UNIVERSITY OF ZIMBABWE

Faculty of Engineering

Department of Civil Engineering

Predicting hydrological droughts from a Standardized precipitation index (SPI) in South Phuthiatsana River basin, Lesotho

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by

Limpho Fobo (R088461G)

A thesis submitted in partial fulfillment of the requirements of the Masters degree in Integrated Water Resources Management (IWRM)

2009

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A thesis submitted in partial fulfillment of the requirements of the Masters degree in Integrated Water Resources Management (IWRM)

2009

DECLARATION

I, Limpho Fobo declare that this thesis is my own work. To the best of my knowledge it has not been submitted before for any degree at any university.

Signed: ………………………………

Date: …………………………………

DEDICATION

To my mom, ‘Me’ ‘Mathuso Fobo, and my brothers Neo and Thuso (late) may his soul rest in peace.

ACKNOWLEDGEMENTS

I am thankful to my supervisors Dr A. Murwira and Eng. E. Kaseke for guidance, advice and their time they devoted during the entire study period. I also wish to acknowledge the Department of Water Affairs and Lesotho Meteorological Services staff for the assistance they gave me during data collection.

I also thank Waternet for the financial assistance and Department of Civil Engineering staff, all my colleagues in the 2008/09 Masters in IWRM group specifically Vuyisile Dlamini and Joanna Fatch for their support.

To my mom who has been praying for me throughout the entire period and to all those who assisted me. Thank you very much and keep up the good work.

ABSTRACT

Droughts affect Lesotho in varying degrees every year leading to shortage of water, posing a threat to nature, quality of life and economy. Although hydrological droughts are defined by below long-term mean of annual flow, the cause is mainly below normal precipitation falling on the catchment. Hydrological droughts characteristics analysis need streamflow data but most rivers in Lesotho are un-gauged and those which are gauged have been recently gauged which makes the data not long enough and unreliable for the analysis. However, reliable meteorological data is available in Lesotho which can be used for predicting hydrological droughts from precipitation so is the main objective of this study. This research is using Standardized Precipitation Index (SPI) at 3, 6, 12 and 24 months time scale to find the correlation of streamflow and SPI values which will result in identifying severity and duration of meteorological drought that causes the below normal streamflow in South Phuthiatsana River basin in Lesotho. The results showed that at 6- months SPI - severity of meteorological droughts- the streamflow can be reduced to below mean annual flow.

Keywords: *Hydrological droughts, Standardized Precipitation Index, severity, streamflow.*

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LIST OF ACRONYMS

CMI:	Crop Moisture Index
ENSO:	El Niño Southern Oscillation
FEWS-NET:	Famine Early Warning System Network
GDP:	Gross Domestic Product
GFCSA:	Global Forecasting Centre for Southern Africa
GIEWS:	Global Information and Early Warning System
GIS:	Geographic Information System
IDW:	Inverse Distance Weighted
LHWP:	Lesotho Highlands Water Project
LLWP:	Lesotho Lowlands Water Project
MAR:	Mean Annual Runoff
masl:	Metres above sea level
ML/d:	Mega Litres per day
Mm^3:	Mega cubic metres
NMDC:	National Drought Mitigation Centre
PDSI:	Palmer Drought Severity Index
Q_o:	Threshold level
SPI:	Standardized Precipitation Index
SPSS:	Statistical Package for Social Scientists
SST:	Sea Surface Temperature
UNOCHA:	United Nations Office of Humanitarian Aid

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Chapter 1: Introduction

1.1 Background

Lesotho's main natural resource is water and are estimated at 5.23 km³/yr, by far exceeding its water demand but due to Lesotho's commitment in the framework of the LHWP, its actual water resources will have decreased to 3.03 km³/yr by 2020 (Kundell, 2008).This situation will be exacerbated by persistent droughts affecting the country.

Droughts affect different parts of the world to varying degrees every year. Severe and extreme drought affects more than 25% of the United States of America in one out of four years (Wilhite and Svoboda, 2000), while in Lesotho droughts occur three years out of every ten (Kundell, 2008). These droughts lead to shortage of water, posing a great threat to nature, quality of life and economy. Conflicts have also arisen especially during times of severe and extensive droughts because of competition for the limited available water resources (Hisdal and Tallaksen, 2003). The minimum of 2- 3 months without rainfall is required for meteorological drought to be established and less than that is referred to as the dry spell. The duration of drought can continue for months or years after the onset (Wilhite and Svoboda, 2000).

There are different types of droughts, each referring to a water deficit in a specific part of the hydrological cycle. There are connections between different types of drought. A drought in one stage of the cycle can lead to a drought also in other stages (NDMC, undated). The connection depends on severity and duration. Meteorological drought starts with a less than normal amount of precipitation and the more severe and longer it gets, leads to the soil moisture deficit which is termed agricultural drought, and lastly hydrological droughts develop which are defined by truncation level - the long-term mean of the annual flow sequences (Panu and Sharma, 2002).

Although hydrological droughts are defined by below long-term mean of annual flow, the cause is mainly below normal precipitation falling on the catchment. There has been considerable research on modelling various aspects of different droughts such as identification and prediction of its duration and severity but not much on showing the link between different droughts characteristics but dealing with them independently. In this research the Standardised precipitation index (SPI) of different time scales will be used, which will result in identifying severity, spatial extent and duration of meteorological drought that causes the below normal streamflow which is considered as hydrological drought in this research.

On the other hand hydrological droughts characteristics analysis need streamflow data but most rivers in Lesotho are un-gauged and those which are gauged have been recently gauged which makes the data not long enough and unreliable for the analysis of hydrological droughts. But with meteorological droughts, the reliable data is available in Lesotho which can be used for predicting hydrological droughts from precipitation. This is evident with the catchment in consideration in this research – South Phuthiatsana River basin - where there are six runoff stations but only three with available data and out of the three, only one has reliable data and long enough (more than 30 years record) to do the drought analysis.

Even though droughts of varying extent are a regular occurrence and poses insufficient water and food in Lesotho, there is still no drought management policy and drought early warning system at present in country. The country still depends on global and regional early warning systems such as South African Weather Services GFCSA -Global Forecasting Centre for Southern Africa, Famine Early Warning Systems Network (FEWS NET), Global Information and Early warning System (GIEWS) and Regional Drought Monitoring Centre which provide countries with climate hazards and related issues but it is necessary for nations or countries to have localised information systems on climate hazards and their impacts especially on vulnerable communities.

The research is trying to establish a link between meteorological drought and hydrological drought characteristics. Deficit of precipitation has negative impacts on the groundwater, reservoir storage, soil moisture, snow pack, and streamflow (Won-Hee et al, undated) but it is not clear at what time scale and severity will this deficit of precipitation reflects effects on these various water related variables, especially streamflow. Hydrological droughts have an effect on water availability in reservoirs and streams. Reservoirs and streams are usually used for domestic water supply, electricity production, agricultural production, navigation, aquatic ecosystem and to meet the international requirements. Therefore knowledge about hydrological droughts and processes causing hydrological drought and its spatial variability is important for the management of these water resources in order to meet the demand of different users (Fleig, 2004) and for a sustainable management of water resources (Sabina et. al, 2004).

1.2 Problem statement

All types of drought refer to a water deficit in a specific part of the hydrological cycle and there are connections between them. A drought in one stage of the cycle can lead to a drought also in other stages (NDMC, undated). The connection depends on severity and duration. The severe and long precipitation deficit (meteorological drought) in the catchment leads to decreased streamflow (hydrological drought) (Stahl, 2001). The previous studies have not shown at what severity and duration of precipitation deficit causes the decrease in streamflow.

1.3 Justification

Deficit of precipitation has negative impacts on the groundwater, reservoir storage, soil moisture, snow pack, and streamflow (Won-Hee et al, undated). Hydrological droughts have an effect on water availability in reservoirs and streams. Reservoirs and streams are usually used for domestic water supply, electricity production, agricultural production, navigation, aquatic ecosystem and to meet the international requirements. There is an ongoing project in the South Phuthiatsana River basin - water supply scheme – Lesotho Lowlands Water Project (LLWP) which will supply water to Roma, Mazenod, Maseru and Teyateyaneng. Therefore knowledge about hydrological droughts and processes causing hydrological drought and its spatial variability is important for the management of these water resources in order to meet the demand of different users (Fleig, 2004), for a sustainable management of water resources (Sabina et. al, 2004) and reduced impacts from future drought events as mismanagement of one drought leads to decreased productivity and greater susceptibility of the next (Chenje and Jonson, 1996).

1.4 Objectives

1.4.1 Main Objectives

The main objective of the research is to establish effects of precipitation deficit on streamflow through the severity and duration of meteorological droughts and predict hydrological droughts for the South Phuthiatsana River catchment in Lesotho.

1.4.2 Specific objectives

1. To determine the severity of meteorological drought events of 3, 6, 12 and 24 month duration in South Phuthiatsana river basin from1974 to 2008.

2. To determine the spatial extent of meteorological drought events of 3, 6, 12 and 24 month duration in Phuthiatsana river basin for the driest year.

3. To establish a relationship of streamflow and SPI of specific duration for South Phuthiatsana river basin.

4. To develop a streamflow drought prediction model using SPI

1.5 Hypothesis

The severe and long precipitation deficit (meteorological drought) leads to decreased streamflow (hydrological drought), so SPI is linked to streamflow.

Chapter 2: Meteorological and hydrological droughts: Literature review

Presently the uncertainty of the climatic environment is one of the major threats in water resources management (Dalezios, Loukas, Vasiliades and Liakopoulos, 2000). The uncertainty is caused by lack of information on when and where and the degree of the climatic extremes (droughts or floods) will occur. A drought event can be described through its characteristics such as duration, time of occurrence, onset and cessation, severity and minimum flow (for hydrological droughts), also through its frequency or return period (Fleig, 2004). The impacts of drought depend on the vulnerability of the area and society. Vulnerability of the area or society is described by a full range of factors that place society or area at risk of becoming affected by disaster. Therefore, this chapter presents the review of literature on different types of droughts, their characteristics, their causes, and impacts in different water related sectors and how they are linked through their characteristics. It will also focus on methods used to analyse meteorological and hydrological droughts characteristics especially severity.

2.1 Definition of droughts

Presently there is no universal definition of drought and therefore drought is usually defined according to its impacts. There are different types of droughts, namely; meteorological, hydrological, agricultural as well as socio-economic droughts. Wilhite and Svoboda, 2000 defined different types of drought as follows: meteorological drought is the degree of dryness in comparison with the average amount and the duration of the dry period. Hydrological drought is associated with effects of precipitation shortfalls on surface and groundwater supply. Agricultural drought is linked to impacts on farming due to shortages in rainfall which leads to soil moisture deficit. Socio-economic drought occurs when the demand for an economic good exceeds the supply as a result of a weather-related shortfall in water supply

Regardless of drought being defined according to their impacts, concern to all this definition is shortage of water due to the absence of precipitation for prolonged periods. Therefore drought can be defined as a condition of abnormal dry weather resulting in a serious hydrological imbalance with consequences such as losses of standing crops and shortages of water needed by people, livestock and wildlife (Chenje and Johnson, 1996).

All these types of drought refer to a water deficit in a specific part of the hydrological cycle and there are connections between them. Figure 1 shows that a drought in one stage of the cycle can lead to a drought also in other stages (NDMC, undated). The connection depends on severity and duration. Meteorological drought starts with a less than normal amount of precipitation and the more severe and longer it gets, leads to the soil moisture deficit which is termed agricultural drought, and lastly hydrological droughts develop which are defined by truncation level - the long-term mean of the annual flow sequences (Panu and Sharma, 2002). Also hydrological droughts are defined as prolonged period of below-normal precipitation as measured by below-normal stream flow, lake and reservoir levels and groundwater levels (NDMC, undated).

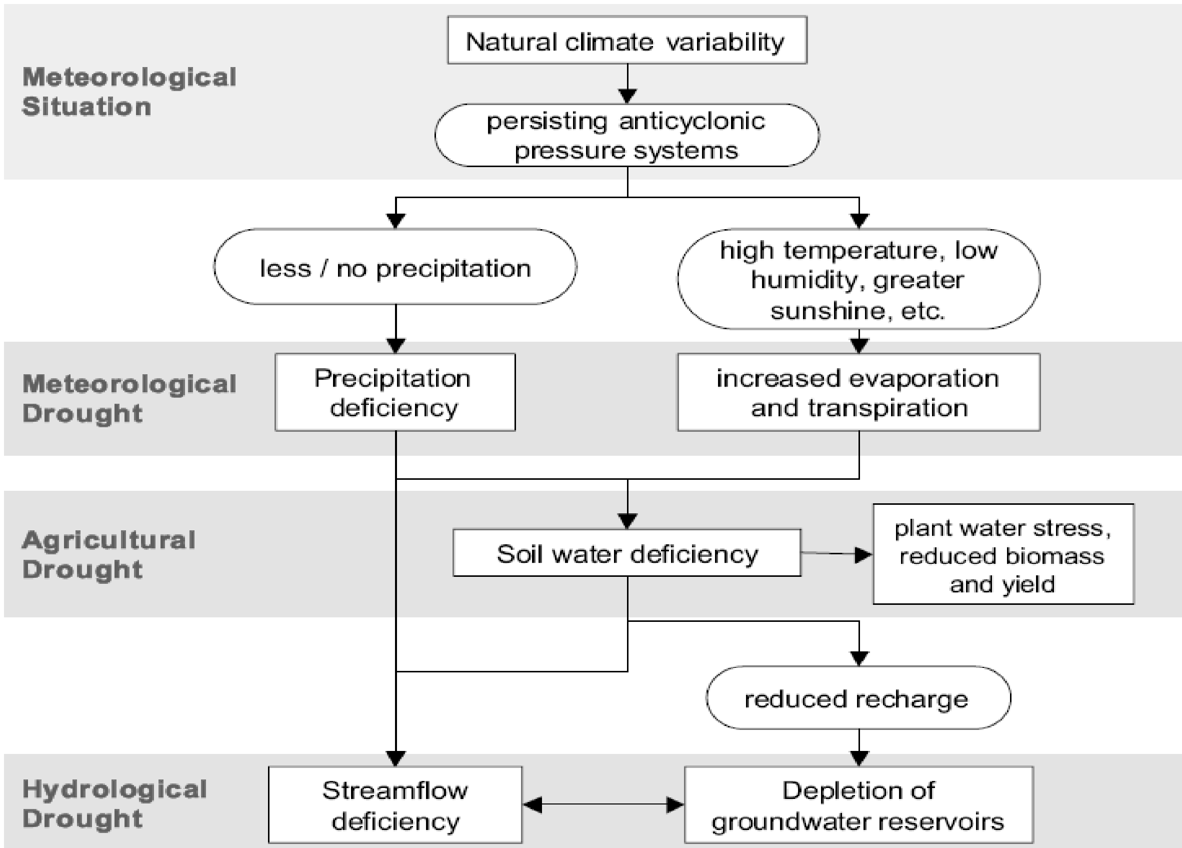

Figure 1 The sequence of drought impacts associated with meteorological, agricultural and hydrological drought (Source: NDMC, http://enso.unl.edu/ndmc/enigma/def2.htm)

2.2 Causes of drought

The main cause of drought is the deficit of precipitation, which is due to various natural phenomena (Panu and Sharma, 2002). The climate and rainfall pattern in Southern Africa is highly variable and leads to recurrent drought of varying severity (Chenje and Johnson, 1996). The fluctuations in seasonal rainfall are associated with the ENSO - El Niño Southern Oscillation Phenomenon (Clay, Bohn and Blanco de Armas, undated). ENSO can manifest itself as either El Niño or La Niña. El Niño is the warming of sea-surface temperatures (SST) in the equatorial Pacific Ocean which influences atmospheric circulation, and consequently rainfall and temperature in specific areas around the world. La Niña is the cooling of sea-surface temperatures in the equatorial Pacific Ocean (Singh, 2006).

During the El Niño there is high rainfall in some parts of Latin America but low rainfall and even drought in Southern Africa. The opposite occurs during La Niña, where unusual heavy rainfall occurs in Southern Africa (Clay *et al.*, undated). The economy of the region is dependent on agriculture and agriculture depends on the region's climate systems. The 1983-1984 and 1991-92 and 1997-2001 ENSO phenomenon clearly demonstrated the profound impact on countries that have weak economies and largely tied to agricultural production (Garanganga, 2003). The 1982-83 and 1991-92 droughts were the most severe meteorological droughts of the 20th century over Southern Africa, which led to 70% crop failure in the region in the 1991-92 droughts only (Monnik, 2000).

Global climate change, due to global warming, is suggested that it might be causing or contributing to drought in the region but there is no scientific evidence yet to support this (Chenje and Johnson, 1996). However, the proportion of land surface in extreme drought at any one time is projected to increase (Bates, Kundzewicz, Wu and Palutikof, 2008)

2.3 Drought impacts

Drought impacts can be economic, social, and environmental. Drought impacts can be direct or indirect as posed by Tabatabaei and Yazdanpanah, 2004. Droughts aggravate environmental degradation through climatic effects, including phenomena such as deforestation, livestock overgrazing, soil erosion, wild fires, biodiversity loss and water pollution. Social effects include reduced potable water supplies with negative health and sanitation consequences, especially for the vulnerable groups, and increased drudgery by women in collecting water for household consumption. Droughts also impact environmental disease incidence and increase the likelihood of food shortages leading to malnutrition and hunger.

The 1984 drought disaster killed 300,000 people in Ethiopia and 2002 drought affected 14.3 million people. The impacts of the 1991/92 drought in Southern Africa included GDP reduction of $3 billion, reduced agricultural production, increased unemployment, heavy government expenditure burden and reduced industrial production due to curtailed power supply. A decade later, the 1992-2001 La Nina-related drought in Eastern Africa cost the Kenya economy alone about $2.5 billion.

The recent droughts experienced in Lesotho in 2007 led to 40 – 50% decrease in cereal compared to previous year leading to significant decreases in the contribution of agriculture to the gross domestic product (GDP). The total cereal needed to feed the population was 320, 000 tons but the production was 72, 000tons (UNOCHA, 2007). The country imports up to 65 percent of maize and 80 percent wheat annually (Kundell, 2008), but the numbers increase during drought events. Measures taken by the government to respond to the situation included cash for work projects, general subsidies for maize and agricultural inputs, and humanitarian aid.

2.4 Characteristics of drought.

Droughts are characterised by their severity or intensity, duration and frequency. Only meteorological and hydrological droughts characteristics will be discussed.

2.4.1 Severity

Severity is defined as the degree of precipitation shortfall or the impacts linked to the shortfall. It is generally measured by the departure of climatic index from normal and is closely linked to duration in the determination of the impact (Wilhite and Svoboda, 2000). Wilhite and Svoboda, 2000 further show that there are several indices that are used to measure severity or intensity such as the deciles approach (by Gibbs and Maher, 1967) and is mostly used in Australia, Palmer Drought Severity Index (PDSI) which uses Crop Moisture Index (CMI) (by Palmer, 1965) mostly used in the US, Yield Moisture Index (by Jose et al, 1991) used in Philippines and Standard Precipitation Index (SPI) (by Mckee et al. 1993, 1995) used in most parts of the world including Africa.

Severity of meteorological droughts is usually measured using SPI which is described in more details in section 2.5. According to McKee et. al, 1993, SPI is a less complicated index which uses different time scales to reflect effects on various water related variables, e.g. soil moisture, streamflow, and groundwater.

This study adopted the definition of hydrological droughts as the flow below the mean annual flow. Therefore the hydrological drought characteristics or deficit characteristics will be defined by the threshold level (Q_0). The choice of threshold level value depends on how one wants to define the abnormal situation. The threshold value can be constant or varying over the year if winter and summer droughts are treated separately (Stahl, 2001). The threshold level value can be a certain streamflow necessary to fill a reservoir, to guarantee health of the river, or certain level required to meet certain water demands (Fleig, 2004, Stahl, 2001). However, for studies for drought characteristics a threshold can be chosen based on the historic streamflow record (Stahl, 2001).

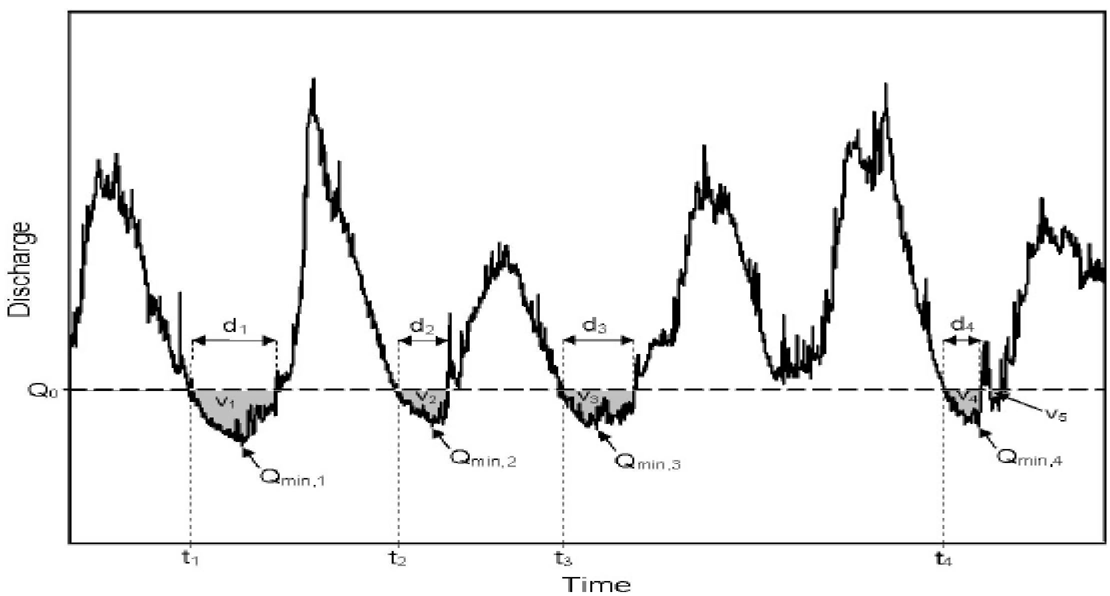

Figure 2: Illustration of commonly used deficit characteristics as defined with the threshold level method: time of occurrence, t_i, duration, d_i, deficit volume or severity, v_i, and the minimum flow occurring during the drought event, $Q_{min\ i}$. (Fleig, 2004)

Hydrological drought or streamflow deficit characteristics include time of occurrence, severity and minimum flow occurring during the drought event as shown in Figure 2. Truncation or threshold level method is usually used to derive hydrological drought events from streamflow time series: a drought event starts when the flow falls below the threshold and ends either when the threshold is exceeded or when the water deficit volume below the threshold has been replenished (Stahl, 2001). Severity is the deficit volume or minimum flow occurring during the drought event as indicated in Figure 2.

2.5 Standardised Precipitation Index (SPI)

The SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable which was developed by McKee et.al., 1993 to give a better representation of abnormal wetness and dryness. According to McKee et al, 1993 SPI is a simple index which is calculated from the long term record of precipitation in each location (at least 30 years). The data is fitted to normal distribution and normalized to a flexible multiple time scale such as 3-,6-,12-,24-, 48-month. The main advantage of SPI is that SPI can be calculated for different time scales, provides early warning of drought and is less complex compared to other indices as it only uses one variable, precipitation (Hayes, 2006).

The drought time scales used in SPI calculation reflects effects on five water usable sources namely; soil moisture, streamflow, groundwater, snowpack and water in reservoirs. Meteorological and agricultural droughts, which have and impact on precipitation and soil moisture respectively, are usually linked to short term time scale which are 3- and 6 month SPI's. The long term time scale which are 12-month SPI or more are associated with hydrological droughts which have an impact on streamflow and reservoir levels (Rouault and Richard, 2003).The short term durations are important to agricultural interest while long term are important to water supply management interest (Guttman, 1998).

The 3-month SPI provides a comparison of the precipitation over a specific 3-month period with the precipitation totals from the same 3-month period for all the years included in the historical record. For instance, a 3-month SPI for December uses the precipitation total of October, November and December in that particular year. A 3-month SPI reflects short- and medium-term moisture conditions and provides a seasonal estimation of precipitation.

The 6-month SPI compares the precipitation for that period with the same 6-month period over the historical record. The 6-month SPI indicates medium-term trends in precipitation. A 6-month SPI can be very effective showing the precipitation over distinct seasons. Information from a 6-month SPI may also begin to be associated with abnormal streamflows and reservoir levels.

A 12-month SPI or longer is a comparison of the precipitation for 12 consecutive months with the same 12 consecutive months during all the previous years of available data. The SPI at these time scales reflect long-term precipitation patterns. Because these time scales are the cumulative result of shorter periods that may be above or below normal, the longer SPIs tend toward zero unless a specific trend is taking place. SPIs of these time scales are probably tied to streamflows, reservoir levels, and even groundwater levels at the longer time scales.

Chapter 3: Methods and Materials

3.1 Study area

Lesotho is a landlocked country that occupies 30,588km² and is between 27 and 30 East and 28 and 31 South. The country is divided into 4 ecological zones: the lowlands (17%), the foothills (15%), the mountains (59%), and the Senqu River Valley (9%). Because of the country's topography, economic activities are largely confined to the lowlands, the foothills, and the Senqu River Valley, leaving the mountain region only suitable for grazing and, in recent years, for water and hydro-power development.

The climate in Lesotho is temperate with cold, dry winters and hot, wet summers. Mean annual rainfall is 788 mm and varies from less than 300 mm in the western lowlands to 1,600 mm in the north-eastern highlands. The research was undertaken in the South Phuthiatsana River Basin which falls in the lowlands and the lowlands are the most populated and intensively cultivated zone and much of the rest of the land area is utilized for extensive animal farming.

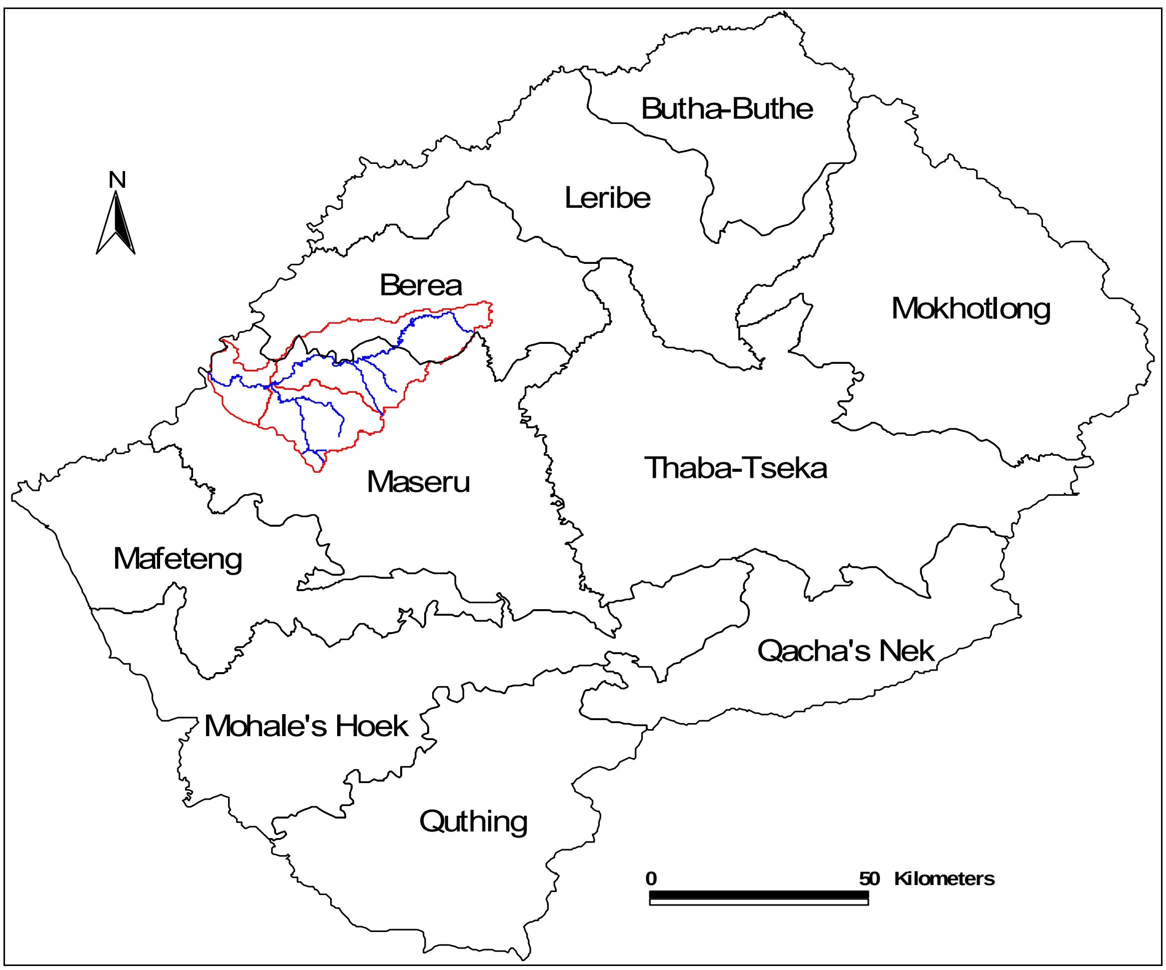

Figure 3: Phuthiatsana River basin (red boundary) in reference to map of Lesotho

The South Phuthiatsana River catchment is part of Maseru and Berea districts in Lesotho with a catchment area of 1354 km² as shown in Figure 3. The Phuthiatsana River is perennial and it originates from Pulane in Berea at 2539 masl and leaves the country in Maseru at 1486 masl with the mean annual runoff (MAR) of 128.47millin m³/year. The South Phuthiatsana River flows into the Mohokare/ Caledon River which forms a boundary between Lesotho and South Africa and is a tributary of the Orange/Senqu system (Botswana, Lesotho, Namibia, and South Africa). There are seven rainfall gauging stations and three runoff stations (Figure 4), with available data, in the catchment one runoff station at Masianokeng.

There is a proposed water supply scheme – Lesotho Lowlands Water Project (LLWP) which will supply water to Roma, Mazenod, Maseru and Teyateyaneng. The volume of the reservoir will be 52Mm³ and the direct abstraction will be 82Ml/d and water release and downstream abstraction will be 92Ml/d.

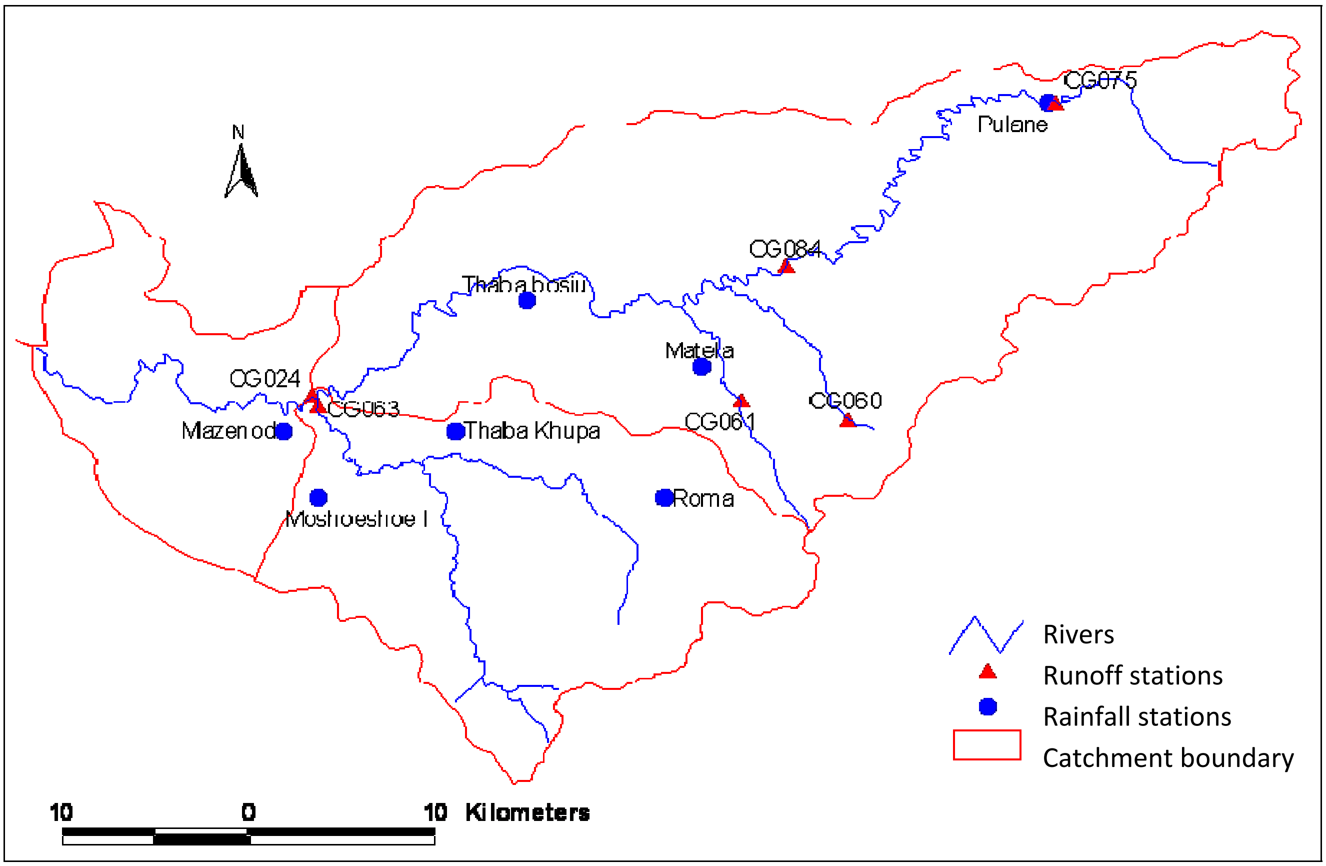

Figure 4: Phuthiatsana River Catchment

3.2 Data selection and preliminary analysis

3.2.1 Data collection

The data required to carry this study was meteorological and hydrological data. The meteorological data collected was rainfall monthly time series and for hydrological data was streamflow daily time series within the catchment. There are seven rainfall gauging stations and six streamflow gauging stations as shown in Table 2 and Table 3 respectively. There are three runoff stations with data but only one station (CG024 – outlet station) has reliable record which can be used for drought analysis.

Table 1: Rainfall stations in South Phuthiatsana Catchment

Station name	Latitude	Longitude	Time of record
Roma	-29.45	27.33	1962 – 2002
Pulane	-29.25	27.92	1971 – 2004
Matela	-29.38	27.75	1978 – 2004
Mazenod	-29.42	27.55	1976 – 2004
Thaba Bosiu	-29.35	27.67	1980 – 2004
Thaba Khupa	-29.42	27.63	1974 -2004
Moshoeshoe I	-29.45	27.57	1985 - 2004

Table 2: Streamflow stations in South Phuthiatsana Catchment

Station name	Time of record
CG024	1974 – 2008
CG60	1990 – 2008
CG75	1989 – 2008
CG61	No data
CG63	No data
CG84	No data

3.2.2. Data quality control

The hydro-meteorological data used in studies of water resources developments and management should be analysed for data quality control. The main concern with regards to the quality of data used to estimate statistical characteristics are possible changes over time. These changes are usually due to changes in climatic and catchment conditions or measuring procedures. There were few gaps in rainfall data in one station and they were filled using the ratio of averages before the data can be analysed.

The rainfall data was tested for inconsistency and non-homogeneity. Inconsistency is a change in the amount of systematic error associated with the recording of data, while non-homogeneity is a change in the statistical properties, causes being either natural or anthropogenic (Dahmen & Hall, 1990). The double mass curve was used to do the test (Appendix I). Moshoeshoe I gauging station was used as it is at the airport and any changes in the observation can only be due to climatic conditions. The results presented in Appendix II showed that the data is consistent but not homogeneous due to the 1990's severe drought. As a result no data correction was required for rainfall data in this study.

3.3 Identification of hydrological droughts using truncation level method

The hydrological drought events were identified by applying the threshold method, where the constant truncation level was regarded as mean annual runoff (MAR) or the annual average flow (q_{ave}). The flow below the average flow (128million m³/yr) was considered to be hydrological drought event. The runoff time series at the CG024 station was used. The hydrological droughts were experienced between 1974 and 2008 with the worst drought in 1994 with the annual flow of 19.11million m³/yr as shown in Figure 5.

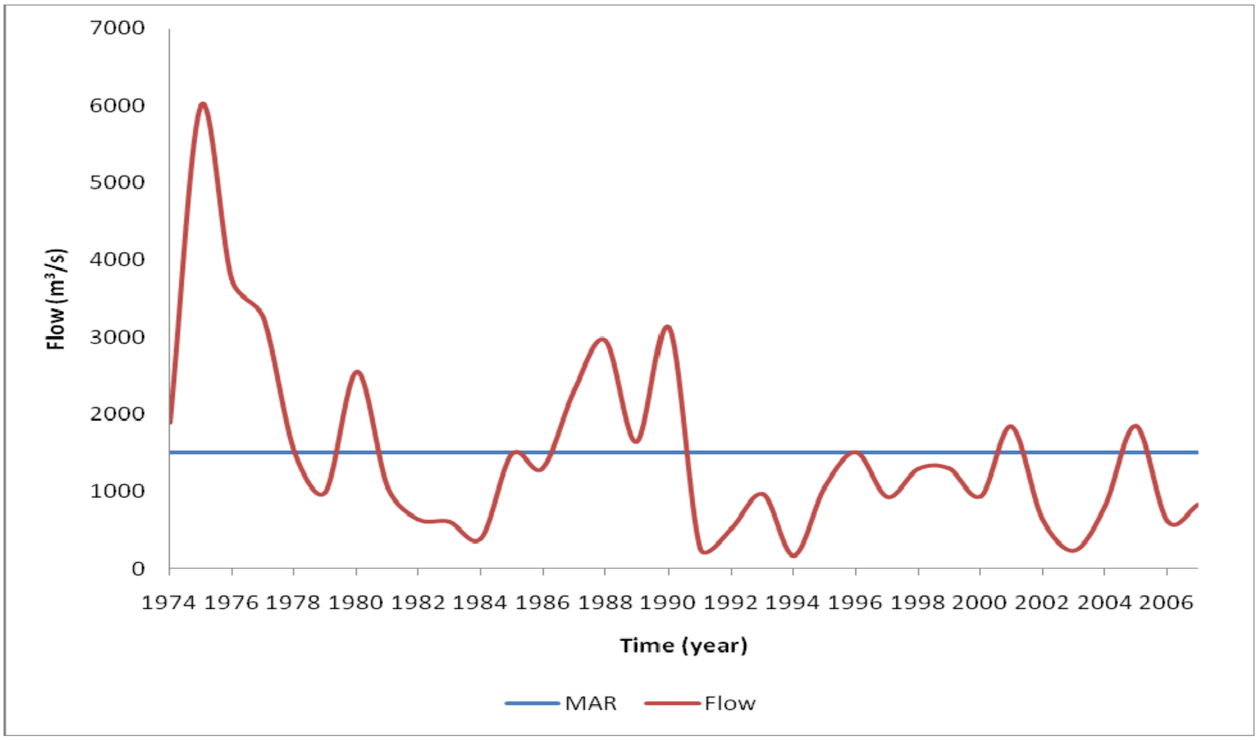

Figure 5: Flow at outlet station CG024

3.4 Standardized Precipitation Index (SPI) calculation

The SPI is based on the probability of precipitation for a given time period. The SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable. The advantage with SPI compared to other indices is that; the index only uses precipitation data which is usually available. SPI also captures accumulated deficit or surplus of precipitation for different time scales, and provides a normalized measure of relative precipitation anomalies (Chopra, Dadhwal and Patel, 2007)

According to McKee et.al, 1993 the Standardized Precipitation Index (SPI) is calculated as follows; a monthly precipitation data set is prepared for a period of m months of a continuous period of at least 30 years. A set of averaging periods are selected to determine a set of time scales of period j months where j is 3, 6, 12, 24, or 48 months as discussed in chapter two of this document. The precipitation rate is then fitted to a gamma distribution for different time scales for each month of the year. The resulting function is used to find the cumulative probability of a rainfall event for a station for a given month and at different time scale of interest (Equation 1). Using the normal distribution, the standard normal variate or z-score is determined with a cumulative probability. The z-score is the Standardize Precipitation Index (SPI). SPI tend to vary from -3.0 to +3.0 (Table 1). Values below zero indicates degree of dryness, while values above zero indicates degree of wetness and zero indicates normal situation

$$G(x) = \int_0^x g(x)dx = \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})}\int_0^x x^{\hat{\alpha}-1}e^{-x/\hat{\beta}}dx$$

……………………….Equation 1

Where;

G(x) = Cumulative probability
x = the precipitation amount >0
$\hat{a}$ = a shape parameter (function of area)
β = a scale parameter
$\Gamma(\hat{a})$ = a gamma function

Table 3: SPI classification (Mc Kee et. al., 1993)

SPI Value	Drought category
2.00 to 3.00	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
-2.00 to -3.00	Extremely dry

3.5 Severity and spatial extent

The SPI was calculated using WinSPI software to derive drought severity of meteorological droughts. The monthly time series of rainfall data from 7 stations in the catchment were used to derive SPI at 3, 6, 9, 12, and 24 month time scales. These SPI values for November, December, January, February and March were interpolated using inverse distance weighted (IDW) to depict spatial patterns of the driest years of the record using Arcview GIS. These months were chosen because they are rainy season months; moreover they often represent more than 40% of the annual amount (Richard, et al., 2001). IDW was used because it is one of the most commonly used techniques for interpolation of scatter points. Inverse distance weighted method is based on the assumption that the interpolating surface should be influenced most by the nearby points and less by the more distant points.

3.6 SPI and streamflow

The median value was calculated from SPI values for November to March for 3, 6, 12, 24 month time scales. A median was used because the time series included positive and negative values ranging from -3 to 3 as a result the mean was not appropriate. The correlation between SPI and streamflow at the outlet gauging station (CG024) was computed using the non- parametric tests, spearman's rank correlation method, even though other techniques were tested and the results were the same for all techniques.

Chapter 4: Results and discussion

4.1 Results

4.1.1 SPI

In order to determine the severity of drought events of 3, 6, 12 and 24 month duration in Phuthiatsana river basin, SPI values were calculated for all stations for different time scales. Figure 6 shows an example of January SPI at one of the stations but similar SPI's have been derived for other stations for the months of November, December, January, February and March (see Appendix II). Most severe and longest droughts (SPI<-2) were experienced between 1991 and 1995.

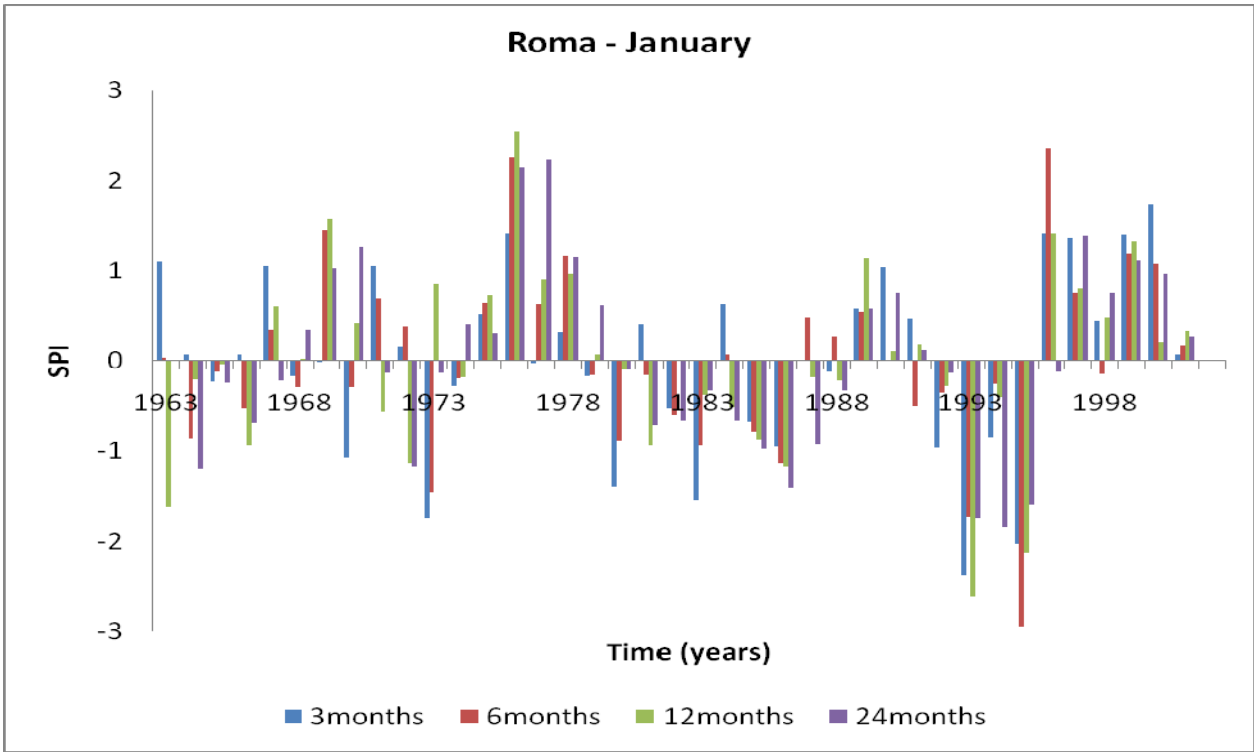

Figure 6: SPI 1962 – 2001 for Roma station

4.1.2 Spatial extend

SPI values for November, December, January, February and March were interpolated using inverse distance weighted (IDW) to depict spatial patterns of the driest years of the record using Arcview GIS. Figure 7 represents the spatial distribution of drought of January 1993 SPI for different time scales and Table 4 shows the area covered by each SPI category extracted from Figure 6. It can be seen that severe to extreme droughts in both magnitude and area covered have been dominating the area. In 1993 25 – 50% of the area has experienced severe droughts with SPI values less than -2.

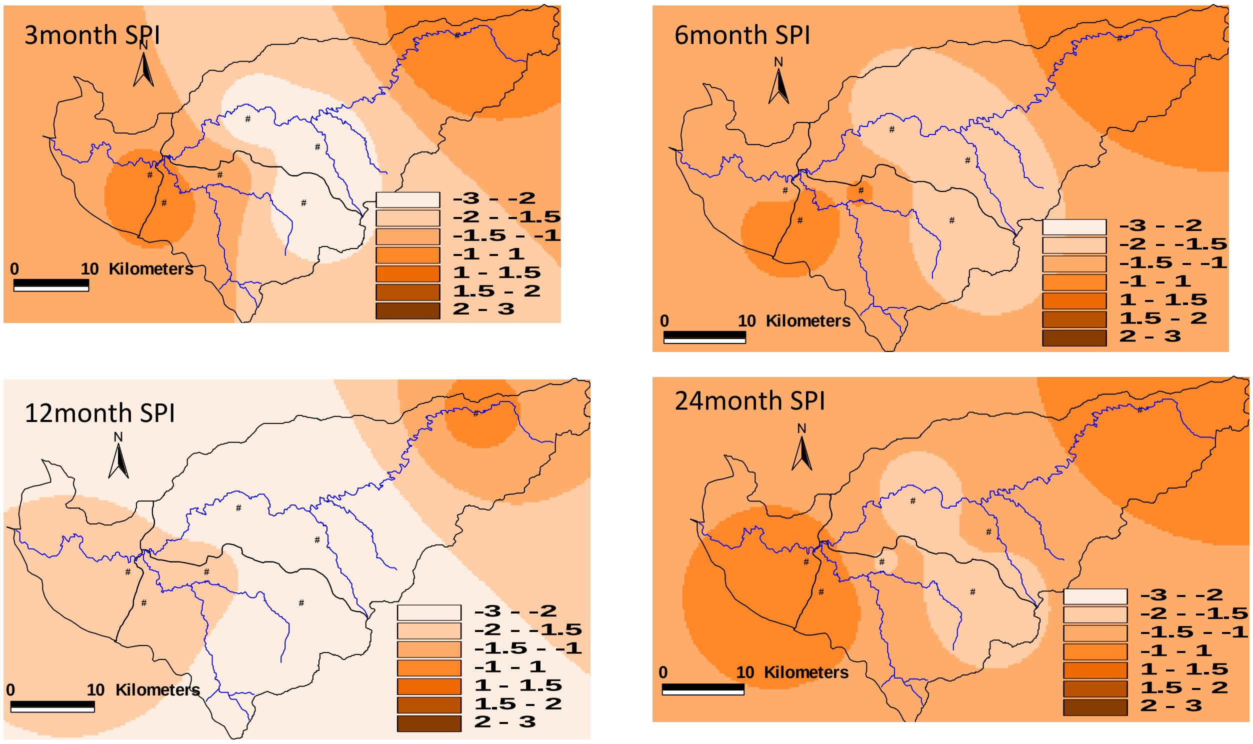

Figure 7: January 1993 drought map

Table 4: Area covered by each SPI category in January 1993

	Area (Km^2)	Percentage of Total Area (%)	Category
3 month SPI	313	23	Near Normal
	343	25	Moderately dry
	376	28	Severely dry
	322	25	Extremely dry
6 month SPI	323	24	Near Normal
	0	0	Moderately dry
	579	43	Severely dry
	452	33	Extremely dry
12 month SPI	43	3	Near Normal

	144	11	Moderately dry
	454	33	Severely dry
	713	52	Extremely dry
24 month SPI	609	45	Near Normal
	0	0	Moderately dry
	482	36	Severely dry
	263	19	Extremely dry

4.3 SPI and streamflow

Correlation analysis between SPI and streamflow was done to test whether hydrological droughts can be significantly predicted from SPI of specific duration. Table 5 shows that there were significant correlation in December and November for 3 month and 6 month SPI and December for 12 month SPI only. The relationship was also established between SPI and streamflow for SPI with significant correlation, results are show in Figure 8 to 11.

Table 5: Correlation and level of significance of SPI and streamflow

	3 month	6 month	12 month	24 month
Nov	r = 0.493 * P = 0.005	r = 0.656* P = 0.001	r = 0.125 P = 0.324	r = 0.212 P = 0.252
Dec	r = 0.405 * P = 0.024	r = 0.495* P = 0.005	r = 0.346* P = 0.006	r = 0.346 P = 0.056
Jan	r = 0.014 P = 0.941	r = 0.128 P = 0.492	r = 0.112 P = 0.377	r = 0.125 P = 0.501
Feb	r = -0.060 P = 0.750	r = 0.067 P = 0.721	r = -0.032 P = 0.799	r = 0.132 P = 0.480
Mar	r = 0.153 P = 0.410	r = 0.144 P = 0.441	r = 0.015 P = 0.905	r = -0.001 P = 0.994

r = correlation coefficient
p = significance
*correlation is significant at 0.01 to 0.05.

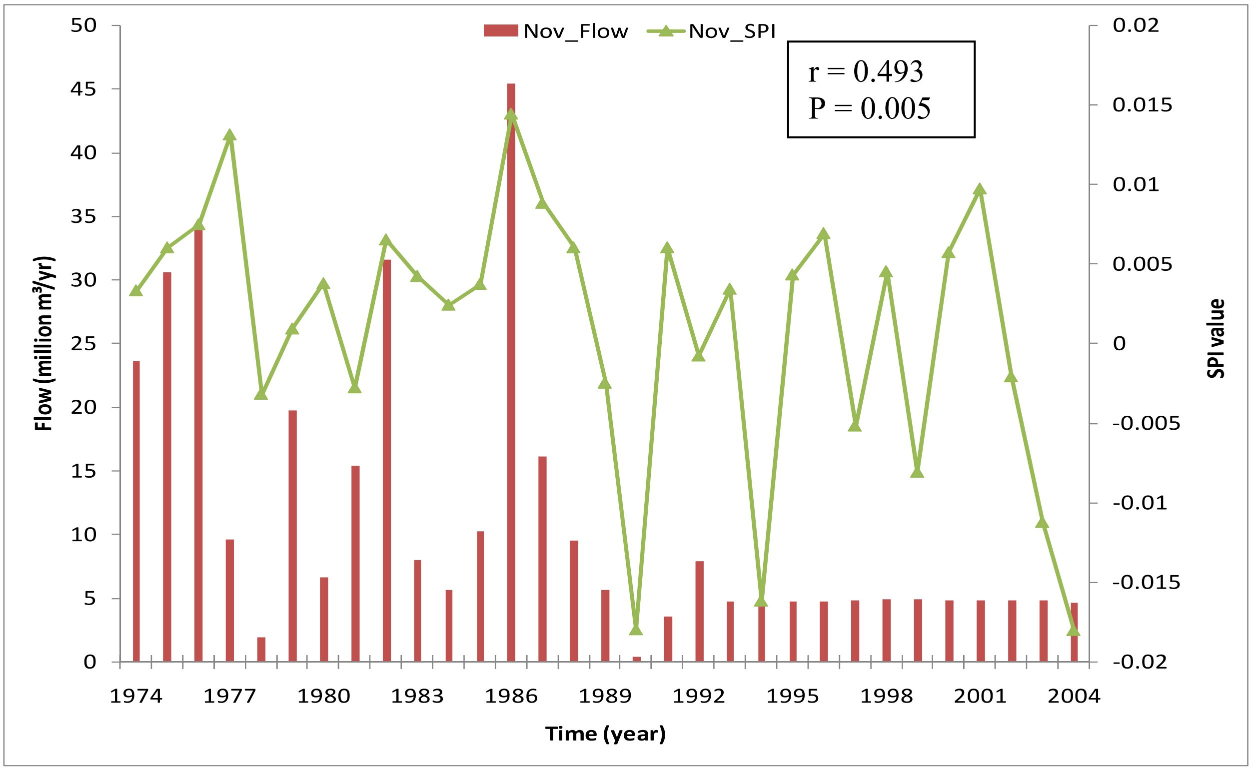

Figure 8: Flow vs 3month –SPI for November

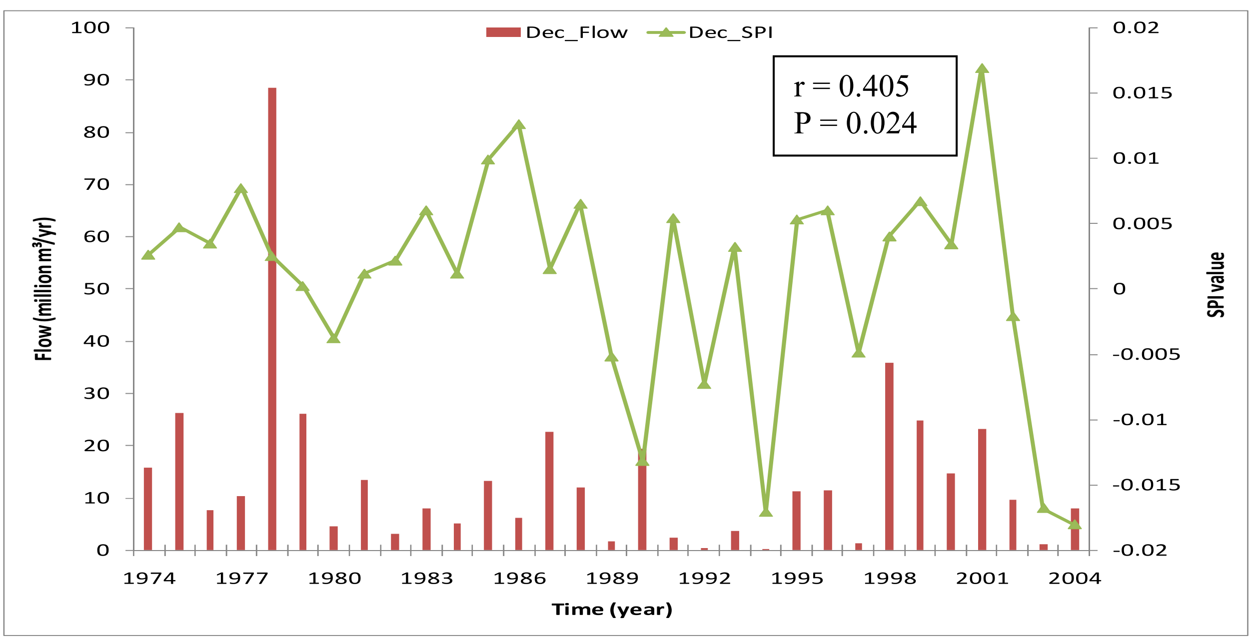

Figure 9 Flow vs 3month –SPI for January

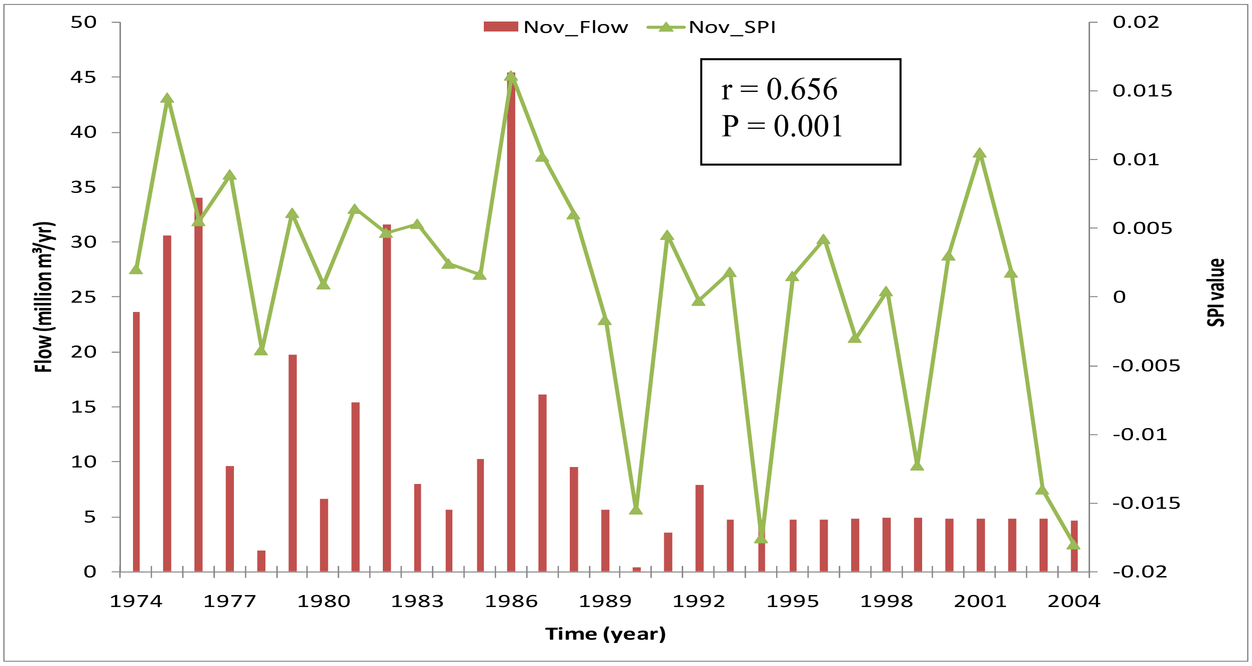

Figure 10: Flow vs 6 month –SPI for November

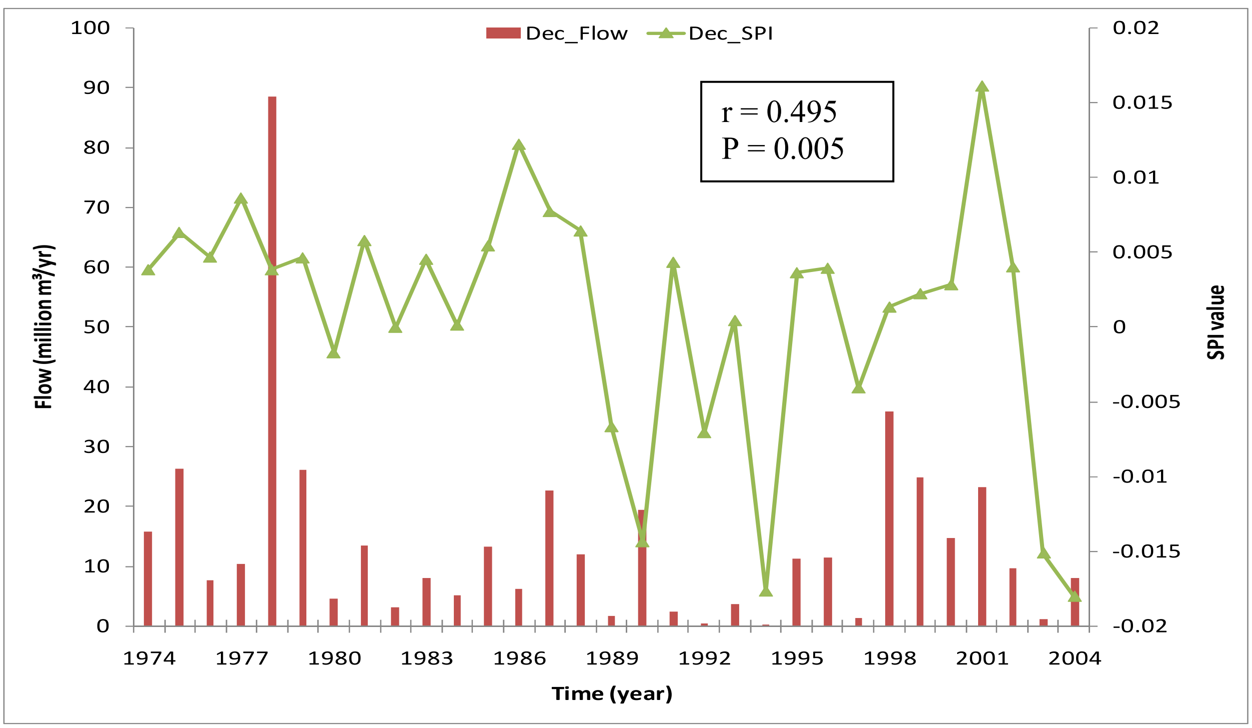

Figure 11: Flow vs 6 month –SPI for November

4.2 Discussion

The results showed that there was hydrological drought from 1991 to 1995 (Figure 5) which correspond with the meteorological drought experienced in the same period (Figure 6). The drought maps showed that area was covered by severe (SPI -1.5 to -2) and extremely severe (SPI <-2) drought, which were;

- 3month – 28% and 25%
- 6 month - 43% and 33%
- 12 month – 36% and 19%
- 24 month - 43% and 33% for sever and extremely severe droughts respectively.

This means that bigger area was covered by severe droughts while only a small part experienced normal conditions (SPI = 0).

The results in this study indicated that there is significant relationship between SPI and streamflow at 3 and 6 month time scale during November and December as shown in Figure 10 and 11 but there is no significant relationship during the months of January, February and March.

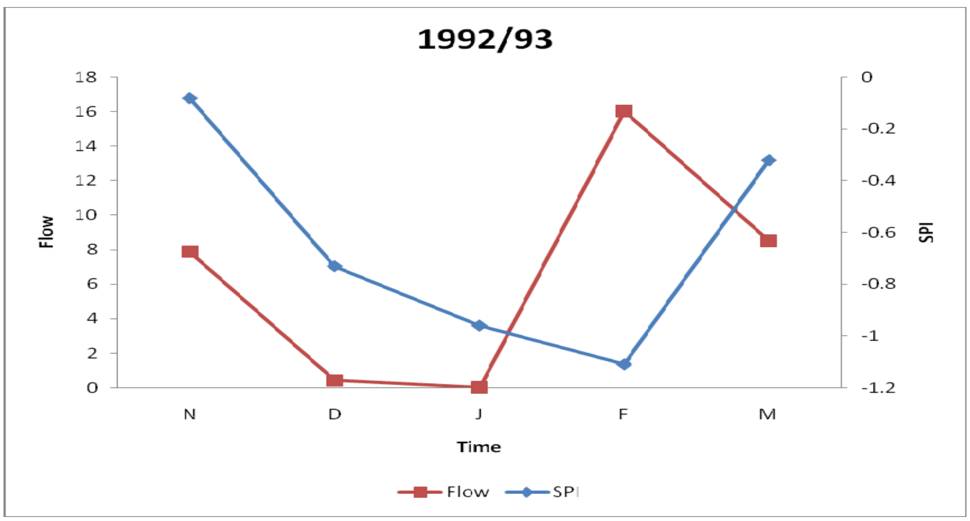

Figure 12: SPI vs Streamflow

By comparing the SPI from precipitation and observed streamflow (Appendix IV to VII) it is seen that the SPI values does not coincide with the streamflow (Figure 12) for January, February and March. The main reason is that streamflow is highly influenced by evaporation losses and response from groundwater storage and snowpack. The groundwater reservoirs are replenished during the season of high precipitation and this storage contributes to the flow during the season of low precipitation. Hence, hydrological droughts are often lagged compared to meteorological droughts. This was also confirmed in a study done in Denmark by Hisdal and Tallaksen (2003) who demonstrated that there is a lag in the start of hydrological droughts compared to meteorological droughts. Also Won-Hee et. al., (undated) confirmed that SPI and observed streamflow show different severity but similar characteristics with streamflow generated from precipitation.

Chapter 5: Conclusions and recommendations

5.1 Conclusions

In this research severity of droughts were studied using the SPI on the 3, 6, 12 and 24 month time scale. It has shown that there is significant relationship between SPI and streamflow for 3- and 6-month time scale during the months of November and December but no significant relationship for January, February and March. This can be explained by the fact that streamflow respond to precipitation shortly after rainfall event and after that it is mainly groundwater and snowmelt contributing to streamflow. Furthermore, during months of December there are high evaporation losses which affect both precipitation and streamflow. Since the streamflow which was used included base flow and the evaporation losses were not included, this compromised the results. Besides, there are no significant abstractions in the catchment but the presence of boreholes in the catchment might be affecting the flow in the river.

The main objective of the study was to predict hydrological droughts from meteorological droughts after testing if there is correlation between SPI and streamflow. It has been found that there is a correlation in some months which suggests further research in order to come up with an accurate prediction model. In summary, the prediction of hydrological drought needs more in-depth study on the hydrology of the catchment.

The most important information which can be obtained from this study is that hydrological and meteorological droughts are persistent, can be severe and they are connected. Therefore knowledge about hydrological droughts and processes causing hydrological drought and its spatial variability is important for the management of these water resources in order to meet the demand of different users (Fleig, 2004) and for a sustainable management of water resources (Sabina et. al, 2004), as surface water is usually used for domestic water supply, electricity production, agricultural production, navigation, aquatic ecosystem and finally to meet the international requirements.

5.2. Recommendations

There is need for further research in South Phuthiatsana River Basin which will include all processes of the hydrological cycle, separation of base flow and deduction of evaporation and transpiration and also quantify the borehole yields. Since there will be a dam construction along Phuthiatsana River, the Hydrological droughts might need to be studied using both streamflow and the reservoir levels.

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APPENDICES

Appendix I: Double mass calculation

Years	i	x_i	y_i	X_i	Y_i	$Y_i - (b_{av} * X_i)$	$a_i = y_i \div x_i$
0	0	0	0	0	0	0	0
1986	1	670.80	680.70	670.80	680.70	91.64	1.01
1987	2	833.00	263.60	1503.80	944.30	-376.25	0.32
1988	3	844.20	961.50	2348.00	1905.80	-156.07	1.14
1989	4	804.00	741.80	3152.00	2647.60	-120.30	0.92
1990	5	781.10	818.90	3933.10	3466.50	12.69	1.05
1991	6	1001.30	664.30	4934.40	4130.80	-202.29	0.66
1992	7	545.20	434.20	5479.60	4565.00	-246.86	0.80
1993	8	549.00	504.80	6028.60	5069.80	-224.16	0.92
1994	9	701.90	736.10	6730.50	5805.90	-104.42	1.05
1995	10	481.90	413.00	7212.40	6218.90	-114.60	0.86
1996	11	854.50	673.10	8066.90	6892.00	-191.87	0.79
1997	12	864.20	839.40	8931.10	7731.40	-111.36	0.97
1998	13	802.10	621.00	9733.20	8352.40	-194.71	0.77
1999	14	558.40	530.90	10291.60	8883.30	-154.17	0.95
2000	15	813.90	915.90	11105.50	9799.20	47.01	1.13
2001	16	745.40	773.50	11850.90	10572.70	165.95	1.04
2002	17	1285.50	962.90	13136.40	11535.60	0.00	0.75

Where:

$b_{av} = Y_i \div X_i = 0.878$

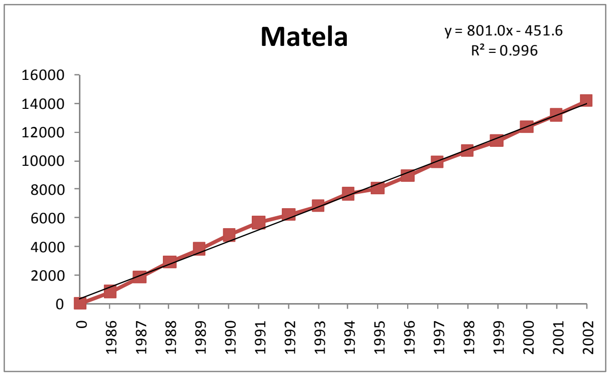
x_i = Base station observation

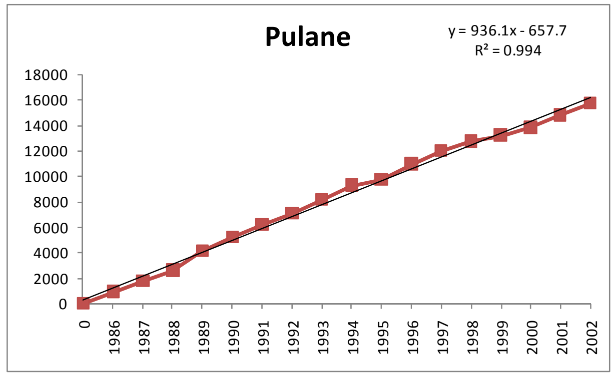
y_i = nearby station observations

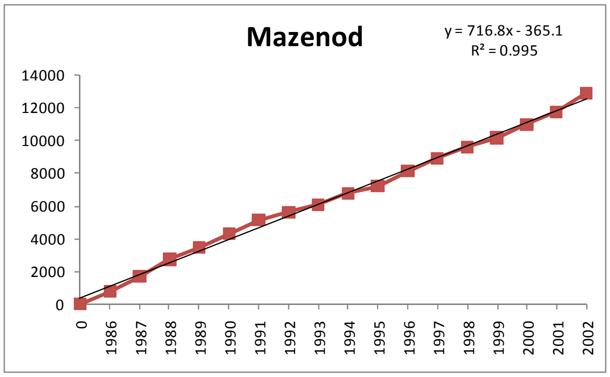
X_i = cumulative x_i

Y_i = cumulative y_i

Appendix II: Chart showing double mass curve for all stations ($Y_i - (b_{av} * X_i)$ vs. Time step)


Matela
y = 801.0x - 451.6
R² = 0.996


Pulane
y = 936.1x - 657.7
R² = 0.994


Mazenod
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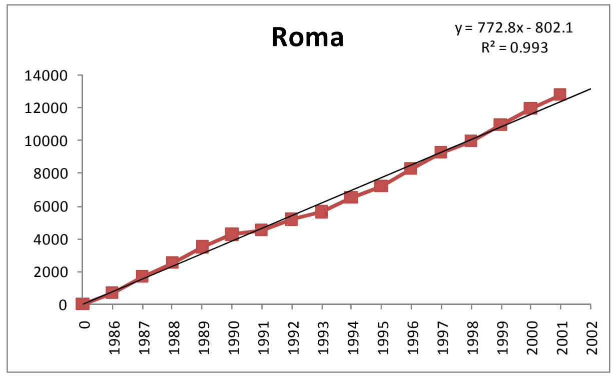
R² = 0.995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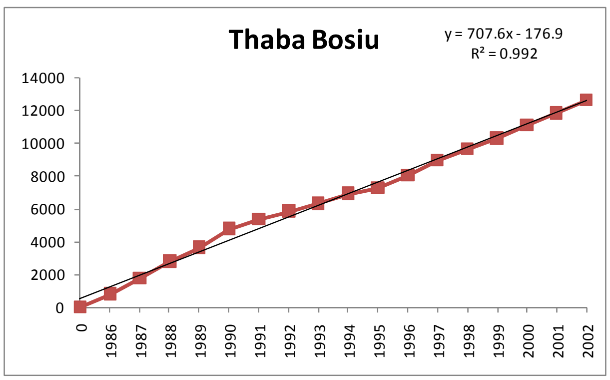
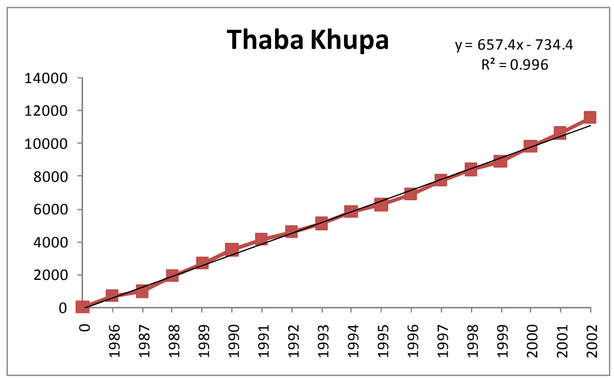
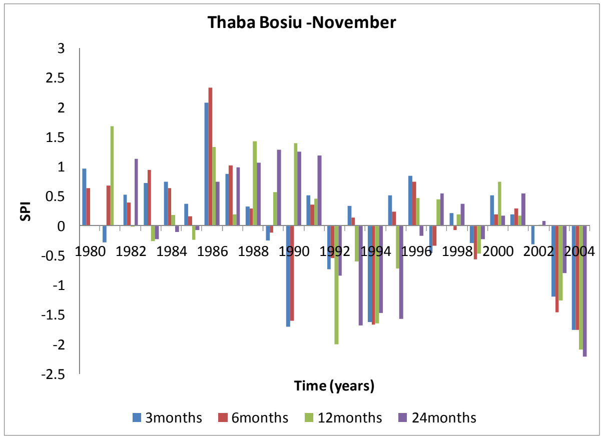
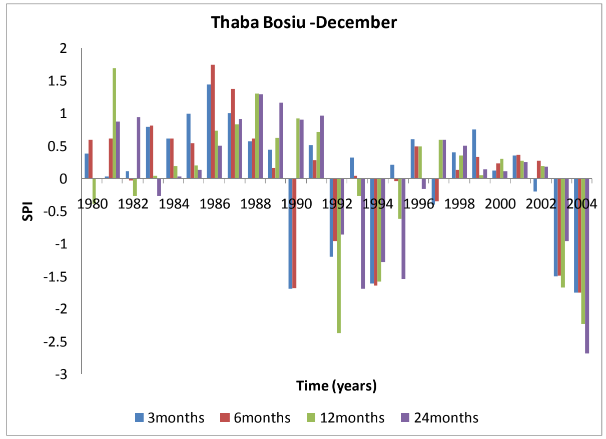
y = 772.8x - 802.1
R² = 0.993

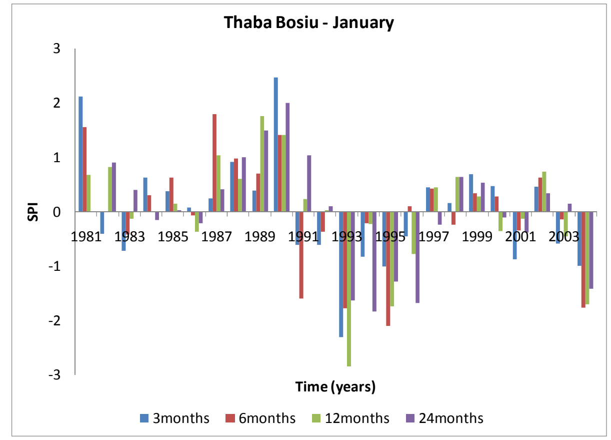

Thaba Bosiu
y = 707.6x - 176.9
R² = 0.992

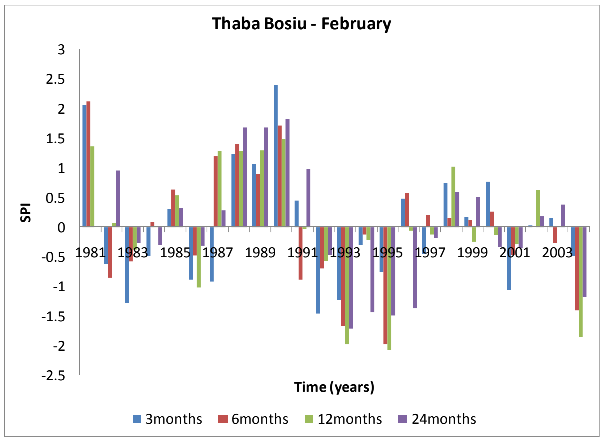

Thaba Khupa
y = 657.4x - 734.4
R² = 0.996

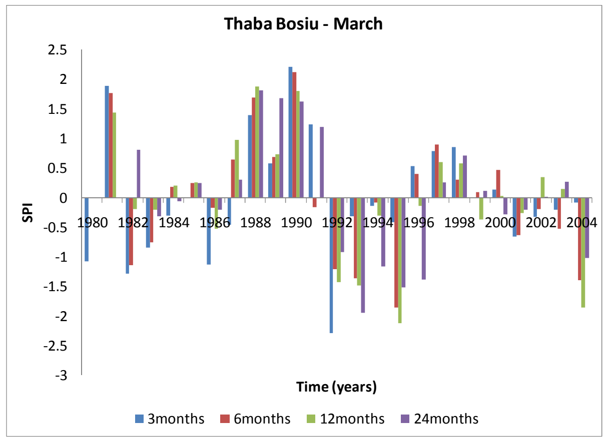
Appendix III: **SPI for all the stations**

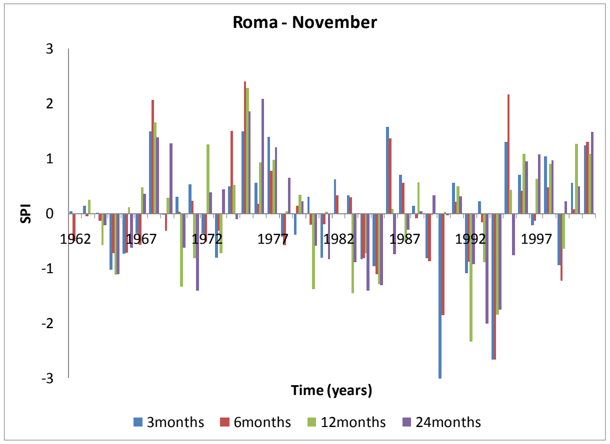


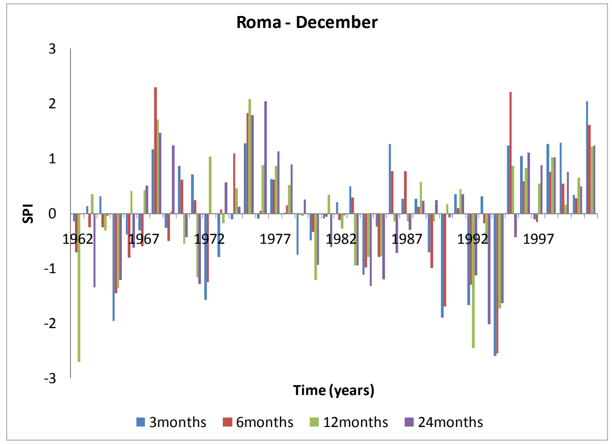









Roma - November
SPI
Time (years)
3months 6months 12months 24months


Roma - December
SPI
Time (years)
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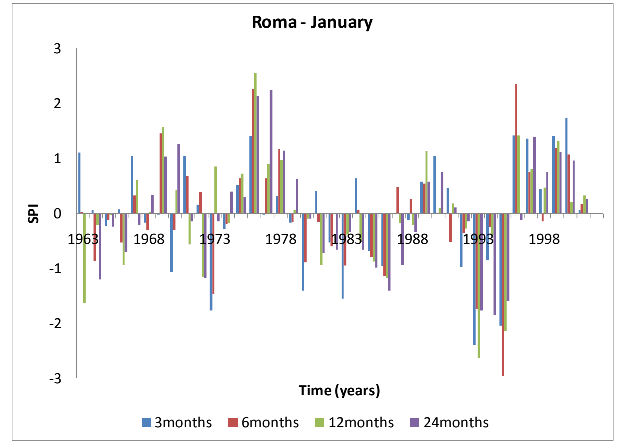
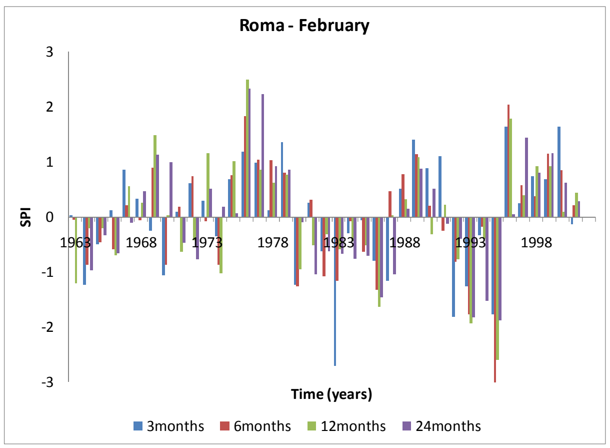
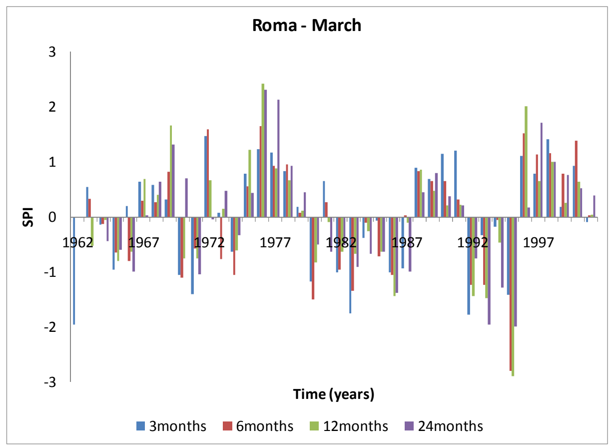

Roma - January
SPI
Time (years)
3months 6months 12months 24months


Roma - February
SPI
Time (years)
3months 6months 12months 24months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SPI
Time (years)
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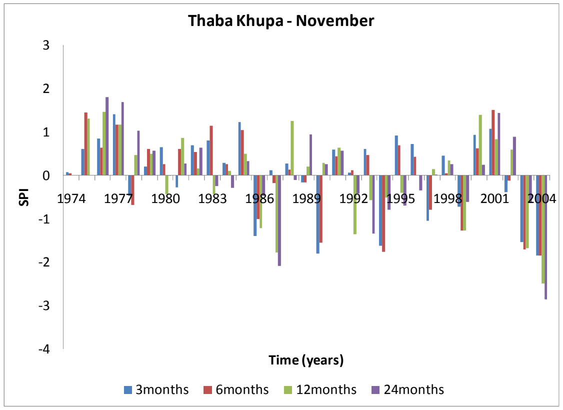
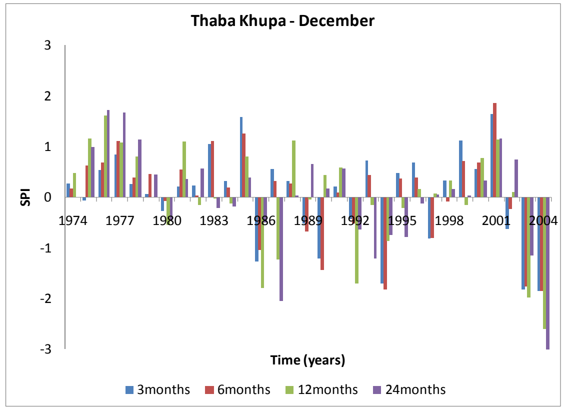

Thaba Khupa - November
SPI
3 2 1 0 -1 -2 -3 -4
1974 1977 1980 1983 1986 1989 1992 1995 1998 2001 2004
Time (years)
3months 6months 12months 24months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Time (years)
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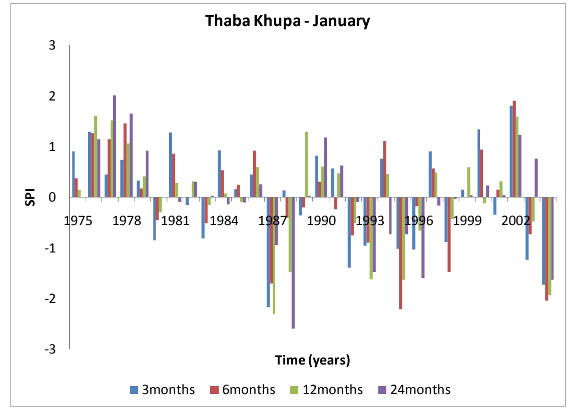
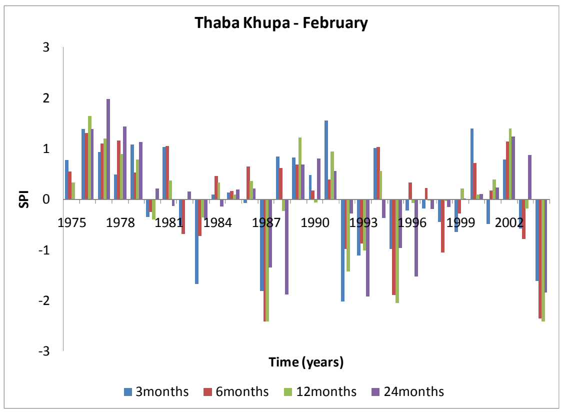
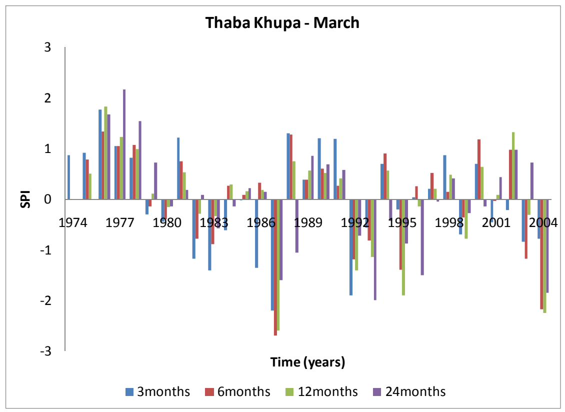
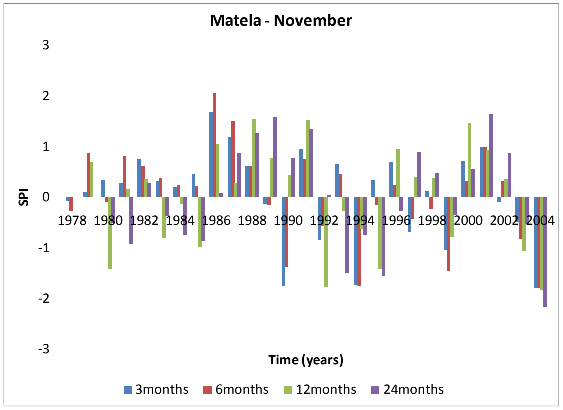
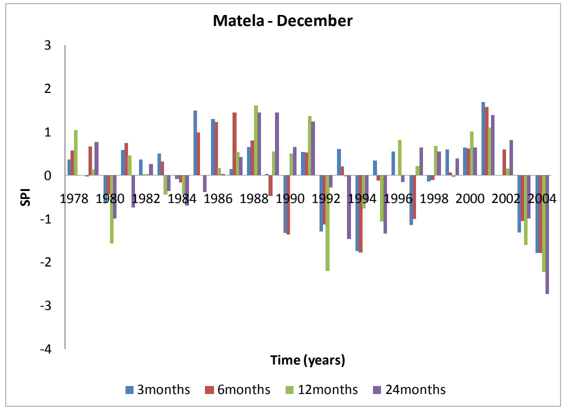
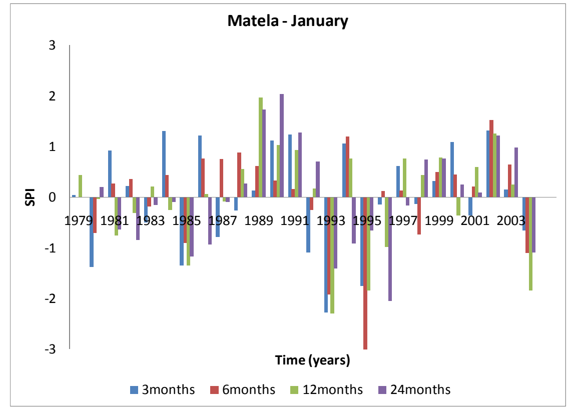

Thaba Khupa - January
SPI
3 2 1 0 -1 -2 -3
1975 1978 1981 1984 1987 1990 1993 1996 1999 2002
Time (years)
3months 6months 12months 24months

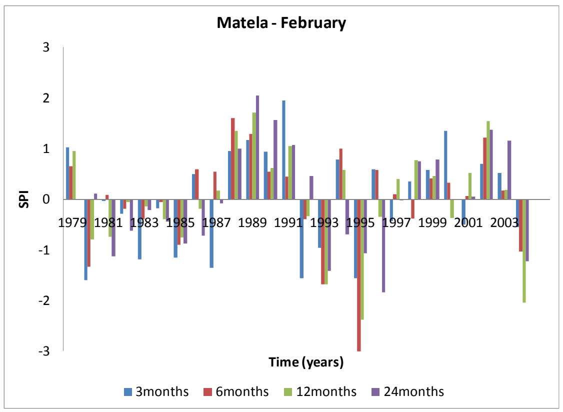

Thaba Khupa - February
SPI
3 2 1 0 -1 -2 -3
1975 1978 1981 1984 1987 1990 1993 1996 1999 2002
Time (years)
3months 6months 12months 24months

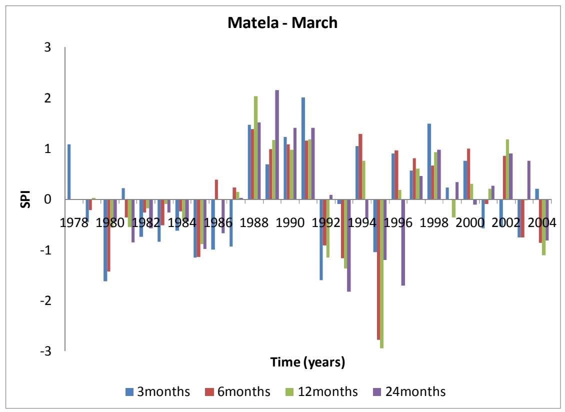

Thaba Khupa - March
SPI
3 2 1 0 -1 -2 -3
1974 1977 1980 1983 1986 1989 1992 1995 1998 2001 2004
Time (years)
3months 6months 12months 24months

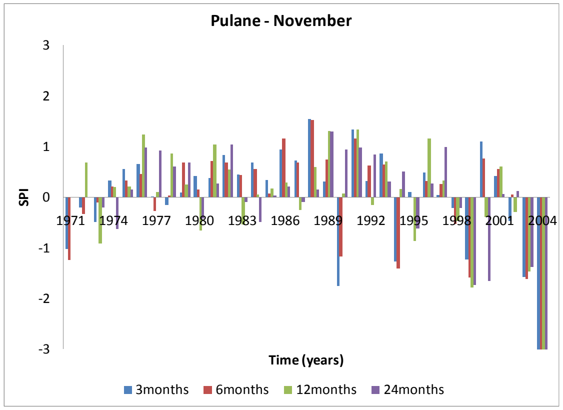

Matela - November
SPI
Time (years)
3months 6months 12months 24months

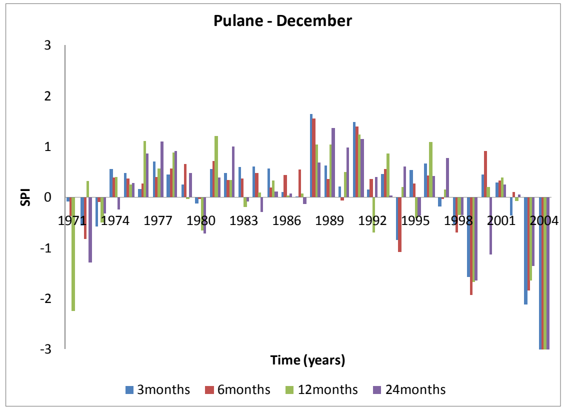

Matela - December
SPI
Time (years)
3months 6months 12months 24months


Matela - January
SPI
Time (years)
3months 6months 12months 24months


Matela - February
SPI
Time (years)
3months 6months 12months 24months


Matela - March
SPI
Time (years)
3months 6months 12months 24months


Pulane - November
3
2
1
0
-1
-2
-3
SPI
1971 1974 1977 1980 1983 1986 1989 1992 1995 1998 2001 2004
Time (years)
3months 6months 12months 24months


Pulane - December
3
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0
-1
-2
-3
SPI
1971 1974 1977 1980 1983 1986 1989 1992 1995 1998 2001 2004
Time (years)
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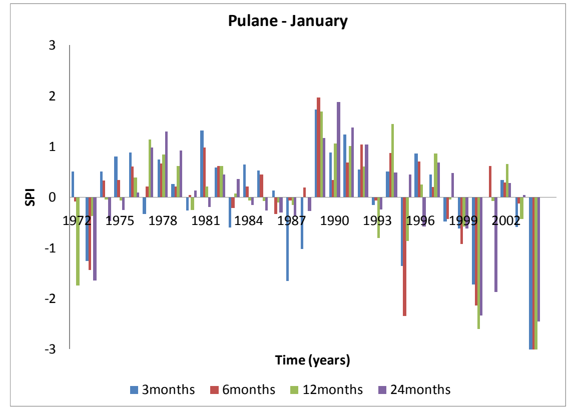
Pulane - January
3
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1
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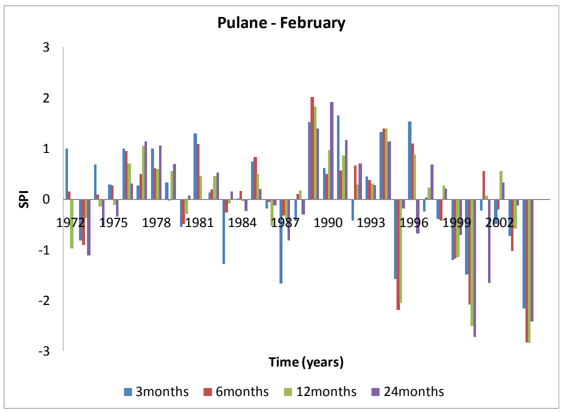
-3
SPI
1972 1975 1978 1981 1984 1987 1990 1993 1996 1999 2002
Time (years)
3months 6months 12months 24months


Pulane - February
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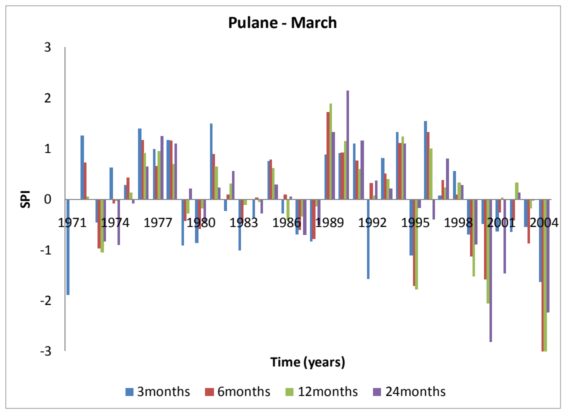
SPI
1972 1975 1978 1981 1984 1987 1990 1993 1996 1999 2002
Time (years)
3months 6months 12months 24months


Pulane - March
3
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SPI
1971 1974 1977 1980 1983 1986 1989 1992 1995 1998 2001 2004
Time (years)
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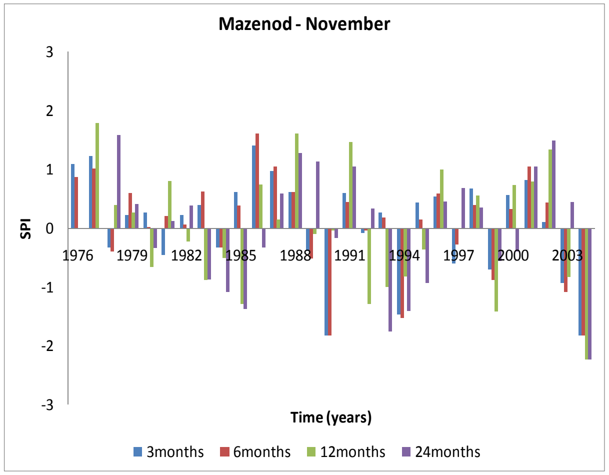
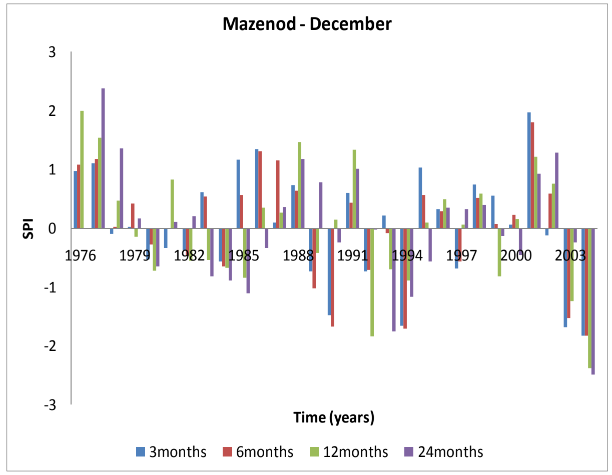

Mazenod - November
SPI
3 2 1 0 -1 -2 -3
1976 1979 1982 1985 1988 1991 1994 1997 2000 2003
Time (years)
3months 6months 12months 24months


Mazenod - December
SPI
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1976 1979 1982 1985 1988 1991 1994 1997 2000 2003
Time (years)
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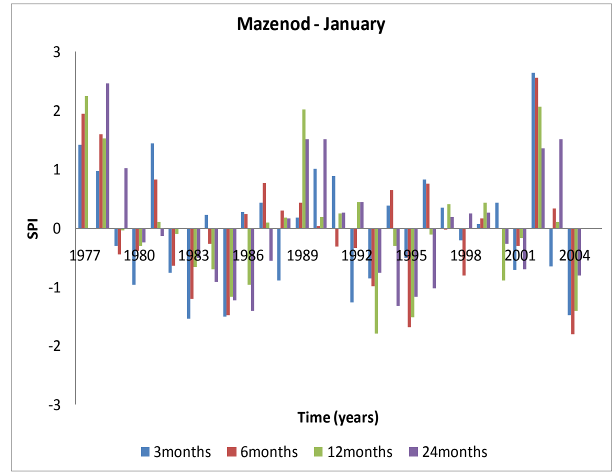
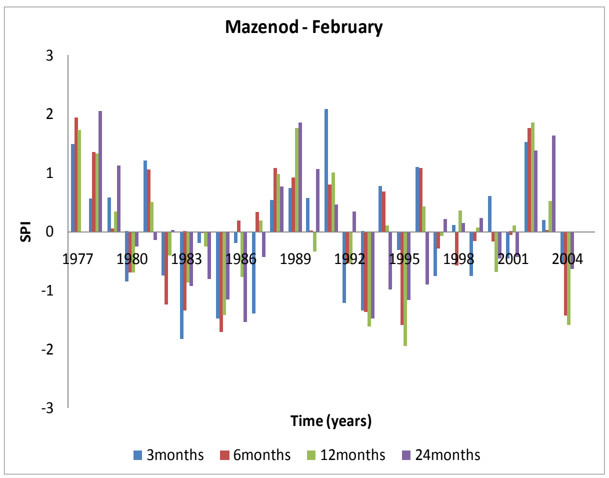

Mazenod - January
SPI
3 2 1 0 -1 -2 -3
1977 1980 1983 1986 1989 1992 1995 1998 2001 2004
Time (years)
3months 6months 12months 24months


Mazenod - February
SPI
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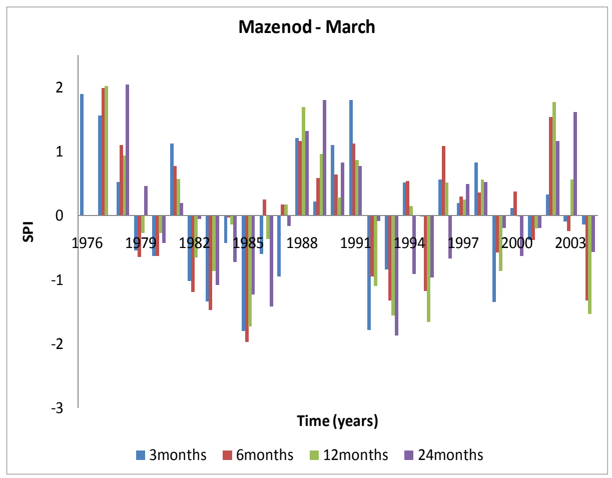
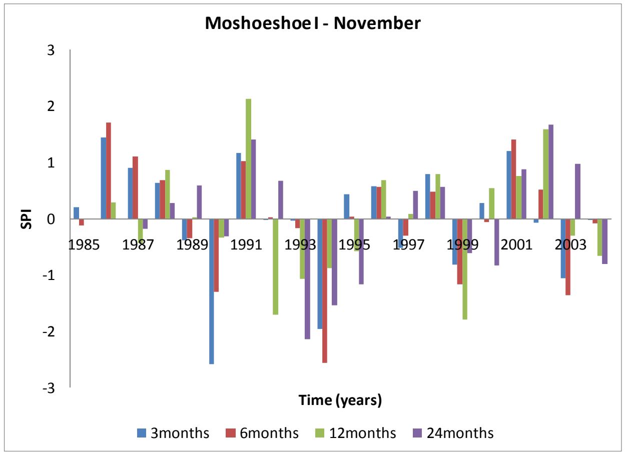
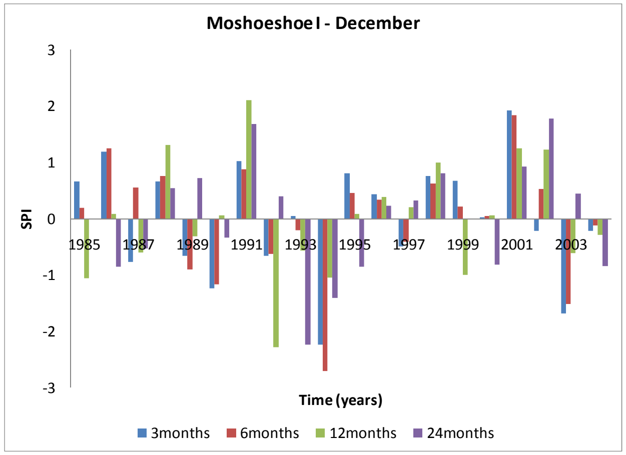
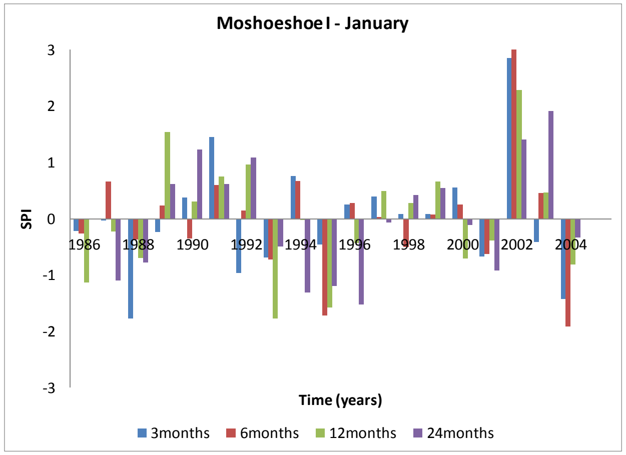
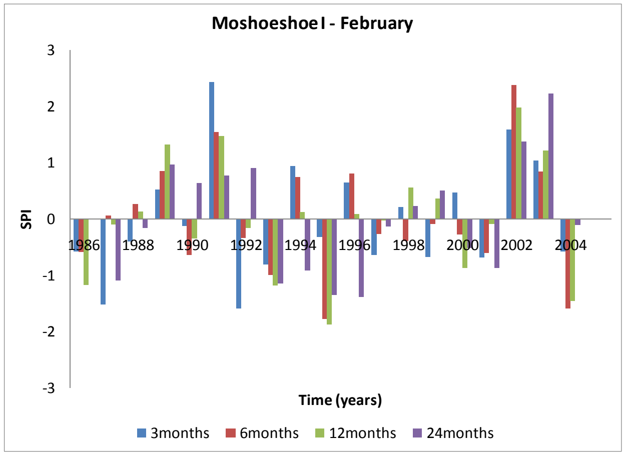
1977 1980 1983 1986 1989 1992 1995 1998 2001 2004
Time (years)
3months 6months 12months 24months

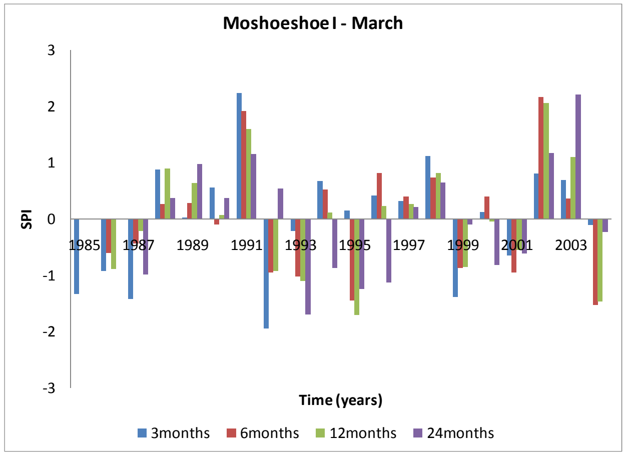

Mazenod - March
SPI
2 1 0 -1 -2 -3
1976 1979 1982 1985 1988 1991 1994 1997 2000 2003
Time (years)
3months 6months 12months 24months


Moshoeshoe I - November
SPI
Time (years)
1985 1987 1989 1991 1993 1995 1997 1999 2001 2003
3months 6months 12months 24months

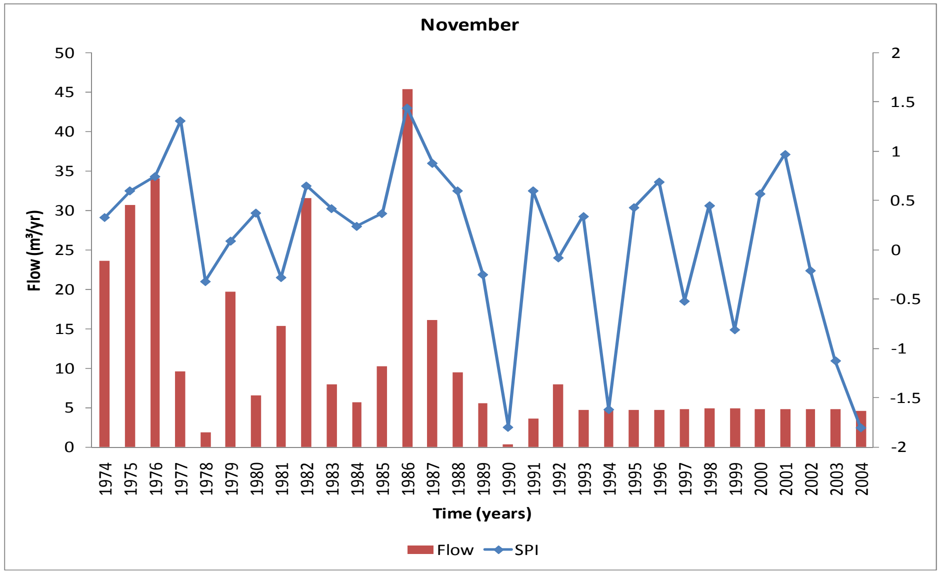

Moshoeshoe I - December
SPI
Time (years)
1985 1987 1989 1991 1993 1995 1997 1999 2001 2003
3months 6months 12months 24months

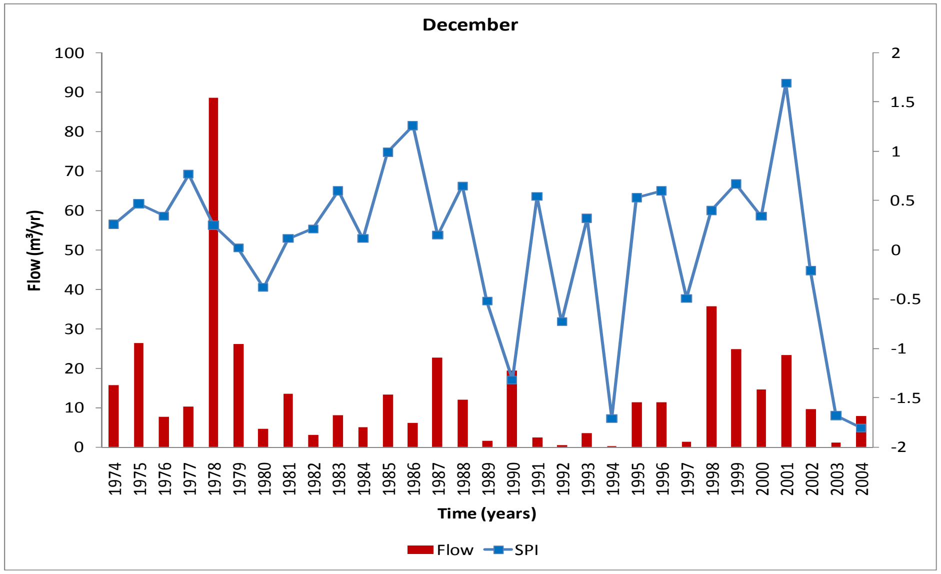

Moshoeshoe I - January
SPI
Time (years)
1986 1988 1990 1992 1994 1996 1998 2000 2002 2004
3months 6months 12months 24months

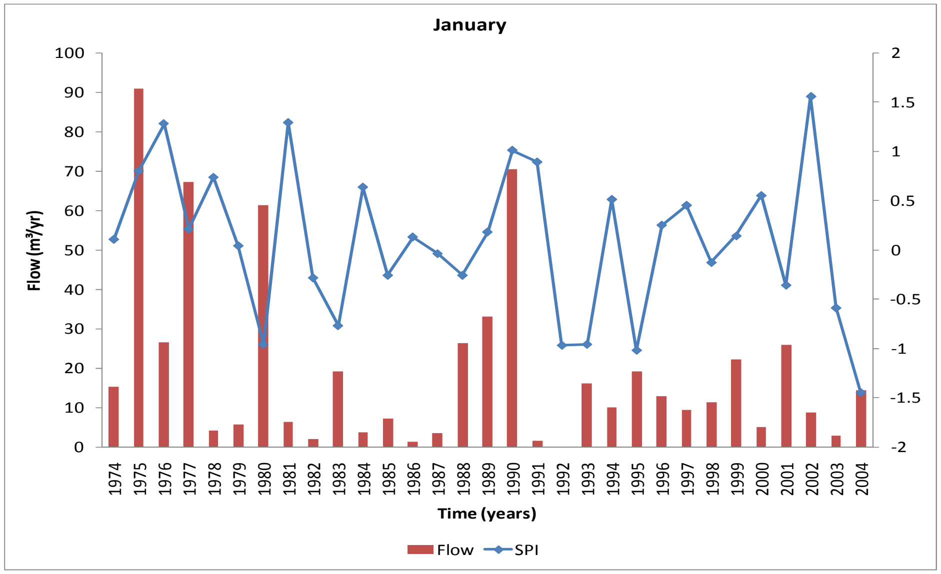

Moshoeshoe I - February
SPI
Time (years)
1986 1988 1990 1992 1994 1996 1998 2000 2002 2004
3months 6months 12months 24months

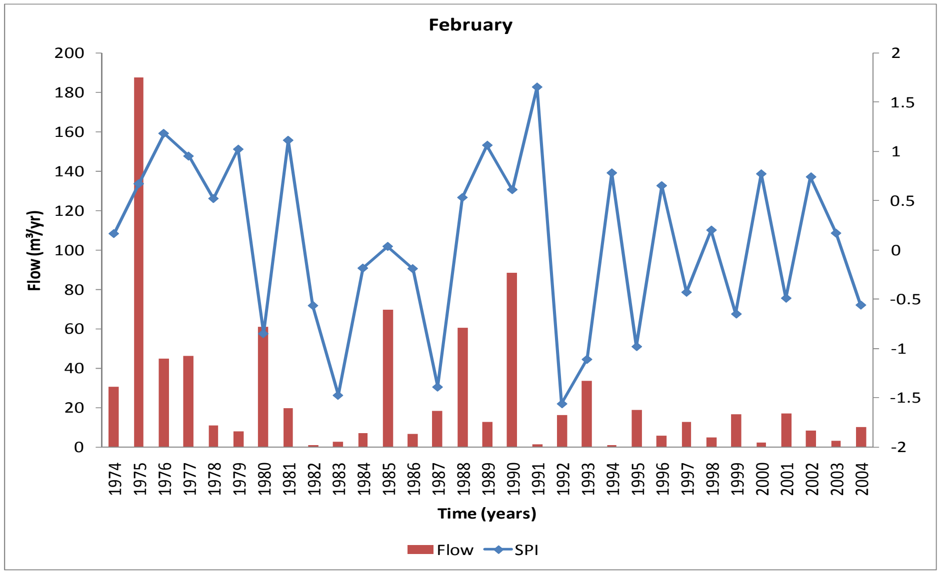

Moshoeshoe I - March
SPI
Time (years)
1985 1987 1989 1991 1993 1995 1997 1999 2001 2003
3months 6months 12months 24months

Appendix IV: 3month SPI vs Streamflow

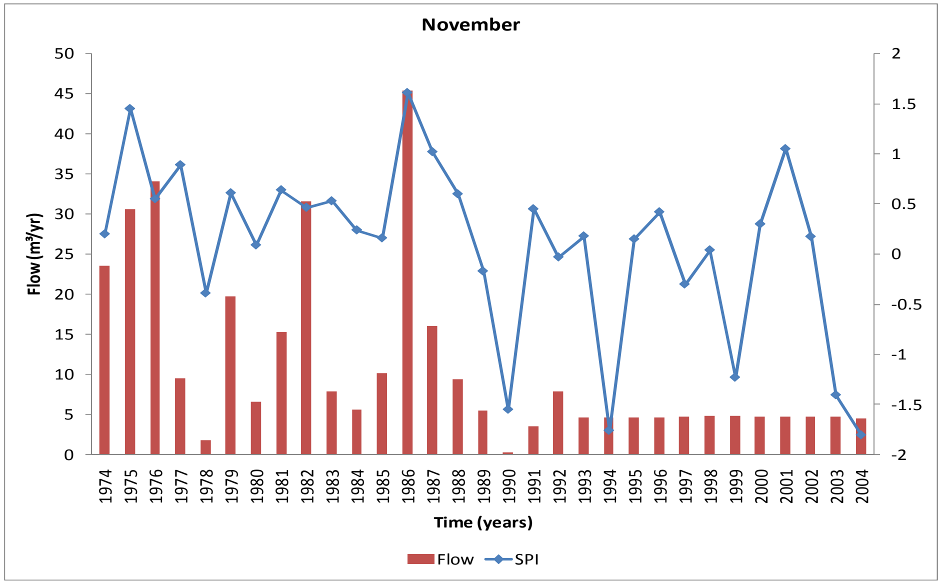


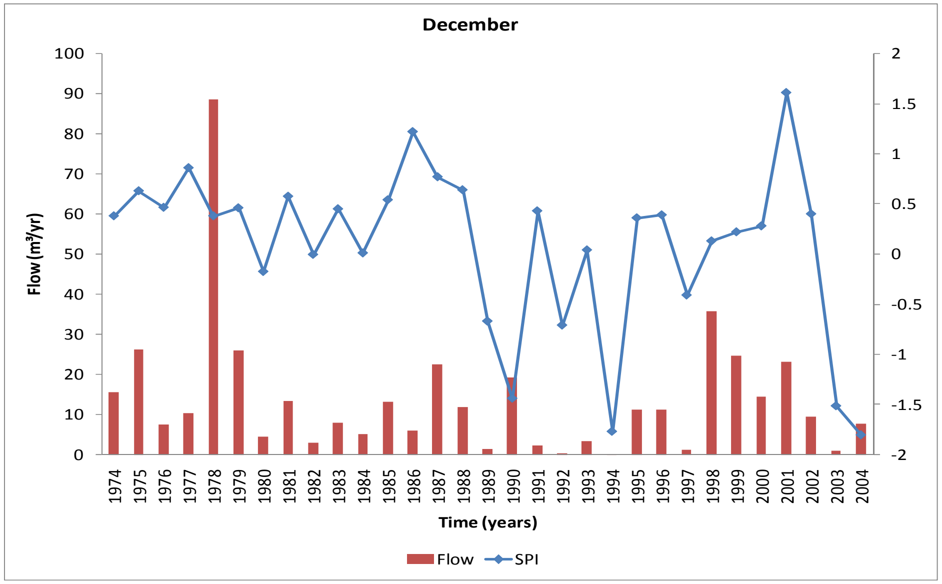


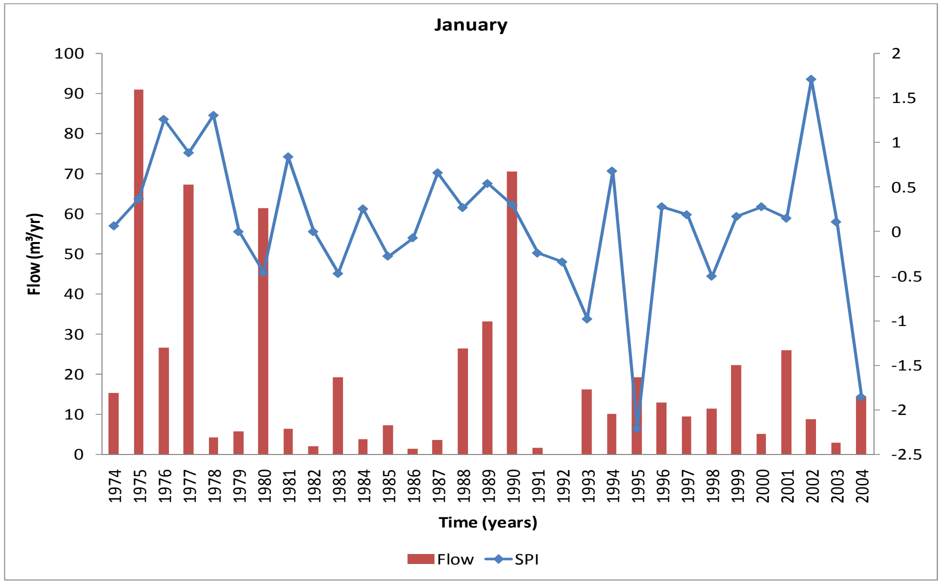


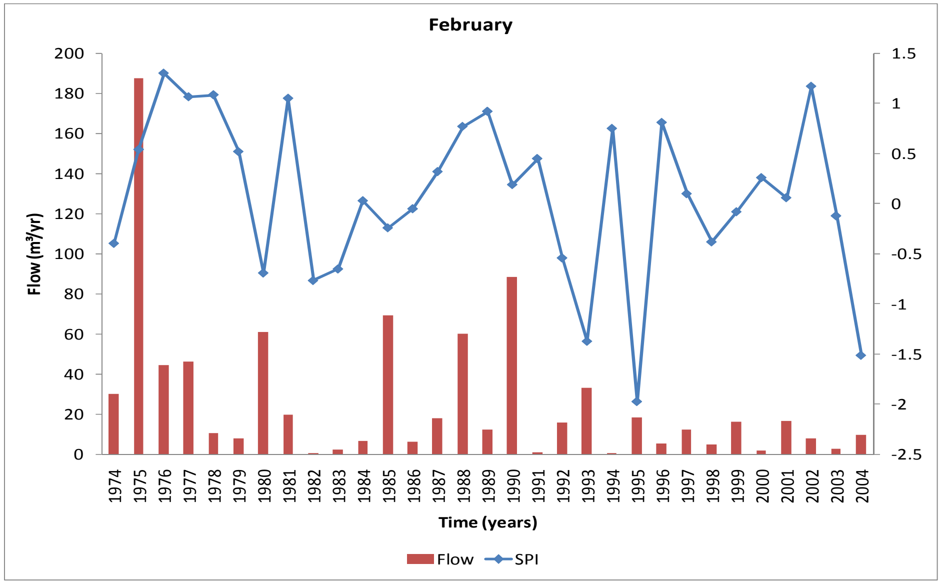


Appendix V: 6 month SPI vs streamflow

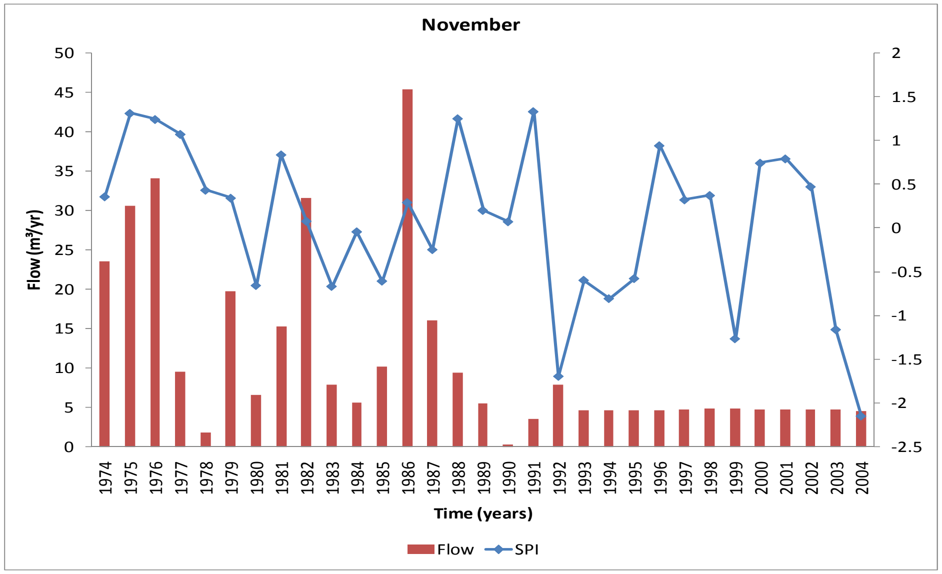


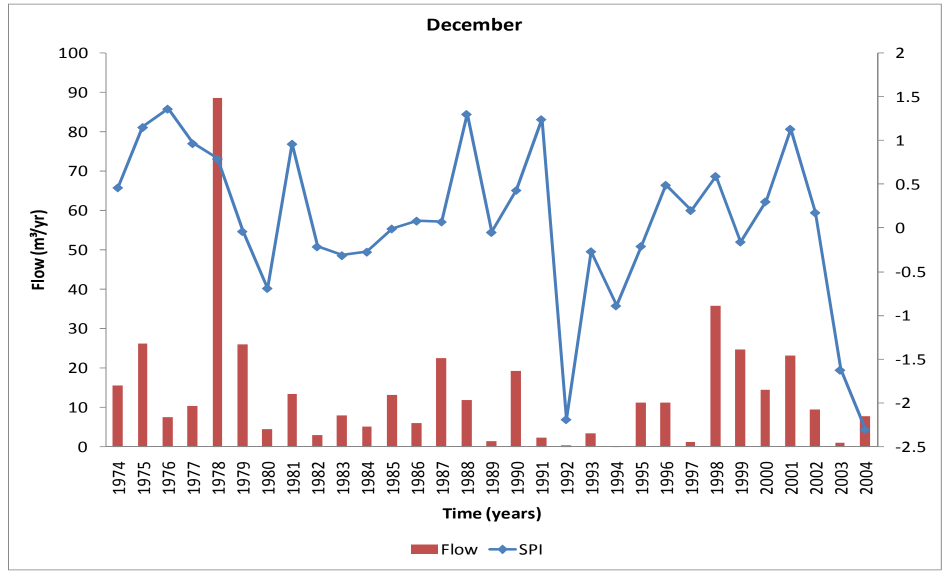


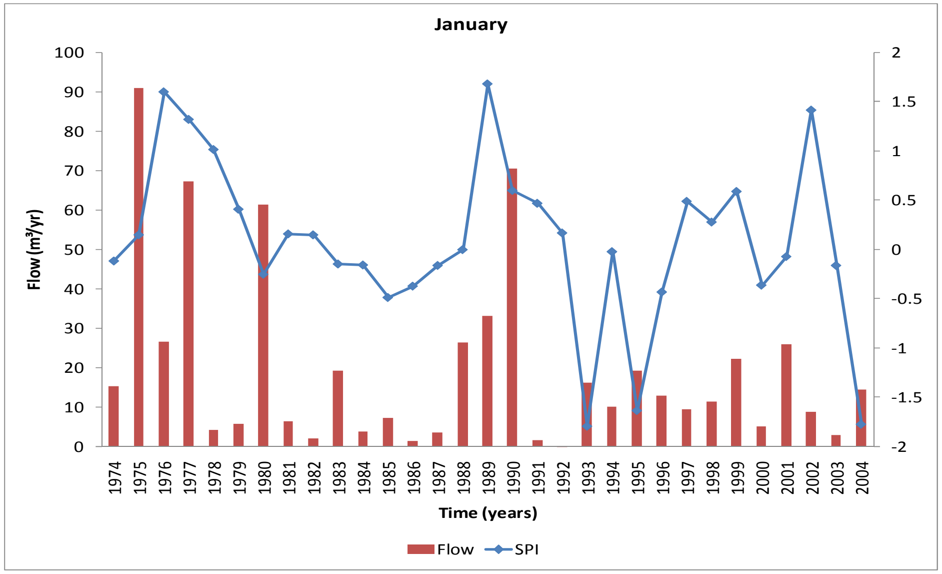


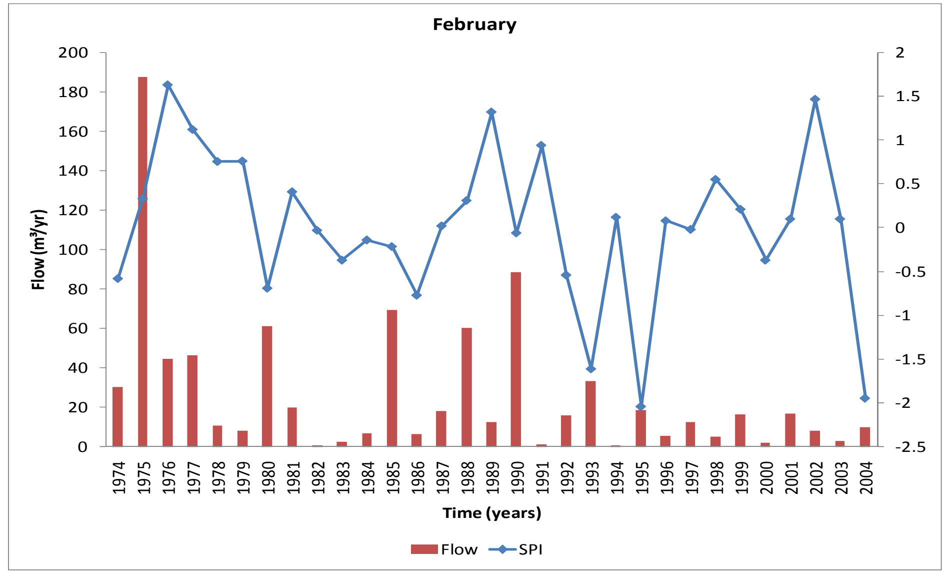


Appendix VI: 12 month SPI vs Streamflow









Appendix VII: 24 month SPI vs Streamflow