration calculations of the water balance. This is done by first determining average NDVI values land cover characteristics for the region during each month of the year. The only data available for actual land cover is the current average. The average NDVI values are calculated from the monthly values available from March 1993 to April 1998. The for each month in this period, the deviation from the mean NDVI value is determined. The scaled NDVI values were used for this calculation as the actual values contain some negative numbers.

The land cover characteristic of interest is the crop coefficient, K_c, which is used to scale the potential evapotranspiration estimates to actual. This is estimated from the FAO 24 procedure and combines the various types of vegetation in the region.

The connection between K_c and NDVI comes from the deviation of each NDVI value. For each month, the percent that the NDVI value deviates from its monthly mean is used to scale the average K_c value for the month. This gives the final K_c value that is used to calculate evapotranspiration from the region.

4.1.6 NDVI and Rainfall

As rainfall leads to vegetation growth, it is expected that there will be a positive correlation between NDVI and rainfall. A 1-2 month lag in this correlation has been shown for East Africa (Kenya, Ethiopia, Somalia) (Elklundh). For example, in a 1 month lag situation, rain that falls in December does not show its effect in vegetation until January.

The actual correlation in the lag data is not expected to be that large. The relationship is complicated by various factors including existing vegetation, crop cultivation, and noise in the signal. However, comparing the correlation for various lags in a given region should give some indication of the relationship.

4.2 Case Studies

Each case study covers an area of 39.6 km^2 in the eastern (Oniipa), central (Okatana), and western (Ombalantu) sections of the general Cuvelai area in central Owamboland (see Figure 4.2). The sites were chosen first on the basis of rainfall data. The availability of monthly rainfall totals corresponding to the months for which land cover data exist is essential to the water balance being attempted. Rainfall is the biggest input of water into the system, and must therefore be very well estimated. The variability of the rainfall in northern Namibia requires the use of actual data rather than data that is spatially interpolated between rainfall stations.

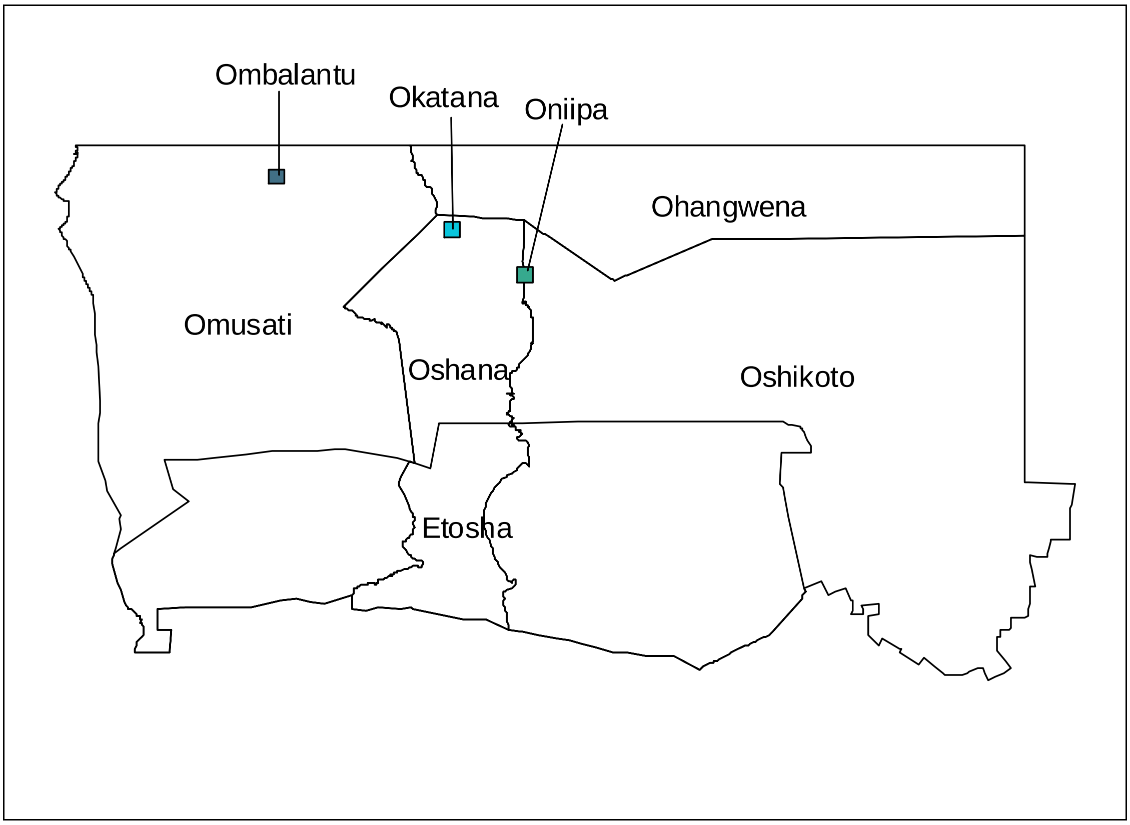


Figure 4.2: Owamboland with the study areas identified

The Okatana study area is located in the north-central part of the Oshana region. It lies to the north of one of the main urbanized towns of the four-O’s, Oshakati. The Oniipa study area straddles the border between the Oshana and Oshikoto regions. Just to the west is Ondangwa, another of the main urbanized towns in the four-O’s. And the Ombalantu study area is off to the west in the northern part of the Omusati region. It is right next to one of the main canals that was part of the original Owamboland Water Supply Scheme of the 1960's.

4.2.1 Rainfall

As in all of Owamboland, the study areas see seasonal and highly variable rainfall. Each has a substantial monthly rainfall record (Table 4.5) which allows for some probability distribution analysis (see chapter 5). The long-term monthly averages are shown in Figure 4.3.

Table 4.5: Charateristics of rainfall data in the three study areas

	Years with monthly rainfall data	Long-term seasonal average (mm)
Ombalantu	57	409.7
Okatana	62	492.5
Oniipa	96	445.9

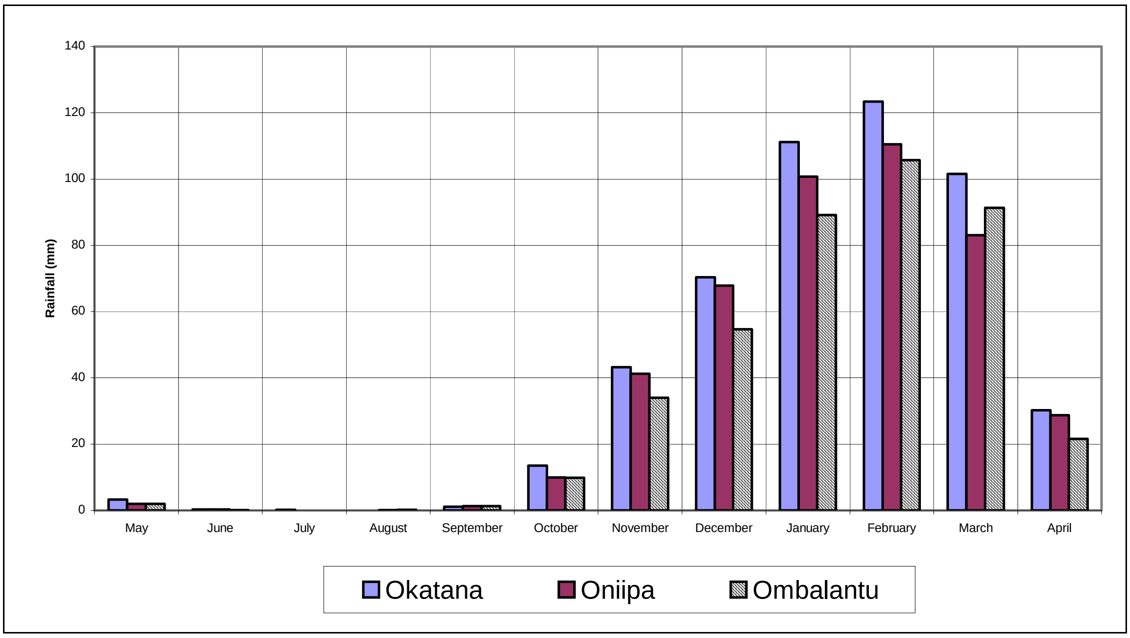


Figure 4.3: Average monthly rainfall totals for the three study areas

4.2.2 Water Supply

In addition to rainfall, the type of water supply used in the site was used to select the cases. Specifically, sites were chosen to be able to compare those with varying degrees of diversity in the type of water supply infrastructure. As seen in Table 4.6, Okatana has the least diversity in water supply as it relies on piped water. The impact that each of these forms of supplied water is conjectural at this point. But understanding the effects of the engineered water system is very important to

Table 4.6:Types of engineered water supply in each case study

	Boreholes	Canal	Dams	Pipeline
Okatana				X
Oniipa	X		X	X
Ombalantu	X	X		X

4.2.3 Agriculture & Land Cover

All three study areas are in the general vegetation category of mopane savanna. (Tarr, 1998) Each has specific vegetation cover characteristics as described in Table 4.7 (see Appendix C a complete list of specific vegetation and relative abundances).

The dominant soil types in Ombalantu and Okatana are solonetzic and planosolic soils with an A-horizon. Oniipa is dominated by halomorphic solenetzic soils. (MET, 1999) All three are characterized by the landform described as: "Flooded and overflowing areas in the Kalahari Region." (Tarr. 1998)

Table 4.7: Types of vegetation cover in each study area. See figure 4.4 below. Also see Appendix C for a complete list of specific vegetation and relative abundances. (DEA, 2000)

Vegetation Cover	Description	Percent Coverage		
		Okatana	Oniipa	Ombalantu
Oshana-Kalahari mosaic	Crop/fruit tree/mopane/oshana mosaic in Cuvelai system with sands	80	49	0
Oshanas	Oshana	20	0	27
Palms and pans mosaic	Crops/S mopane with L cover/palms/Oshana mosaic in Cuvelai system with sands	0	51	0
Cuvelai palms and fruit trees on loamy sands	Upland area in Cuvelai system with loamy sands, dominated by crops & fruit trees	0	0	73

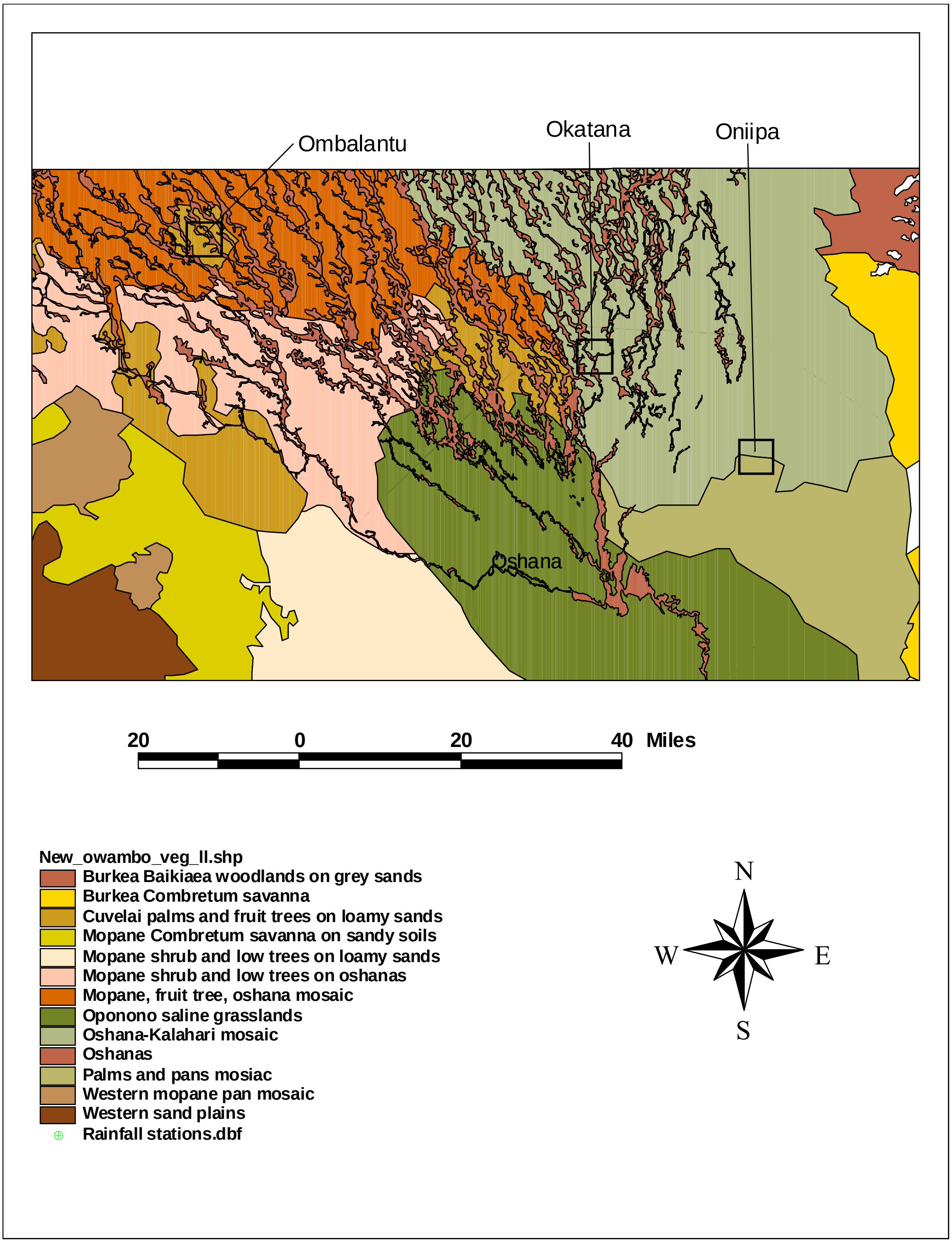


Figure 4.4: Vegetation cover in the study areas (from DEA data, 2000)

4.2.4 Elevation

All of the four-O's fall between 1000m and 1200m above sea level. And in the central areas it is even flatter. Figure 4.5 shows the elevation profile for a cross-section between Ombalantu, Okatana, and Oniipa. The lack of elevation change in Owamboland has a great effect on the landforms that support water movement, and therefore on the fate of water.

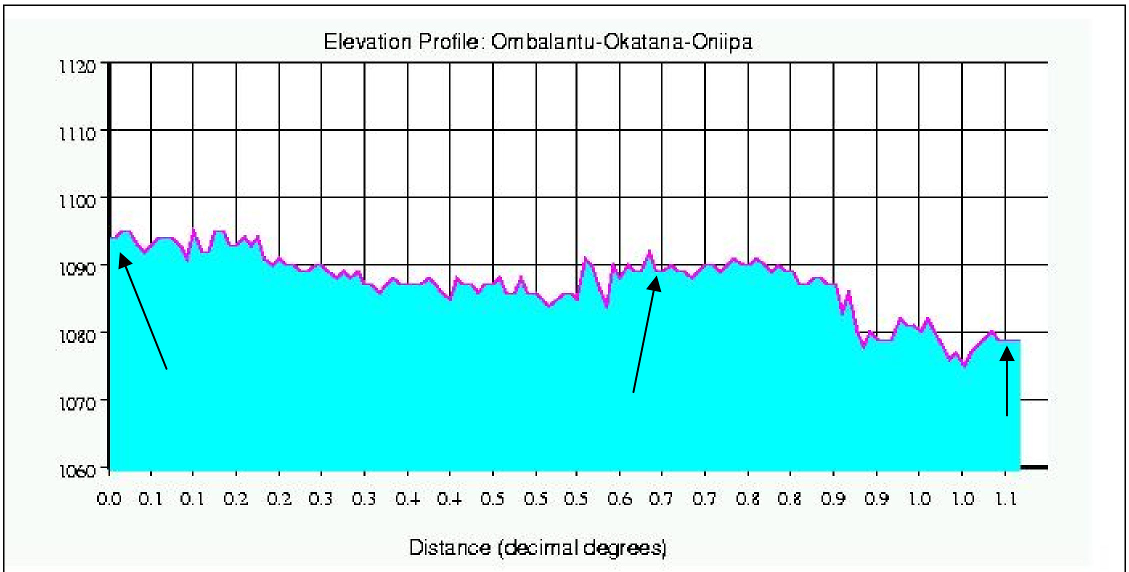


Figure 4.5: Elevation profile showing left to right Ombalantu-Okatana-Oniipa

4.3 Results

The methodology of the water balance outlined at the beginning of this chapter includes rainfall, evapotranspiration, human and stock demand as the inputs and outputs of water to the system defined as the soil column. The initial results of this study showed that the rainfall and evapotranspiration parameters are orders of magnitude larger than the summation of all human and stock demand terms. This is illustrated by the values of water supply and demand to the heavily populated area of Ondangwa. High estimates have Ondangwa receiving 75,000m^3 of water each month. Translating into depth, this gives about 3.1mm of water supplied. Comparing these values to water balance calculations (presented below) for the much more sparsely populated areas of Okatana (to the north of Oshakati) and Oniipa (to the west of Ondangwa) shows that changes in the demand terms will not have a large impact on the overall water balance for the area as a whole. However, it should be said that changes in demand can and do have a large impact on the very small-scale water balance. Here, small-scale is meant in both a spatial and temporal sense.

This clarification points directly to the scope of this analysis. That is, the study is meant to take initial steps toward the study of the large-scale, both spatially and temporally, water balance in north-central Namibia. It only points indirectly at the small fluctuations in water balance that can affect the availability of water on a day to day basis. It is important to recognize this as the results are presented.

4.3.1 Storage

Results of the overall water balance show that Ombalantu, the westernmost study area, fared very badly in terms of overall terrestrial storage during the period of March 1993 to April 1998 (figure 4.6). According to this analysis, the storage has seen a loss equivalent to over one meter in the region surrounding Ombalantu. Oniipa, in the east, also saw a loss, but only about 300 mm over the 5-year period. In Okatana there was a steady increase in overall storage during the first half of the period, but a decline in the second half ending around 40 mm below the 1993 level.

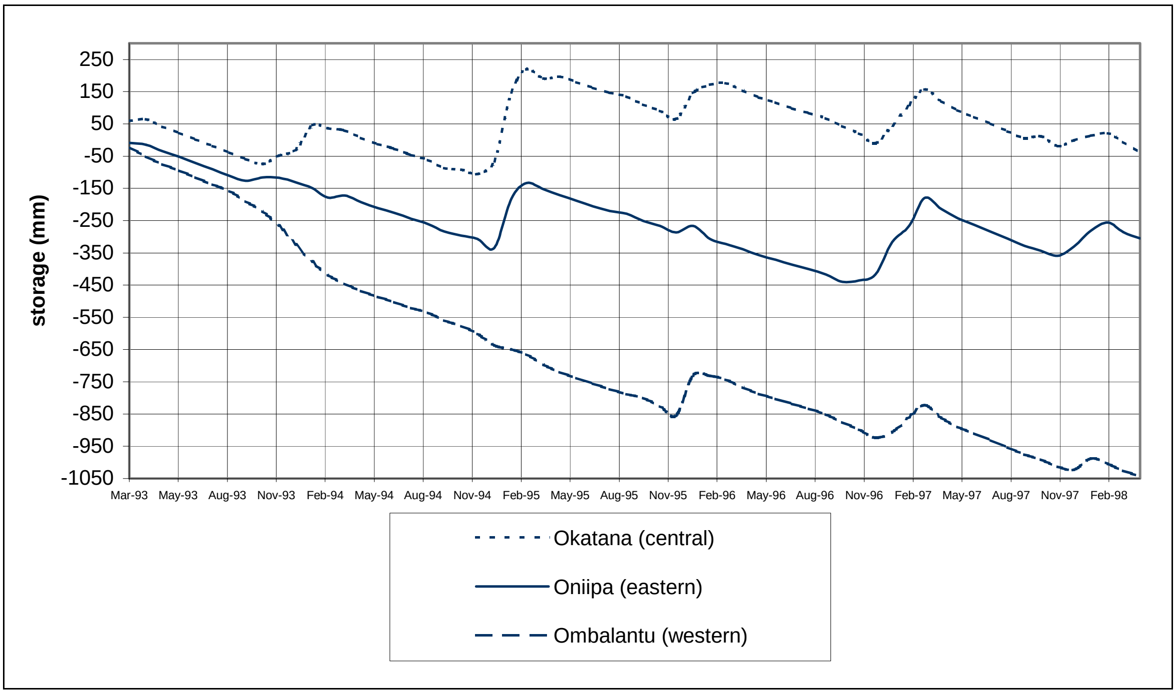
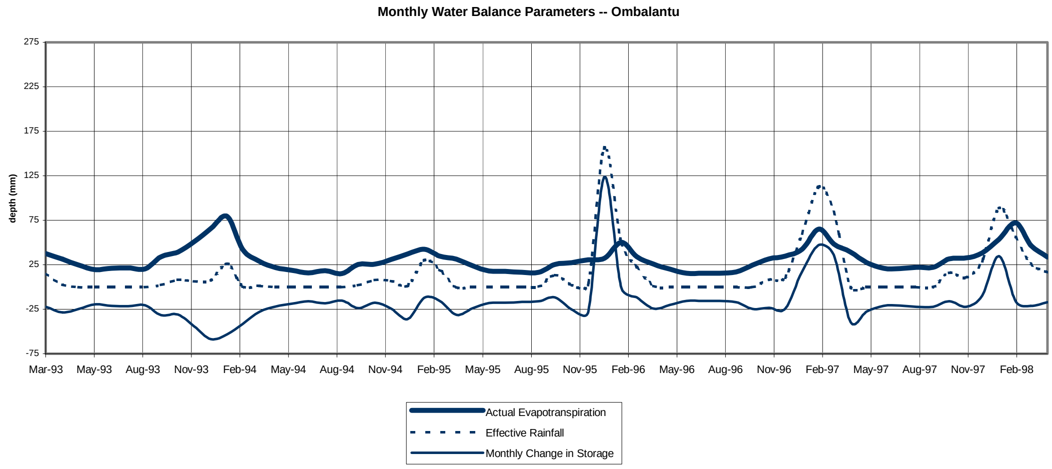
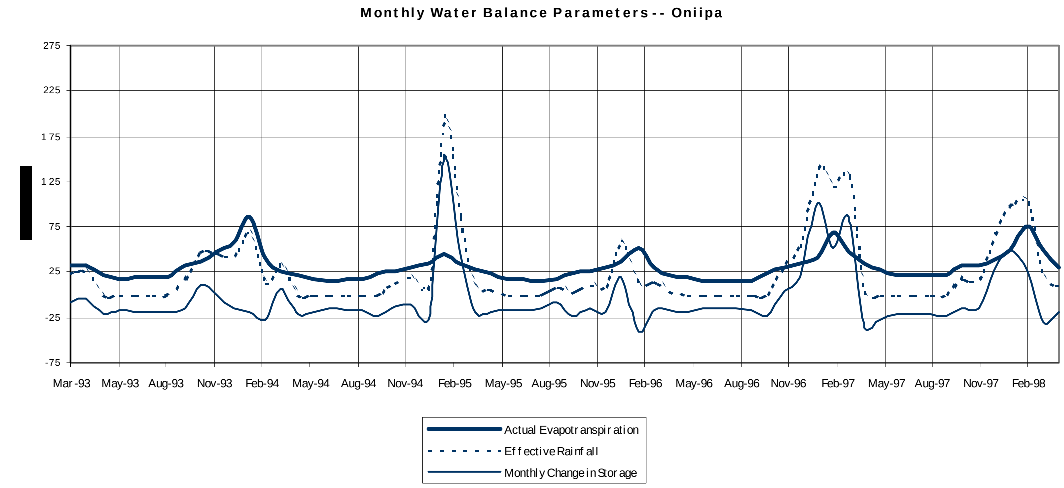


Figure 4.6: Cumulative monthly storage for the three case studies.

Each study area shows the seasonal fluctuations that are expected in a region that has such well-defined wet and dry seasons. This also indicates that the character of terrestrial storage is generally governed by rainfall with adjustments by evapotranspiration. But some seasons show very little rise in storage during the wet season. Causes for this can be seen in the breakdown of rainfall and ET for the individual study areas (figure 4.7). It's also helpful to look at the corresponding NDVI values to get a sense of the vegetation cover at the time (Figure 4.10).





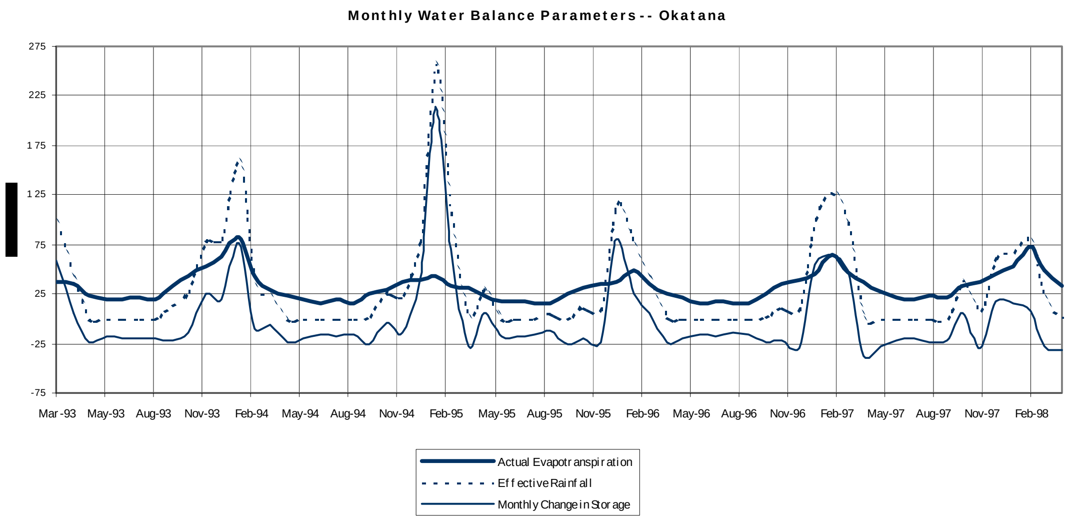


Figure 4.7:Water balance parameters

4.3.2 Evapotranspiration

The Penman-Monteith and Blaney-Criddle ET calculation methods performed very closely in all three case studies (figure 4.8). This result coincides well with the 1990 revised FAO performance study that put the two methods very close to each other in estimating ET for arid environments. The transition months show a general higher estimate from the Blaney-Criddle method. This is consistent with the FAO 24 recommendations.

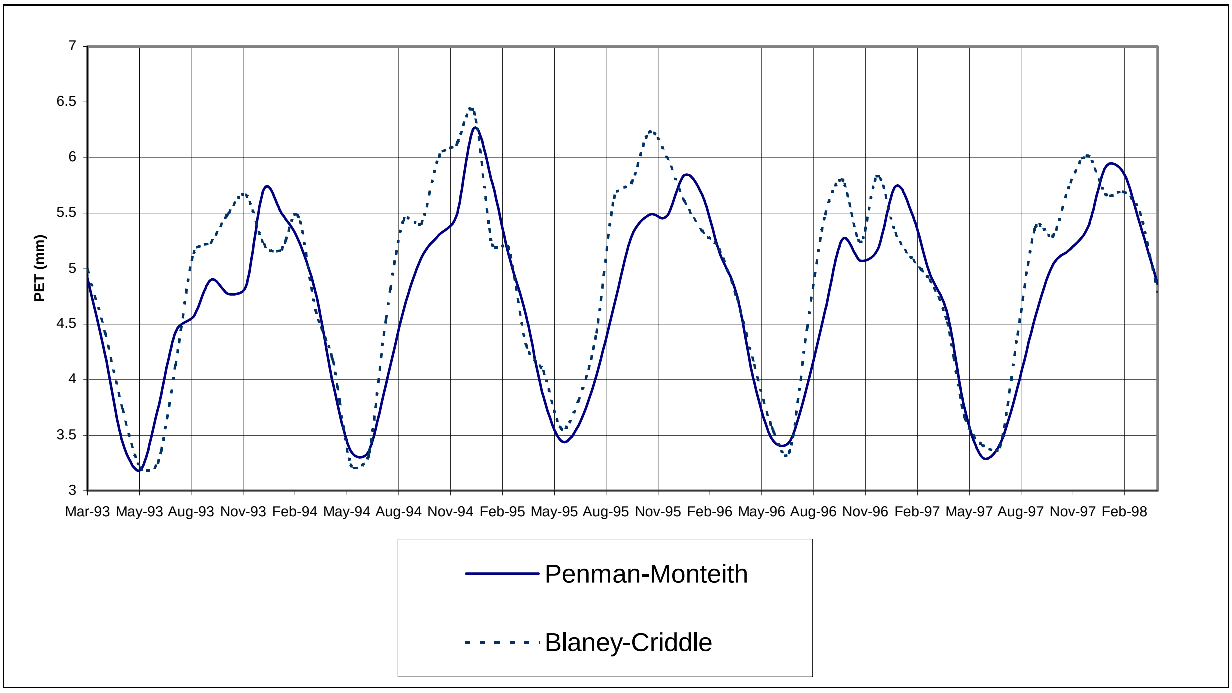


Figure 4.8: Penman-Monteith and Blaney-Criddle PET calculations for Okatana

Crop coefficient estimates based on average vegetation cover and NDVI deviations in each month show the expected strong seasonal trend. Monthly average K_c values are shown in Table 5.8. The fall, winter, and spring coefficients were determined by the FAO 24 procedures, and monthly breakdowns interpolated. For the growing season months in the summer, more detailed estimates were made for the portion of the groundcover affected.

Table 5.8: Monthly K_c values

	Okatana	Oniipa	Ombalantu
Mar	0.257	0.246	0.255
April	0.230	0.220	0.229
May	0.203	0.194	0.202
June	0.185	0.177	0.185
Jul	0.167	0.161	0.167
Aug	0.149	0.145	0.150
Sep	0.130	0.128	0.132
Oct	0.180	0.172	0.179
Nov	0.226	0.197	0.204
Dec	0.256	0.222	0.230
Jan	0.257	0.247	0.256
Feb	0.387	0.376	0.385

A comparison with published average values is a good check of the PET values calculated. Hutchinson gives mean monthly values for Ondangwa (Moorsom et al, 1995), which is just to the west of Oniipa. The comparison shows similar trends, but a later peak in the calculated values for Oniipa than in Hutchinson's for Ondangwa (Figure 4.9).

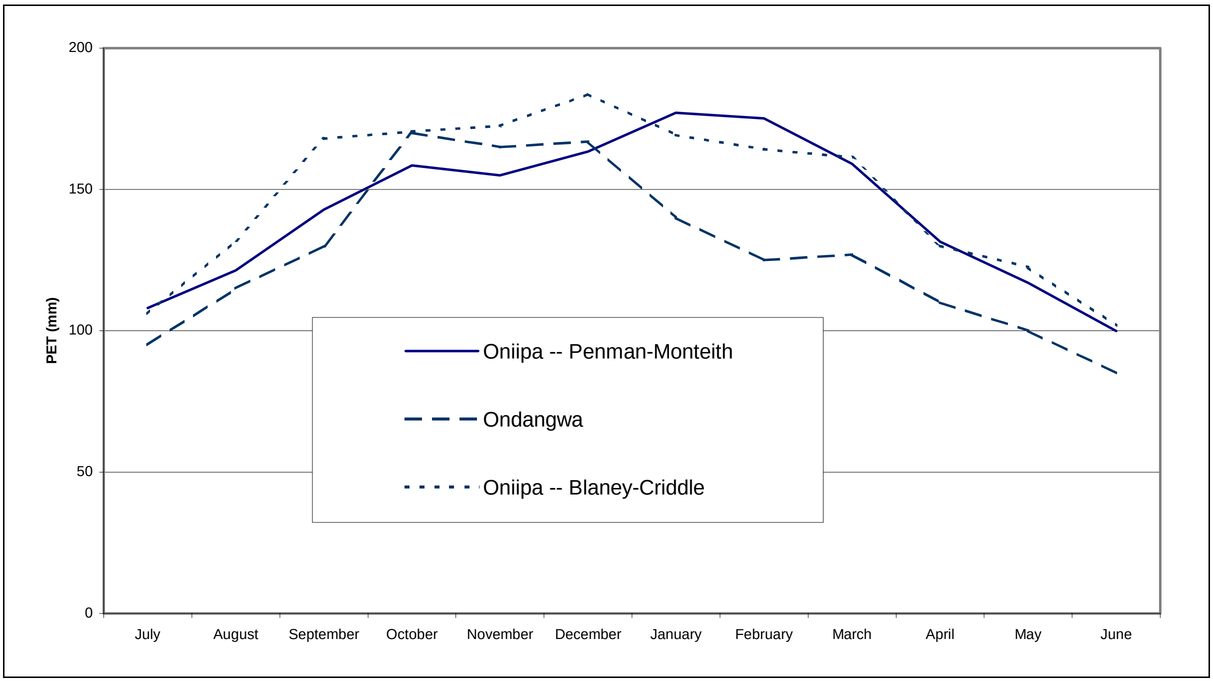


Figure 4.9: PET calculated values for Oniipa (this study) and Ondangwa (Moorsom, et al, 1995).

4.3.3 NDVI

The monthly NDVI values show a general seasonal trend as expected (figure 4.10). The largest peaks usually occur at the end of the wet season in March and April. This makes sense as the vegetation has had time to react to the rainfall and develop its 'greenness' fully. The main exception to this trend is the 1993-1994 season when the largest peak occurred during February. This is possibly to the rainfall in December, which was 50% higher than its monthly average in Okatana.

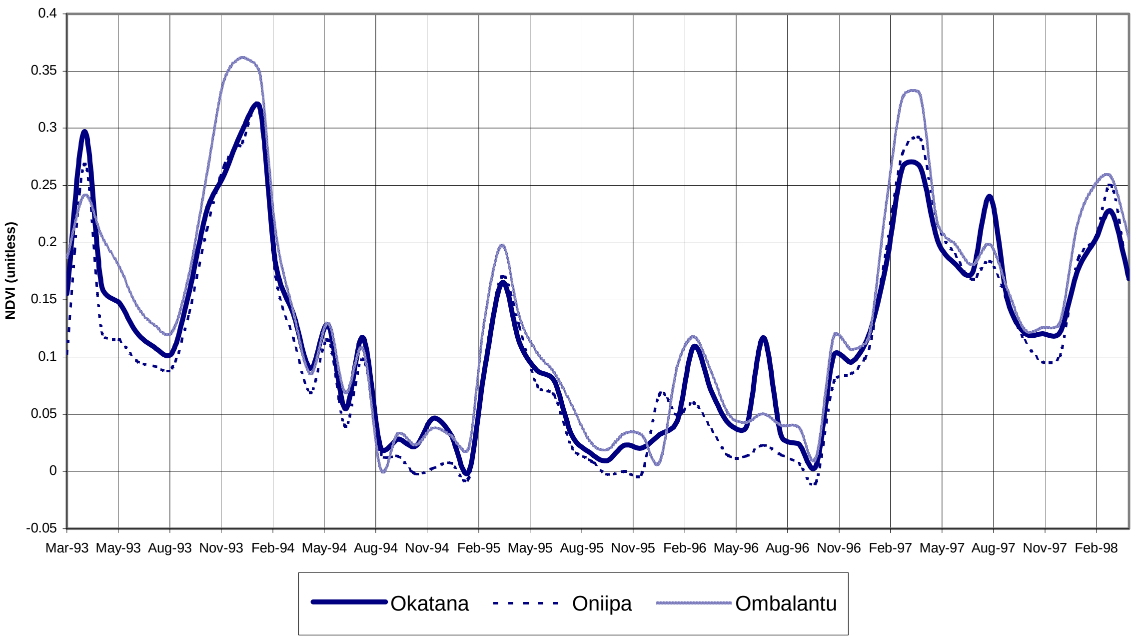


Figure 4.10: Monthly NDVI values for the three case studies.

The character of the NDVI data indicates that the 6-by-6 pixel, 39.6 km^2 composite value is a good measure of the areas NDVI. That is, within this spatial range there is not much variability. The standard deviations of the 6-by-6 pixel are similar in all three cases (figure 4.11). This supports the idea that the composite value capturing the area's NDVI well. This was also seen in East Africa (Eklundh, 1996).

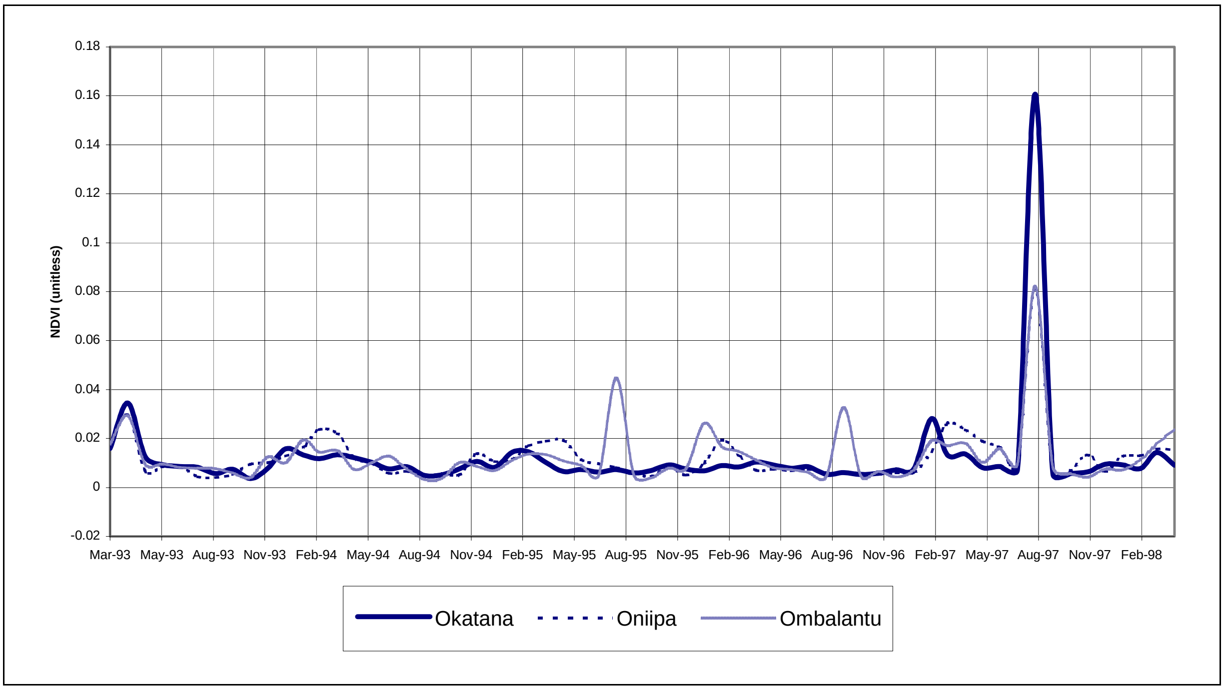


Figure 4.11: NDVI 6x6 pixel composite standard deviations for the three study areas.

Noise in the data was not calculated. But an indication of variation in the measurements can be seen by comparing the values in June, July, and August. These months see very little if any rainfall with a combined long-term average of 0.17mm. So, there should be a steady decline in vegetation cover in theory. But each dry season shows a general variation of between 0.03 and 0.05. That is, June may be at 0.1; then July at 0.05; and August back to 0.01.(figure 4.10)

4.3.4 NDVI & Rainfall

The correlation between NDVI and rainfall was found to be weak as expected due to the complexity of the relationship. But the examination does show a definite improvement in correlation with varying monthly lags (table 4.9).

Table 4.9: R-squared values for NDVI-rainfall calculations at various monthly lags.

	Lag = 0	Lag = 1	Lag = 2	Lag = 3
Ombalantu	0.0296	0.130	0.117	0.0468
Okatana	0.0326	0.126	0.141	0.252
Oniipa	0.0659	0.245	0.323	0.1368

These data hint at a trend towards a 2-month lag in the east, and moving to a 1-month lag in the west. This is obviously just a hint from the data. But the correlations are based on 62 data points for each study area. This is a specific relationship that should be studied in the future.

Chapter 5: Stochastic Modeling 1999-2020

Given the problems with resource management outlined in the previous chapters, long-term predictions of resource availability would be extremely useful especially for large-scale planning. So it is necessary to examine the predictive capabilities of the parameters used in the water balance study.

In this study, a stochastic modeling procedure was used to estimate rainfall from 1999-2020. These rainfall values were then used to estimate land cover using the correlations developed from the period 1993-1998. Specifically, the study area with the strongest observed NDVI-rainfall lag correlation, Oniipa, was modeled using a linear, 2-month lag as described in section 4.3.4. Figure 5 shows the results for the 21-year model combined with the 6-year observations.

Table 5.1: Distributions and fit test values for each month -- Oniipa

	May	June	July	Aug	Sep	Oct
Distribution	Gamma	Gamma	Gamma	Gamma	Weibull	Beta
Parameters	Loc: 0.0 Scale: 20.1 Shape: 0.10	Loc: 0.0 Scale: 3.2 Shape: 0.10	Loc: 0.0 Scale: 0.3 Shape: 0.10	Loc: 0.0 Scale: 0.9 Shape: 0.10	Loc: 0.0 Scale: 0.5 Shape:0.43	Alpha: 0.37 Beta: 5.84 Scale: 168.9
Chi-squared test	571.37	866.5	930.85	864.1	459.8	21.7
P-value	0	0	0	0	0	0.0055

	Nov	Dec	Jan	Feb	Mar	Apr
Distribution	Weibull	Beta	Gamma	Gamma	Beta	Weibull
Parameters	Loc: -1.5 Scale: 46.5 Shape: 1.34	Alpha: 1.08 Beta: 4.72 Scale: 365.2	Loc: 5.0 Scale: 71.2 Shape: 1.35	Loc: 0.0 Scale: 46.7 Shape: 2.37	Alpha: 1.09 Beta: 3.72 Scale: 367.4	Loc: -0.2 Scale: 27.9 Shape: 0.92
Chi-squared test	9.62	4.868	6.226	2.696	5.144	18.87
P-value	0.2931	0.7716	0.622	0.9520	0.7367	0.0156

A modeling program[2] that uses a Monte-Carlo Simulation procedure was used to fit a relevant distribution model to the long-term monthly total data for each month (Table 5.1). This is an automatic fitting procedure that ranks the relevant distribution models based on either the Chi-squared test or P-value. Running a simulation consisting of 1,000 trials produced a realization of rainfall data for each month through the years 1999-2020.

[2] Crystal Ball Pro – an add-in for Microsoft Excel. All software used is described in Appendix B

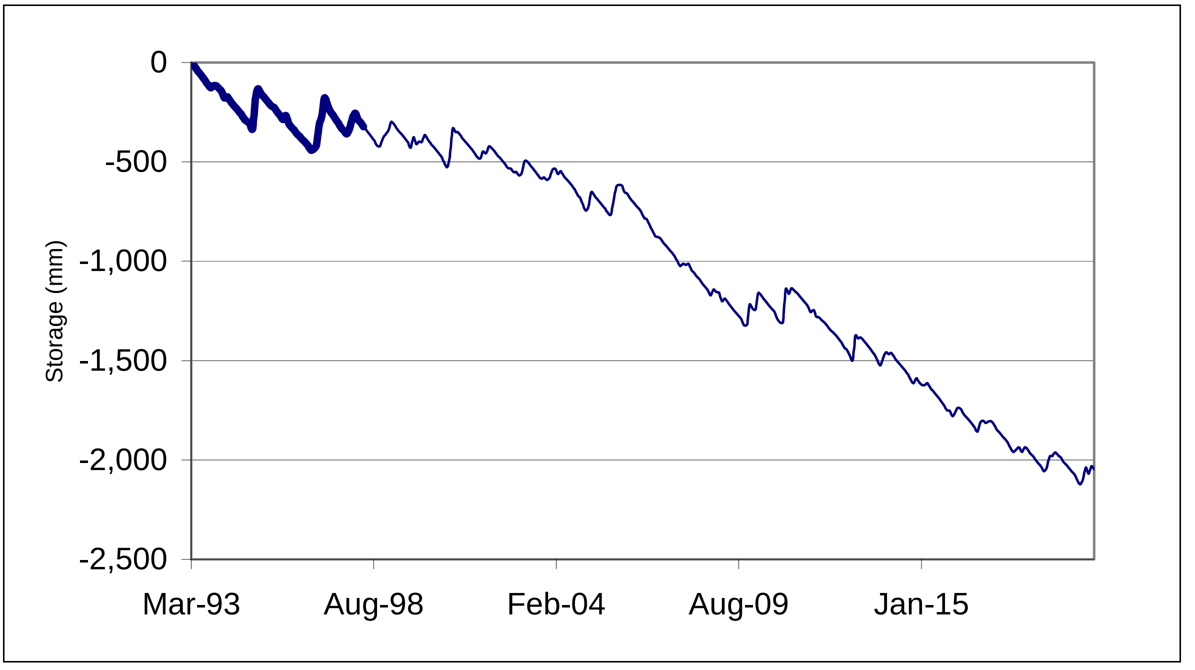


Figure 5: Cumulative storage for Oniipa from data (1993-1998) and modeled (1998-2020)

The rainfall distributions turned out to be very accurate for the time frame chosen, and would be accurate for long-term estimates barring a major shift in climate for Northern Namibia. The mean values for just a single realization of the 21-year prediction window come very close to the long-term average for the each corresponding month (Table 5.2). This accuracy makes sense as Oniipa has a 96-year monthly rainfall record. In general terms, using 96 years to predict 21 is a pretty safe bet.

Table 5.2: Mean monthly & seasonal rainfall (mm) for data and model results -- Oniipa

	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Season
Long-Term Mean	2.8	0.5	0.0	0.0	1.2	11.0	42.7	64.5	103.0	112.2	85.0	26.9	449.8
Predicted Mean 1999-2020	1.1	0.7	0.0	0.1	0.7	9.3	43.5	72.4	78.4	93.0	66.3	19.2	384.6

The results show that while rainfall can be statistically accurate, the linear relationship between rainfall and NDVI leads to a very drastic storage profile. Although, losing 2 meters in 28 years is not necessarily unreasonable since Ombalantu lost over 1 meter in the span of 6 years.

The main goal of the modeling procedure was to test the feasibility of using a linear lag relationship to model NDVI from rainfall predictions. The results show that this procedure is not unreasonable, but will require a much more careful dissection of the relationship. Still, this finding is encouraging since there is a large amount of satellite NDVI data with which to study the relationship with rainfall.

Chapter 6: Conclusion

It is sometimes hard to see when issues with natural resources should be dealt with, given the variety of problems the world faces. It is essential to recognize that these issues will necessarily take a central role in the development and well-being of the world whether or not they are at the center of a political agenda. This is particularly true in Southern Africa where most of the people live close to the sensitivities of the land. Namibia has shown great leadership in stressing the importance of natural resources and the environment.

The original goal of this project was to gain a detailed understanding of the natural and anthropogenic effects on the state of the environment in north-central Namibia. This remains the overall goal. The water balance analysis provides a very good start towards this end. Future research outlined in the next section will make further advances. Specifically, tracing changes in the overall water balance along with changes in the climate, engineered water supply, population, infrastructure, and urbanization will identify the general effects of each of these elements.

The water balance covers the period March 1993 to April 1998. The main aim of the balance is to trace the terrestrial storage of the three study areas during this time. In theory, it is expected that storage will not change from year to year. Water is added during the wet season, and taken out during the dry season. And any differences in this balance indicate either a problem with the water balance analysis, or there is an actual change in the soil water. This balancing process could be on a larger time scale than that used in analyses. For example, the storage balancing process may be on a 20-year deviation from the mean during the five year time frame of this analysis. And therefore the analysis would not see any balance in the path of terrestrial storage.

However, looking at the period just before this analysis could give an indication of the direction of the storage path. Before the timeframe of this analysis, the 1992/93 season was an especially bad drought year for the central Oshana area. So it is expected that the storage of those areas would have been depleted to a point. And the next 5 years could possibly see a recovery from that depleted state.

The question here is how long will this measure of storage remain unbalanced? This is the kind of question that can be answered by the type of analysis performed in this project. The results here lead the way for further research on North-Central Namibia's water resources. Future studies can build on this study and go much further in depth.

Recommendations & Further Research

A very important and potentially useful issue on this subject is the use of NDVI data for prediction. Eklundh, 1996, found NDVI imagery to be of moderate to low usefulness for predictions in East Africa. But the potential benefit from this is so high that it is worth the time and effort. The potential is so high because of the large amounts of high-resolution data. This would specifically involve the study of NDVI frequencies through Fourier analysis, as well as correlation these frequencies with rainfall. The frequency distributions used in the stochastic modeling of this analysis provide a good first step for a future project on this topic.

Related to the study of ground cover, a more in depth analysis of the relationship between NDVI and ground cover is needed. This study made use of average vegetation cover correlated with deviations of the NDVI to obtain an estimate of the ground cover. But an accurate direct correlation between NDVI and vegetation in Owambo would be very useful. This could involve the use of areal photographs that map specific vegetation for a given area.

Also as part of this effort, an index could be developed to describe how a given area responds to rainfall in terms of storage. This was attempted with little luck for the data in this study by normalizing a month's change in storage by the corresponding rainfall, and then at various monthly lags in rainfall. In theory this index would be useful in outlining an areas water balance characteristics.

Finally, the next step from the water balance analysis is to connect changes in the balance with specific anthropogenic and natural changes on the land. To get at this, the water balance must be refined to a spatial and temporal resolution that allows for the analysis of small-scale fluctuations missed by the broad first step taken in this study.

The Northern Namibian Environmental Project is taking great steps in this direction with surveys on the impact of the engineered water supply on people's lives. Other survey data like that in the OMITI database at Princeton University provide a good baseline from the early 1990's. As discussed in the data section of chapter 4, this type of data will be essential in expanding the analysis provided here towards an understanding of the relationship between people and the environment.

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Appendix A: Data Sources

Climatic Data:
Weather Bureau Windhoek, Namibia
http://www.ncdc.noaa.gov

GIS data:
DEA Windhoek, Namibia
NRSC Windhoek, Namibia

NOAA NDVI data:
DEA Windhoek, Namibia

Topographical data:
Http://www.ngdc.noaa.gov

Appendix B: Software Used

B.1: Arcview3.1

This program was used for GIS data processing and display. It is very useful for working with large amounts of data and focuses on display options.

The software is available on the campus of Princeton University.

B.2: Crystal Ball (Excel Add-In)

This is an add-in for Microsoft Excel that adds stochastic modeling functionality to spreadsheet calculations. It offers a wide variety of distribution models, as well as the ability to customize them. One can manually or automatically fit the models to data.

The software was made available through a course at Princeton University.

B.3: IDA image processing

The IDA program was used to process NDVI images initially into both text and IDRISI formats so that they could be used in other GIS programs. It is a DOS-based program with a fairly self-explanatory menu. It also supports some image calculation and display options.

This program was obtained from NOAA NDVI processors.

B.4: IDRISI32 (Clark University)

This program was used to process NDVI images after converting to IDRISI format in the IDA program. It supports NDVI images specifically, and offers many more processing options than Arcview. The display capabilities for NDVI images were particularly helpful.

The software (30-day trial version) was obtained from:

http://www.clarklabs.org/main.htm

Appendix C: Vegetation Cover

The numbers are relative abundance values (0 = none,5 = highly abundant)

Biological Name	English	Afrikaans	Oshivambo	Okatana	Oniipa	Ombalantu
Colophospermum mopane	Mopane	mopanie	Omufyati/Omusati	4	3	4
Sclerocarya birrea	Marula		Omwoongo/Omugongo	3	2	2
Berchemia discolor	birdplum	voelpruim wildedadel	omuve/omuye	3	2	2
Hyphaena petersiana				2	3	2
Ricinodendron rautenniana	mangetti tree	manketti	omunghete/omunkete	1	0	1
Acacia erioloba	Camel thorn	Kameeldoring	omwoodne	2	1	2
Acacia nebrownii	water thorn	waterdoring	omuhaloweyo	1	1	2
Acacia reficiens/luederitziae	red umbrella thorn	lekkerruikpeul	omutyuula	2	1	2
Acacia flecki/erubescens	plate thorn	bouhaak	omangadjaba	1	0	1
Acacia arinaria				2	2	2
Catophractes alexandri	-	skaapbos	okalyadi/okalyanzi	3	2	3
Terminalia prunioides	lowveld cluster-leaf	deurmekaar	omuhama/omunghama	2	1	2
Terminalia sericia	silver cluster-leaf	vaalboom/(sand) geelhout	omwoolo/omugolo	3	2	1
Ficus sycamorus	wild fig	wildevy	omukwiyu/omukuyu	2	1	1
Burkia africana	wild seringa	sandsering	omutundungu	2	1	1
Peterocarpus angolensis	wild or tansvaal teak/dolf	kiaat	omuuva.omuguya	2	1	1
Baikia plurijuga	rhodesian teak	rhodesiese teak	omupapa	2	1	1
Combretum apiculatum	red bushwillow	rooibos	omulama/omunaluko	2	1	1
Dichrostachys cinerea	sickle bush	sekelbos	onyege/ongete	1	2	1
Combretum collinum				2	1	1
Combretum psidioides				2	1	1
Combretum imberbe	leadwood	hardekool	omukuku	2	1	2
Combretum celastroides				2	1	1
Spirostachys africana				0	0	0
Lonchocarpus nelsii	kalahari appleleaf	kalahari-appelblaar	omupanda	2	1	1
C.mollis, pyracanthoides, multijuga, glausescens, teniopetiolata				2	1	1
Kirkia accumunata				0	0	0
Diospiros mespiliformes	transvaal or african ebony	jakkalsbessie	omwandi	2	2	1
Pechuel-loeshea leubnitziae				4	3	4
Croton gratisimus/menyarthi	lavender fever-berry	lanetelkoorsbessie	ombango	1	0	1
Sesamothamnus quaritciana				0	0	0
Schmidtia kalahariensis				4	4	4

Schmidtia pappophoroides				1	1	1
Aristida stipitata				1	2	1
Aristida stipoides				3	4	3
Aristida meriodinalis				1	1	1
Eragrostis pallens				1	0	1
Eragrostis rigidior/trichophora				2	2	2
Eragrostis nindensis				0	0	0
Eragrostis porosa				2	3	3
Eragrostis annulata				2	3	2
Eragrostis rotifer				3	2	3
Enneapogon desvauxi				1	1	2
Enneapogon cenchroides				3	2	3
Aristida adscensionis				2	3	2
Aristida rhiniochloa				2	3	2
Antephora pubescens				1	0	1
Antephora schinsi				2	1	2
Stipachrostis hirtigluma				3	2	3
Stipagrostis uniplumis				1	1	1
Triraphis rammosissima				0	0	0
Odycea paucinervis				4	4	4
Sporobolus spicatus				3	3	3
Sporobolus tenellus				4	4	4
Cynodon dactylon				1	1	1
Digitaria eriantha				2	1	2
Digitaria serata (has now another polevansii ??)				1	0	1
Brachiaria nindensis				1	0	1
Wilkommia sarmentosa				4	4	4
Monolytrum luederitzianum				3	3	3
Panicum novemnerve				2	1	2
Panicum maximum				0	0	0