SPATIAL AND TEMPORAL CHANGES IN THE RAINFALL PATTERNS OF BOTSWANA, 1998-2013

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A Research Report submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science.

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DECLARATION

I declare that this Research Report is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

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(Signature of candidate)

__________2016-10-28__________

(Date)

ABSTRACT

Rainfall is a complex phenomenon, which has previously been explored by assessing rainfall patterns in time and space, typically using ground-based weather stations. Rainfall patterns in southern Africa tend to have a direct impact on vegetation growth and surface water availability, and an indirect impact on animal movement.

This study investigated rainfall in Botswana by analysing changes in spatial and temporal patterns from 1998 to 2013, using satellite imagery. Tropical Rainfall Measuring Mission (TRMM) 3B43 dataset (1998-2013) was used to document monthly rainfall magnitude and variability over the 15-year period. Additionally, a GIS spatial analysis approach, the Anselin Local Moran's I tool, was used to determine changes (i.e. persistence) of rainfall conditions on a year by year basis during the study period. WorldClim precipitation data (1950-2000) were utilised as a longer term average reference dataset against which TRMM data could be compared.

This study found that the rainy season consisted of relatively high rainfall magnitudes and variability, while the post rainy season consisted of relatively lower rainfall magnitudes and variability across Botswana. Higher magnitudes persisted into April, indicating the occurrence of late summer rainfall during this observation period. From a regional perspective, the Okavango Delta remained a region of relatively higher rainfall magnitude and variability compared to surrounding regions, regardless of the season. The rainy season was associated with a high frequency of rainfall events above the long term WorldClim average, and the post rainy season with a high frequency of rainfall below the long term WorldClim average. The spatial analysis indicated an annual persistence of high rainfall clusters in northern Botswana, and a persistence of low rainfall clusters in southern Botswana throughout the 15-year analysis. In addition, a progressive drying trend towards the end of the time series was observed.

These findings suggest that Botswana has experienced both wetter conditions and drier conditions within the 15-year analysis period, than have been historically documented. The progressive drying trend towards the end of the time series may be indicative of a changing climate in Botswana. However, due to the length of this analysis period it cannot be proven conclusively that the detected wetter and drier conditions, than historically documented, are a signal of climate change.

This rainfall analysis provides a comprehensive understanding of recent spatial and temporal rainfall patterns and changes in Botswana. More specifically, this rainfall study fits into a bigger research project focused on herbivore conservation in Botswana. Together, these studies will collectively enable protected areas authorities to better manage herbivore migration, improving conservation in Botswana over time. Ultimately, this study stands to make a positive contribution towards the development of existing conservation practices in Botswana.

DEDICATION

This Research Report is dedicated to my parents, for their continuous support and encouragement. Thank you for teaching me to work hard for the things I aspire to achieve.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank God for granting me the capability to complete this research.

I would like to express my deepest gratitude to my supervisors, Prof. Barend Erasmus and Dr. Kaera Coetzer, for their untiring guidance, and patience throughout this study.

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ABBREVIATIONS

COType	Cluster/Outlier type
ENSO	El Nino Southern Oscillation
GHCN	Global Historical Climatology Network
GIS	Geographical Information Systems
GISS	Goddard Institute for Space Studies
GPCC	Global Precipitation Climatology Centre
GPCP	Global Precipitation Climatology Project
HH	High-High
HL	High-Low
IPCC	Intergovernmental Panel on Climate Change
LH	Low-High
LISA	Local Indicator of Spatial Association
LL	Low-Low
NASA	National Aeronautical and Space Administration
NDVI	Normalized Difference Vegetation Index
NE	Northeast
Netcdf	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
PCA	Principal Component Analysis
PR	Precipitation Radar
RMS	Root-Mean-Square
SADC	Southern African Development Countries

SARVA	South African Risk and Vulnerability Atlas
SST	Sea-Surface Temperature
SW	Southwest
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
USA	United States of America
WMA	Wildlife Management Areas
WNV	West Nile Virus

CHAPTER 1: INTRODUCTION

Variability in rainfall is a significant component of semi-arid regions. Previous research on rainfall in semi-arid regions has indicated that rainfall can vary from year to year, within a year, and within a single rainfall event, as well as seasonally (Grist et al. 1997; Veenendaal, 1996; Batisani and Yarnal, 2010). Changes in rainfall influence factors such as the amount, distribution, timing and frequency of rainfall in time and space. According to the Intergovernmental Panel on Climate Change (IPCC) climate models have projected a decrease in average annual precipitation over both northern and southern Africa, during the mid-late twenty first Century (IPCC, 2014). Similar climate models over southern Africa have projected an annual rainfall decrease by at least 20% by 2080, accompanied by a temperature increase of approximately 2-3°C above the global average. These projections stand to have implications for rain dependent components such as surface water, soil, and vegetation. Conway et al. (2015) relates these projections to a reduction in regional surface water availability and soil moisture, and as a result, relatively lower crop yields. The authors argue that the projections serve as warning systems for global governments to invest in measures for promoting sustainable water and food security. However, these warning systems need to be accompanied by a thorough understanding of the distribution of water resources, water needs, and efficient water use, in time and space (Conway et al. 2015).

With consideration of the above mentioned projections, rainfall studies over southern Africa (Botswana, Namibia and Zambia) published in the last 20 years over a 30-year period show evidence of consistently lower rainfall measurements compared to historic rainfall records (e.g. Adedoyin and Mphale, 2002; Batisani and Yarnal, 2010), suggestive of progressively drier conditions in time and space in the region. Various authors argue that it is likely for rainfall variability in Botswana to increase as relatively drier conditions continue to emerge (Lazaro et al. 2001; Modarres and Rodrigues da Silva, 2007). Recent studies predict the occurrence of greater local rainfall variability and stronger seasonal rainfall, than previously anticipated over southern Africa (Conway et al. 2015). These rainfall analyses have been conducted at a national level, and appear to be sensitive to the time period chosen for analysis, particularly when there has been large rainfall variability between years. Therefore, a more detailed analysis conducted at finer scales of observation is required.

Additionally, a more recent assessment of rainfall variability for Botswana would be highly beneficial for the Botswana government and conservation authorities. Given the known influence of rainfall on vegetation and the indirect influence on animal populations (Bartlam-Brooks et al. 2011; Birkett et al. 2012), it is of considerable interest to conservation authorities to comprehend the nature of recent rainfall patterns across the country. During the last 10 years Botswana has experienced relatively wet conditions (McCarthy et al. 2003; Molefe et al. 2015). However, there has been a consistent decline in the number of large grazers in protected areas across Africa, including Botswana, during the same time (e.g. Ogutu and Owen-Smith, 2003). According to Chase (2011), a trend analysis of wildlife estimations from aerial surveys in Botswana showed a severe decline in population numbers during the last 10 years, and an explanation for this serious decline is required.

Rainfall research over southern Africa has determined that rainfall variability influences the availability of surface water and vegetation cover, and indirectly affects herbivore movement across the southern African landscape (Dahlberg, 2000; Ogutu and Owen-Smith 2003; Bartlam-Brooks et al. 2011; Birkett et al. 2012). A more recent rainfall study over Botswana would be advantageous for the development of sustainable, effective and efficient measures for on-going water and food security, as well as wildlife conservation in Botswana. Furthermore, clarification on the complexities and limitations surrounding rainfall in semi-arid regions makes for valuable research for conservation practices in southern Africa. Therefore, this report is considered a positive contribution towards on-going conservation studies in Botswana; by providing a clearer understanding of recent rainfall patterns.

1.1 Rationale

Rainfall is a complex phenomenon, yet a vital component of the earth's system. Rain has been previously investigated by analysing rainfall patterns related to timing (i.e. when it rains), magnitude (i.e. the amount of rainfall), intensity (i.e. the amount of rainfall within a given time), and frequency (i.e. how often it rains). Traditionally, rainfall studies have been conducted using rainfall data from ground-based weather stations, which while reliable, offers spatially incomplete rainfall information. As a consequence of this, detailed research surrounding rainfall magnitude, frequency, intensity, timing and gaps is limited. Ground-based weather stations are usually clustered in specific areas with their spatial locations based on accessibility conditions, and the location of relevant rainfall research needs (http://www.noaa.gov/features/02_monitoring/weather_stations.html). As such, a lack of rainfall measurements in areas beyond the immediate localities of ground-based weather stations is evident. The method of interpolation may be applied to produce complete rainfall datasets, but this approach is associated with a level of uncertainty (Fernandez et al. 2013), and tends to require further evaluation of the rainfall measurement in order to ascertain the quality of the data.

In recent years the use of satellite imagery has played a significant role in addressing issues around access to certain localities and incomplete ground-based data. The use of satellite imagery has become an increasingly recognised methodology, and a tool for analysing spatial and temporal rainfall patterns worldwide. Satellite imagery has been extensively used to detect land cover change, and for assessing the nature and status of vegetation around the world (Relton, 2015). Since 1997, satellite products like the Tropical Rainfall Measuring Mission (TRMM) (http://trmm.gsfc.nasa.gov/3b43.html) have been making use of merged high quality, infrared precipitation data to provide accurate, continuous and comprehensive measurements of rainfall in the tropics (http://trmm.gsfc.nasa.gov/3b43.html).

The TRMM satellite has been purposely designed to monitor rainfall within the tropics, which is convective in nature and rains intensively over short durations (Hughes and Collier, 2011). The main objective of the TRMM satellite is to provide complete and continuous rainfall records over the tropics, at a high spatial resolution (Krummerow et al. 2000; Houze Jr et al. 2015). Valuable aspects of TRMM include, the satellite's ability to provide i) rainfall measurements for locations which were previously regarded as inaccessible; and ii) complete spatial and temporal rainfall data in areas where standard ground-based rainfall data are incomplete. The most striking attribute of TRMM, is the satellite's ability to overcome historical limitations associated with rainfall measurement over the tropics. TRMM satellite data are also good for conducting comprehensive rainfall variability studies for specific times in space, particularly in low latitude (0°-23.5° N/S) convective rainfall regions (Houze Jr et al. 2015). In addition, the continuous attribute of the satellite data allows for variations in rainfall patterns to be predicted with reference to time and space.

This research report analyses and describes the spatial and temporal patterns of rainfall in Botswana from 1998 to 2013. Using satellite imagery, this study seeks to understand the limitations that go beyond known ground-based rainfall measurements. The Botswana landscape fulfils many of the requirements for which TRMM was designed, i.e. convective rainfall. Thus, it is argued that TRMM may provide valuable information for exploring recent rainfall patterns in Botswana; beyond that which has previously been documented in the literature. The aim of this study is to fill the knowledge gap concerning complete ground-based rainfall data in Botswana, which results in an incomprehensive understanding of the spatial extent of rainfall measurements in the country.

Furthermore, this study considers the direct influence of rainfall patterns on rain dependent factors such as surface water and vegetation, and the indirect influence on animal movement. This rainfall research feeds into a bigger research project related to herbivore conservation in Botswana. At present, there are on-going studies assessing the greening of vegetation in Botswana using NDVI, tracking herbivore movement, as well as the interactions between these two aspects. An updated evaluation of rainfall patterns in Botswana, specifically one that captures spatial and temporal changes in recent years, is considered an urgent research requirement that has yet to be addressed. There appears to be no other recent studies that have carried out a similar TRMM satellite based study to obtain a comprehensive understanding of rainfall measurements for the full extent of Botswana, between 1998-2013. Hence, this study fills the research need for i) extensive and continuous rainfall data monitoring across Botswana, as well as ii) provision of a more comprehensive understanding of the rainfall patterns, and their changes in space and time.

1.2 Aim

The aim of this research is to investigate rainfall in Botswana by analysing spatial and temporal rainfall patterns, and changes in these rainfall patterns, over a 15-year period from 1998 to 2013.

1.3 Objectives

1. To document the spatial and temporal rainfall patterns of Botswana using monthly TRMM rainfall measurements over the period 1998-2013.

2. To describe changes in spatial and temporal patterns of rainfall in Botswana over the period 1998-2013.

1.4 Research questions

1. What is the magnitude, variability, frequency and duration of rainfall events in time and space in Botswana for the period 1998-2013?

2. Have there been any observed changes in magnitude, variability, frequency and duration of rainfall events in time and space in Botswana during 1998-2013?

3. If there have been changes, what are these observed changes in magnitude, variability, frequency and duration of rainfall events in time and space in Botswana during1998-2013?

4. What are the implications for herbivore movement, and consequently, conservation, in Botswana?

CHAPTER 2: LITERATURE REVIEW

2.1 Climate and vegetation of Botswana

Botswana, the designated study area, is a semi-arid country located in southern Africa (Nicholson and Fairar, 1994; Veenendaal, 1996; Grist et al. 1997). It is a landlocked country, bordered by South Africa to the south and southeast, Namibia to the west and northwest, and Zimbabwe to the northeast (Figure 1). Botswana forms part of the southern African Development Countries (SADC). The country has a surface area of approximately 600 000km^2, and is situated on a flat plateau with an elevation of 1000m.

Figure 1: Map of southern Africa illustrating the geographic location of Botswana, which is the study area for this rainfall analysis (Created by Relotilwe Maboa, 2014).

The nature of rainfall in Botswana is localised, convective, and strongly seasonal in nature (Nicholson and Fairar, 1994; Regenmortel, 1995; Grist et al. 1997). The wet season occurs during the summer months (October-March) and is associated with an increase in rainfall events, coupled with an increase in surface water and vegetation cover (Nicholson and Fairar, 1994; Birkett et al. 2012; World Wildlife Fund, 2015a). These high rainfall periods coincide with high evaporation rates, with summer temperatures exceeding maximum of 33^{o}C (Winterbach et al. 2014). The dry season (May-July) is associated with a decrease in rainfall events, a reduction in surface water and vegetation cover (Nicholson and Fairar, 1994; Birkett et al. 2012; World Wildlife Fund, 2015a).

The rainfall gradient in Botswana increases gradually from the dry southwest (arid) to the wet northeast (less arid) (Nicholson and Fairar, 1994; Grist et al. 1997) (Figure 2). As a semi-arid region, rainfall patterns in Botswana have an annual rainfall variation of approximately 450-550mm between seasons, and regions (Regenmortel, 1995; Veenendaal, 1996).

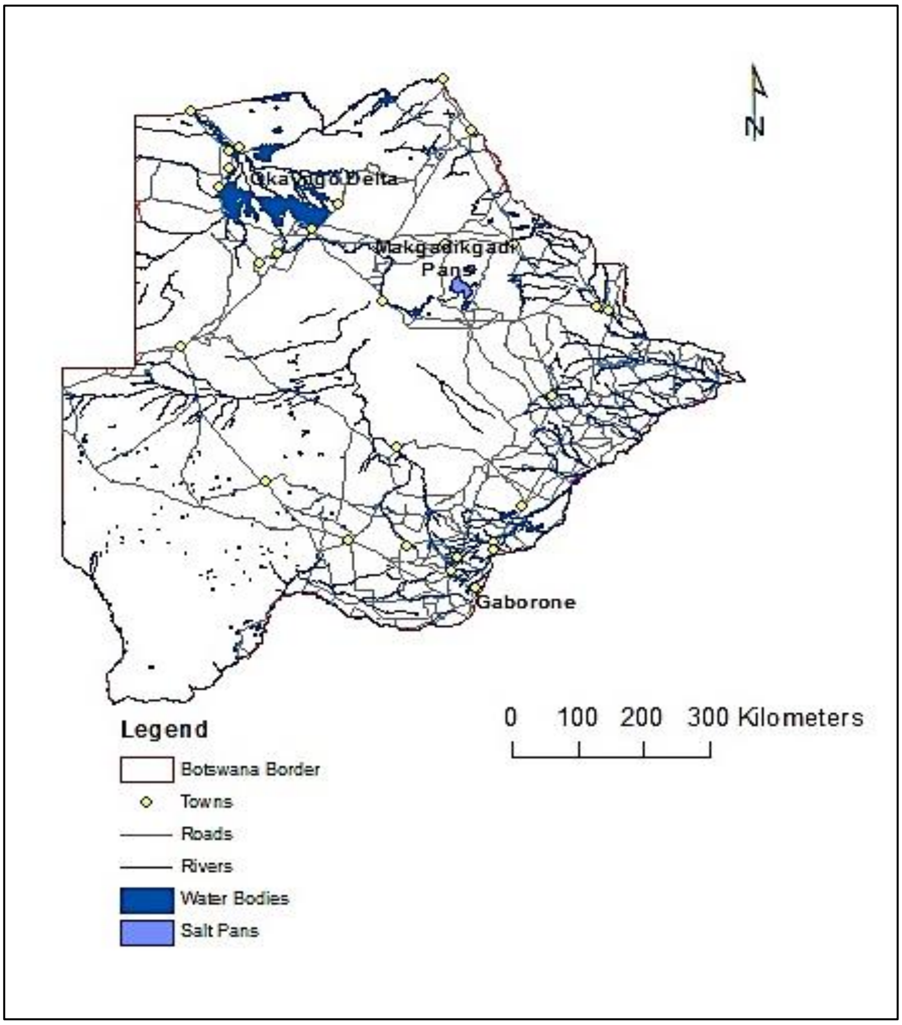


Figure 2: Map indicating rivers and large surface water bodies in Botswana. The abundance of rivers and surface water bodies serves as a proxy for displaying the rainfall gradient, increasing from southwest to northeast (Created by Relotilwe Maboa, 2014).

Approximately 70% of the country is covered by the Kalahari Desert and semi-arid plains of unconsolidated sands (Nicholson and Fairar, 1994). Botswana consists of a predominantly flat landscape with poorly developed sandy soil, and relatively uniform sandveld vegetation cover (Regenmortel, 1995; Grist et al. 1997). The vegetation is mainly savanna with grasses, shrubs and trees in varying proportions (Nicholson and Fairar, 1994; Grist et al. 1997) (Figure 3). The diversity of groundcover and the abundance of trees increase from southwest to northeast (Nicholson and Fairar, 1994).

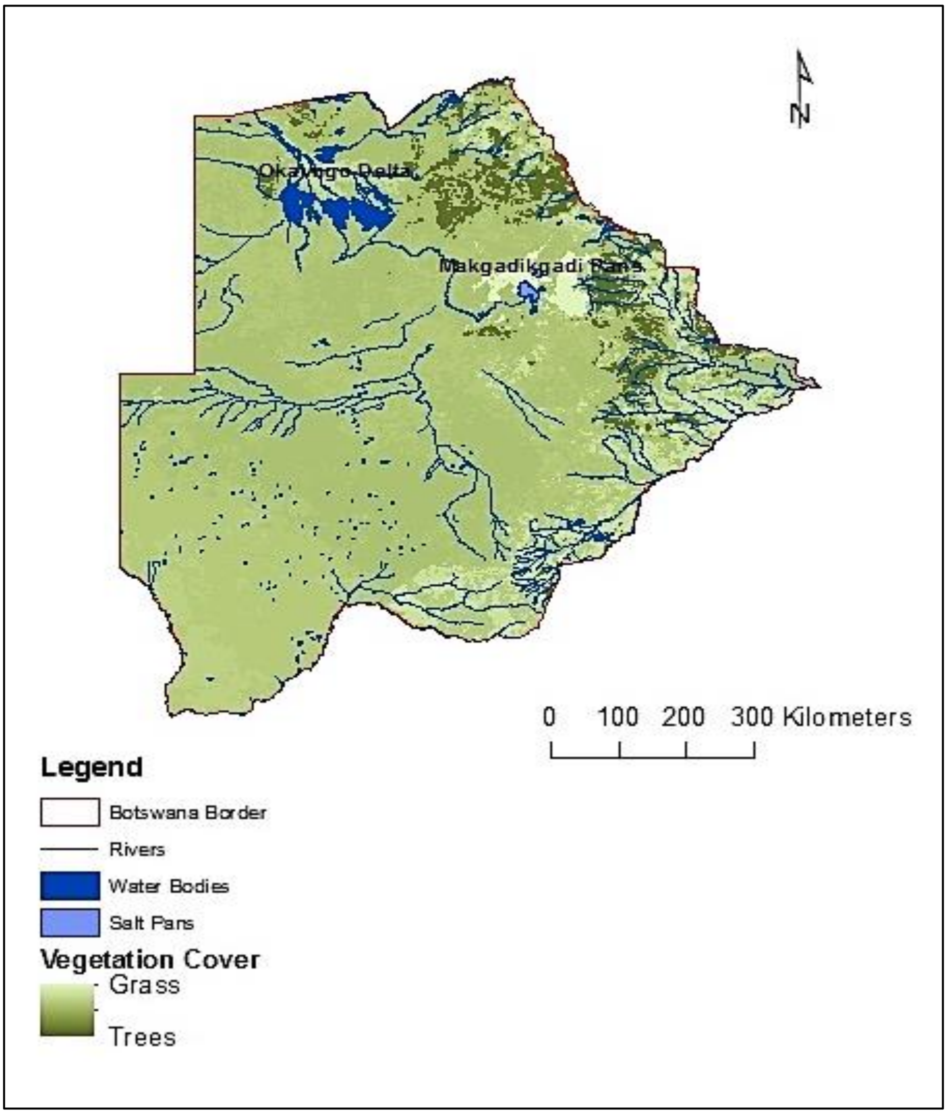


Figure 3: Map showing the vegetation cover along the rainfall gradient of Botswana, which increases from a southwest to northeast direction (Created by Relotilwe Maboa, 2014).

The extremely dry southwest is characterised by sand dunes, separated by grassland with occasional trees and shrubs. More specifically southwest Botswana consists of Acacia shrub savanna and Acacia thorn bush savanna. Towards eastern Botswana *Croton sp*. and

Combretum sp. tree savanna, and dense woodland such as Mopane savanna woodland *(Colophospermum mopane)* is apparent. The wet northeast is characterised by high rainfall, and a canopy forest consisting of Acacia tree savanna (Weare and Yalala, 2009).

It is understood that the seasonal and variable nature of rainfall in Botswana has an influence on rainfall dependent factors such surface water and vegetation growth, with rainfall events with a minimum of 10mm known to be conducive for vegetation growth in Botswana (Knight, 1991).

2.2 Herbivore movement

Comprehension of the impact of the country's rainfall patterns on herbivore movement is limited. Previous studies surrounding the causes of herbivore migration in arid landscapes have related the migration of herbivores in southern Africa to emergence of seasonal conditions, i.e. change in the availability of surface water and vegetation between rainfall seasons (Fryxell and Sinclair, 1988; Bergstrom and Skarpe, 1999; Traill, 2004; Fynn et al. 2014). Yet, studies have indicated that during the last 10 years, periods of good rainfall in Botswana have not resulted in the associated increase in herbivore population as expected (McCarthy et al. 2003; Ogutu and Owen-Smith, 2003; Molefe et al. 2015). Therefore, further research on factors related to herbivore conservation is required.

The greater Serengeti grassland ecosystem is well known for impressive animal migrations, with more than a million blue wildebeest *(Connochaetes taurinus)*, zebra *(Equus burchelli)* and Thomson's gazelle *(Eudorcas thomsonii)* moving across Eastern Africa (World Wildlife Fund, 2015b). Various authors argue that the contributing factors towards herbivore migration in southern Africa are namely seasonal conditions, herbivore physical attributes, and the development of fencing systems (Fryxell and Sinclair, 1988; Berger, 2004; Traill, 2004; Brooks et al. 2011; Fynn et al. 2014). Some of these studies are discussed below:

Seasonal conditions: Smit (2010) conducted a study on resources driving the migration patterns of grazers in African savanna, and found that forage quality and surface water are the main contributors towards herbivore movement within the region. An investigation of changes in elephant *(Loxodonta africana)* movement in relation to rainfall patterns over the Kruger National Park, South Africa, determined that herbivore migration patterns are influenced by the rainfall patterns (Birkett et al. 2012). Bartlam-Brooks et al. (2011) completed herbivore migration research in Botswana, which found that zebra first migrate towards the Okavango Delta during the dry season, and thereafter move towards the Makgadikgadi grasslands during the rainy season.

Physical attributes: Berger (2004) completed research on the sustainability of land distance-migration in mammals, and found that the physical attributes, (i.e. body size) of terrestrial mammal influences the distance of the migration. According to this study, the forage quality threshold for large bodied herbivores is higher than for small bodied herbivore. This means that large bodied herbivores are more likely to accept a broader range of forage quality, compared to smaller herbivores during the dry season. This finding is based on the fact that the metabolic and nutritional requirements for herbivores increase with body size (Smit, 2010).

Fencing: The historic positioning of fencing across the Botswana landscape is another factor influencing herbivore migration. Veterinary cordon fences in Botswana were erected, between 1950-1980, as part of the condition (i.e. disease regulation) for the export of livestock to Europe (Mbaiwa and Mbaiwa, 2006). As a consequence, the migration routes of migratory wildlife species such as wildebeest, zebras, giraffes (*Giraffe camelopardis)* and buffalo *(Syncerus caffer)* were blocked (Mbaiwa and Mbaiwa, 2006; Bartlam-Brooks et al. 2011). Unfortunately, there was a lack in detailed understanding of impacts of the fences on the wildlife at the time. These impacts included, i) disturbance to animal migratory patterns, ii) increased habitat fragmentation, and iii) changes in animal behaviour and population genetics (Cozzi et al. 2013). Mbaiwa and Mbaiwa (2006) conducted a study on the effects of veterinary fences on wildlife populations in the Okavango Delta, Botswana. The authors attributed the observed decline in wildlife numbers over the past decade to the fencing system, which was associated with the obstruction and restriction of wildlife movements.

Similarly, Rahm et al. (2006) identified that about 99% of the wildebeest population in Botswana had declined since the establishment of the fencing system in 1954. This decline in wildlife prompted conservation authorities in Botswana to establish Wildlife Management Areas (WMA). Thirty-five percent of the land in Botswana is reserved for Wildlife Management Areas (WMA), for the primary purpose of protecting wildlife heritage and exercising effective wildlife management (Rahm et al. 2006; Winterbach et al. 2014). Protected areas in Botswana are located distances apart from each other (Figure 4), characterised by an open fence system, traversing private farms, ranches and communal lands (Rahm et al. 2006).

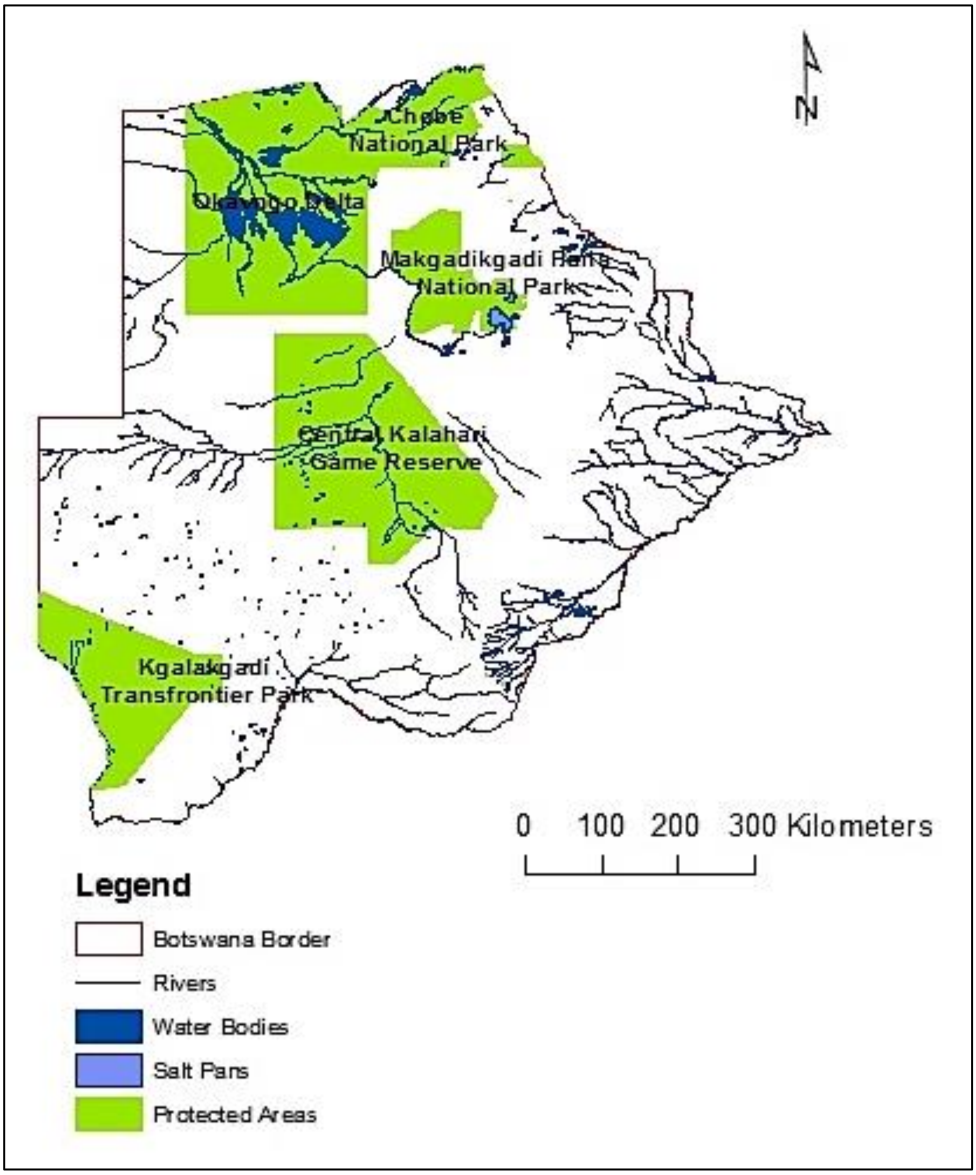


Figure 4: Map illustrating the position of national protected areas (parks and reserves) within the study site (Created by Relotilwe Maboa, 2014).

With regards to the future development of conservation in Botswana, contributing factors towards herbivore movement should be investigated further by conservation authorities. This will provide conservation authorities with a comprehensive understanding of the complexities and limitations surrounding herbivore migration within the country, as well as how to improve current conservation practices.

2.3 Drivers of rainfall variability

Climate predictions over southern Africa place emphasis on the occurrence of variable rainfall patterns, including a decrease in annual rainfall and frequency, as well as an increase in temperatures (Conway et al. 2015). Richard et al. (2000) related these projections of drier climate conditions to the El Nino Southern Oscillation (ENSO) effect. Numerous studies have investigated the relationship of rainfall variability to climatic phenomena like ENSO and the Inter Tropical Convergence Zone (ITCZ) (Nicholson and Kim, 1997; Richard et al. 2000; Nicholson et al. 2001; Reason et al. 2006; Collier and Hughes, 2011).

El Nino Southern Oscillation: ENSO is a climatic phenomenon which involves changes in sea-surface temperature (SST) and the direction of the winds across the oceans (Camberlin et al. 2001; Kane, 2009). ENSO events are prone to occur approximately every three to seven years and have been related to distinct differences in temperature and rainfall measurements worldwide. Thus, ENSO is considered a substantial driver for change in climate, particularly a change from usual rainfall patterns. Nicholson et al. (2001) carried out a study on the relationship of ENSO and drought in Botswana, and deduced that ENSO events have an effect on the magnitude, timing and duration of rainfall. A substantial amount of literature surrounding rainfall variability in relation to ENSO is available, some of which have been described below.

Over the last decade various studies in southern Africa have determined that ENSO has a modulating effect on rainfall, which is coupled by the occurrence of drought conditions during an ENSO event (Nicholson and Kim, 1997; Richard et al. 2000; Conway, 2008; Kane, 2009; Yeh et al. 2009; Mpheshea, 2014). Richard et al. (2000) support this notion, and attributes the series of drought occurrences in southern Africa prior to the year 2000 (Camberlin et al. 2001) to the ENSO effect. More recently, 2015 was recorded as the hottest year globally (Hansen et al. 2016; Otto, 2016). The Goddard Institute for Space Studies (GISS) conducted a global temperature analysis (GISTEMP), which found 2015 to be the warmest year to date and exceeded the previous record by more than $0.1^{o}C$ (Hansen et al. 2016). The analysis correlated the warmer temperatures in 2015 with the strong presence of El Nino, and indicated that these warm weather conditions were likely to continue in 2016, even as the impact of El Nino starts to weaken (Hansen et al. 2016). According to Otto (2016), January 2016 recorded the hottest temperatures on record and based on the observed global temperatures, 2016 may be the hottest year on record (Hansen et al. 2016). Furthermore, an observation of long term global warming trends related to ENSO occurrences, shows that over the past three decades ENSO has had a similar suppressing effect on rainfall (Reason and Rouault, 2002).

Inter Tropical Convergence Zone: The ITCZ is another phenomenon known to influence rainfall patterns over southern Africa (Reason et al. 2006). The ITCZ is an atmospheric convergence zone along the equator, where north easterly and south easterly trade winds from the northern and southern hemisphere converge (Reason et al. 2006; Collier and Hughes, 2011). The location of the ITCZ varies throughout the year as the sun traverses the tropics, resulting in wet and dry seasons (Tyson and Crimp, 1998; Reason et al. 2004; Zhou et al. 2005; Chikoore and Jury, 2010; Collier and Hughes, 2011). Authors argue that seasonal rainfall patterns experienced over southern Africa are largely influenced by the ITCZ (Tyson and Crimp, 1998; Collier and Hughes, 2011). Over the African continent the ITCZ moves from the equator, and towards either the Tropic of Cancer (northwards) or Tropic of Capricorn (southwards) in response to the sun's annual cycle of declination (Reason et al. 2004; Collier and Hughes, 2011). Convergence at the ITCZ is associated with deep convection which produces intense thunderstorm activity over the tropics (Chikoore and Jury, 2010; Collier and Hughes, 2011).

2.4 Measuring rainfall remotely

The measurement of rainfall is an important aspect for understanding rainfall patterns in time and space. For decades meteorologists have studied rainfall patterns over the land using ground-based rainfall data, yet rain gauge data are prone to produce spatially unreliable measurements (Kummerow, 2000; Javanmard et al. 2010). This issue of spatial unreliability leads to i) incomplete ground-based data, and ii) an inconsistent representation of rainfall measurements spatially.

The most recent approach for rainfall research is the use of satellite observations, which allow for accurate rainfall measurements in areas where ground-based weather stations cannot detect. The quality of the satellite rainfall measurements is validated and corroborated using corresponding ground-based rainfall measurements (Adeyewa et al. 2003; Nicholson et al. 2003; Javanmard et al. 2010). This is an effective method for reducing the occurrence of meteorological errors, and increases the level of confidence associated with rainfall satellite products such as the Tropical Rainfall Measuring Mission (TRMM).

Literature shows that TRMM satellite data are considered sufficiently accurate for global use, due to the extensive validation and corroboration effort associated with the data. TRMM has carried out a long term (1998-2010) study comparing global TRMM 3B43 data to Global Rain gauge data (compiled by Global Precipitation Climatology Centre (GPCC) (Huffman and Bolvin, 2014). The study found that TRMM 3B43 and rain gauge data were consistently similar, with high levels of comparison over both land and ocean. The difference between the averages for each dataset is as follows: over the land TRMM 3B43 = 3.19mm/day; rain gauge = 3.16mm/day and over the ocean TRMM 3B43 = 3.00mm/day; rain gauge = 2.79mm/day. Franchito et al. (2009) validated TRMM precipitation radar monthly rainfall estimates with rain gauge data over 5 geographic regions in Brazil, from December 1997 to November 2000. The results show that TRMM correlated with the rain gauge data over most of Brazil, with significant correlation coefficients at a 99% confidence level. Zhong (2015) conducted a study evaluating the precipitation climatology (1998-2013) derived from TRMM 3B43 over land with two rain gauge products (GPCC, and Wilmott and Matsuura (WM)). The results indicated a strong agreement throughout the study period, although accuracy is shown to decline in relatively lower rainfall conditions (i.e. rainfall rate regions = <0.5mm/day) such as the Sahara Desert, Arabian Peninsula and the Andes (Zhong, 2015). However, Nicholson et al. (2003) conducted rainfall estimates with a high density gauge dataset (Global Precipitation Climatology Project) for West Africa. The study found that TRMM demonstrated a strong agreement with the gauge dataset, with a difference of less than 0.5mm/day during May-September (i.e. the relatively dry season).

The TRMM satellite was developed to produce remote rainfall measurements, and is considered an important part of the National Aeronautical and Space Administration (NASA) (http://trmm.gsfc. nasa.gov /3b43.html). TRMM has provided continuous, high quality rainfall measurements over tropical regions, for more than a decade. The satellite's data has been successfully used worldwide, which includes research in Iran, Africa, India and Bangladesh (Adeyewa et al. 2003; Nicholson et al, 2003; Islam and Uyeda, 2005; Nair et al. 2009; Javanmard et al. 2010).

TRMM is a joint venture between NASA in the United States of America (USA) and Japanese Space Agency JAXA, with the aim of measuring tropical rainfall. The TRMM observatory was launched in 1997 into a near circular orbit of approximately 350km altitude, an inclination of 35 degrees and a period of 92.5 minutes (Sherperd et al. 2000; Tian et al. 2007; Immerzeel et al. 2009; Nair et al, 2009). This circular orbit allows TRMM to record rainfall at different locations and at different local times each day, which is very useful for detailed temporal rainfall studies. TRMM rainfall estimates (measurements) are on a 3-hour temporal resolution and a fine spatial resolution of 0.25 by 0.25 degrees, in a global belt extending from 50 degrees south to 50 degrees north (Immerzeel et al. 2009;

http://trmm.gsfc.nasa.gov/3b43.html). TRMM's altitude of 350 km is considered low compared to other satellites. This is attributed to the fact that satellites at lower altitudes obtain higher resolutions, thus producing high resolution images (Ceccanti and Marcuccio, 2000).

At the present time, TRMM is considered as one of the satellites producing some of the best available remotely sensed rainfall measurements in global tropical regions (50^{o} N-50^{o} S, 0-360^{o} E) (Nair et al. 2009; http://rain.atmos.colostate.edu/CRDC/ datasets/TRMM_3B43. html). TRMM has a number of rainfall measurement products, produced from passive microwave and precipitation radar sensors, namely TRMM Microwave Image (TMI) and Precipitation Radar (PR) (Kummerow and Barnes, 1997; Kummerow et al. 2000; Tian et al. 2007; Immerzeel et al. 2009; http://rain.atmos.colostate.edu/CRDC/datasets/TRMM _3B43.html). TMI is a microwave sensor for measuring water vapour, cloud water and rainfall intensity by detecting the energy released by the earth and its atmosphere. PR is used to locate and calculate the motion of rainfall (http://trmm.gsfc.nasa.gov/3b43. html; Kummerow, 2000; Sherperd. 2001). This study uses the TRMM 3B43 monthly product, which is designed to produce reliable precipitation measurements at a monthly temporal resolution, and a fine spatial resolution of 0.25 by 0.25 degrees. TRMM 3B43 is a combination product of 3B42 dataset (3-hourly temporal resolution dataset) and monthly global rain gauge measurements (http://trmm.gsfc.nasa.gov/3b43.html; http://rain.atmos. colostate.edu/ CRDC/datasets/ TRMM_3B43.html).

2.5 Spatial analysis

There are various approaches for identifying rainfall patterns spatially. In general, a cluster analysis helps group objects (cases) or datasets into classes (clusters) on the basis of similarities, and or dissimilarities within different classes (Mostashari et al. 2003; Singh et al. 2004). Clusters can be defined as relative points in space with similar variables or characteristics (Gong and Richman, 1995; Lyra et al. 2014). For this reason, the cluster analysis approach has been used in a number of studies (rainfall and risk assessment) as an effective method of consolidating large amounts of data (Pan et al. 2009). There are a number of different statistical techniques commonly used for performing cluster analysis namely Principal Component Analysis (PCA), Euclidean Distance, and Ward's Method (Gadgil and Iyengar, 1980; Drosdowsky, 1993; Mu˜noz-D´ıaz and Rodrigo, 2004; Singh et al. 2004; Pan et al. 2009).

Principal Component Analysis (PCA): PCA is a multivariate statistical technique for carrying out data cluster analyses, by statistically converting a set of observations or variables with similar characteristics into principal components (clusters) (Drosdowsky, 1993; Mu˜noz-D´ıaz and Rodrigo, 2004; Singh et al. 2004). This method has been used for grouping and correlating a vast number of variables and is a preferred approach within rainfall research (Gadgil and Iyengar, 1980; Ronen and Avinoam, 1999; Mu˜noz-D´ıaz and Rodrigo, 2004). For example, Ronen and Avinoam (1999) made use of PCA to determine the distribution of plant species in relation to variable rainfall in Israel, and found that the cluster of plants species distribution corresponds to the rainfall gradient.

Euclidean Distance: The Euclidean Distance is a cluster technique which indicates data clusters, based on real or derived measures of distances between variables. This technique analyses the square root differences between variables and is commonly used in computer science for data mining, which makes use of hierarchical clustering approach to find patterns in large datasets (Kardi, 2015).

Ward's Method: Ward's Method is another clustering method associated with hierarchical data clustering. This approach involves the calculation of the distance between clusters, as the sum of squares between two clusters, and then summed up over all variables (Gadgil and Iyengar, 1980; Pan et al. 2009). Ward's method is used when the objective of the analysis is to build a hierarchy of small clusters.

A cluster analysis is not only useful for grouping variables, but it also useful for interpreting data and identifying patterns in space. For this reason, the spatial cluster analysis is a widely used technique for investigating clusters spatially. Where variables have a spatial dimension with geographic properties; a computational spatial analyses tool within Geographical Information Systems (GIS) can be used. Motashari et al. (2003) made use of a geographic cluster analysis, which involved the use of spatial scan statistics to i) represent the geographical clusters, and ii) to spatially predict dead bird clusters. These bird clusters indicated regions where people may be at risk of contracting the West Nile Virus (WNV) in New York (Motashari et al. 2003). The Anselin Local Moran's I tool is another GIS approach, which provides i) a 'by region' assessment of spatial data, and ii) a comparison of the regions to surrounding regions (neighbourhood pattern).

A number of studies have used the Anselin Local Moran's I tool as a method to detect spatial clusters in rainfall, temperature and pollution, as well as for identifying spatial outliers, i.e.

areas surrounded by regions that have opposite or contrasting patterns of rainfall occurrence (Anselin, 1995; Sugumaran et al. 2009; Fischer and Getis, 2010). Brody et al. (2008) used Anselin Local Moran's I to determine clusters of high and low climate risk, in order to inform local climate change policy in the United States of opportunities to adopt mitigation strategies against adverse risks of climate change. Zhang et al. (2008), also made use of Anselin Local Moran's I to detect pollution hotspots of lead (Pb) concentrations in urban soils of Galway, Ireland in order to improve environmental management. Although, the literature cited in this section does not consist of specific rainfall examples using the Anselin Local Moran's I tool, it has been used it to illustrate how a similar approach can be applied to TRMM rainfall data. This particular spatial cluster approach may be used to identify local scale patterns and variation in recorded rainfall measurements.

CHAPTER 3: MATERIALS AND METHODS

This is a desktop study using satellite derived rainfall measurements extending across the full extent of Botswana. A spatial and temporal analysis has been carried out to investigate rainfall magnitude, variability, frequency, and the duration of rainfall events in Botswana. In addition, a GIS spatial analysis approach, the Anselin Local Moran's I tool was used to determine the persistence of wet and dry conditions in space and time.

3.1 Data sources

TRMM 3B43 real-time monthly rainfall data with a spatial resolution of 0.25 by 0.25 degrees (0.463km x 0.463km), for the period of 1998 to 2013 was downloaded from the NASA Goddard Space Flight Centre website (http://disc.sci.gsfc.nasa.gov/TRMM). The TRMM 3B43 monthly product was particularly good at producing complete spatial coverage of rainfall measurements in Botswana (Figure 5).

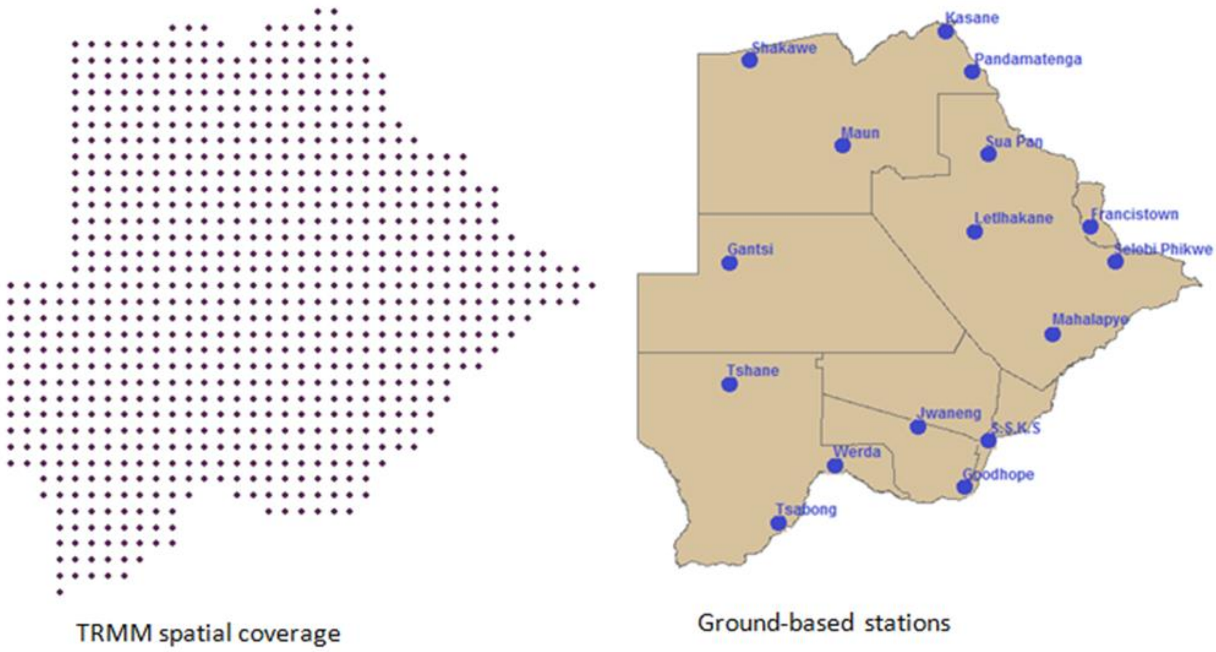


Figure 5: Maps depicting the spatial comparison of TRMM rainfall measurement points and ground-based rainfall points in Botswana (Created by Relotilwe Maboa, 2014).

WorldClim precipitation data was downloaded from the WorldClim website (http://www.WorldClim.org). The WorldClim data layers were generated through the interpolation of average monthly climate data from weather stations on an arc-second resolution grid (i.e. $1km^2$) (Hijmans et al. 2005; http://WorldClim.org/methods). WorldClim data are described as interpolated, since it has been generated based on known historical rainfall data. The data interpolation was initiated using the smoothing spline algorithm from the ANUSPLIN software. The occurrence of errors in the data was considered, and all weather stations were checked to ensure correspondence between the recorded data and mapping (Hijmans et al. 2005). Monthly averages of climate were measured at weather stations from global, regional, national, and local surfaces for the period 1950-2000 (Hijmans et al. 2005). Major climate databases were compiled by the Global Historical Climatology Network (GHCN), the International Centre for Tropical Agriculture and numerous other databases around the world (Hijmans et al. 2005; http://WorldClim.org/methods).

In this report, WorldClim precipitation data are representative of the global long term rainfall average between 1950 and 2000 (50-year period). The spatial extent of the WorldClim precipitation dataset was converted to 0.25 by 0.25 degrees in order to maintain spatial consistency with the TRMM rainfall data. This study used the WorldClim precipitation dataset as a 'long term average rainfall reference', for determining the frequency of rainfall events above and below the long term reference, specific to localities across Botswana.

3.2 Data analysis

TRMM 3B43 monthly data were downloaded as rainfall intensities ($mm.hr^{-1}$), which were converted to millimetres (mm) to obtain rainfall total values. The rainfall totals were further transformed into the relevant rainfall variables for this research. The dataset was then used to determine rainfall magnitude, variability, frequency and spatial clusters of high and low rainfall regions across the time series. The software used to process the data includes ArcGIS 10.2 (Esri, 2014) and Microsoft Excel 2010.

3.2.1 Magnitude

The purpose of investigating rainfall magnitude is to understand on average, the amount of monthly rainfall falling in Botswana during the analysis period. A total of 180 TRMM 3B43 monthly files were downloaded in Network Common Data Form (Netcdf) format and imported into ArcGIS. The Multi-dimensions tool in ArcGIS was used to convert each Netcdf file into raster format. The global extent of each data output was clipped, using the Clip tool in ArcGIS to represent the Botswana landscape. All 180 clipped monthly raster outputs from 1998 to 2013, were used to calculate *average monthly magnitude rainfall*. The raster calculator tool in ArcGIS was used to calculate the average monthly magnitude rainfall over the 15-year period. Below is the raster calculator expression, using January as an example:

Average Rainfall$_{January}$: $\sum$January$_{1998}$ + January$_{1999}$ + January$_{2000}$ + ………… January$_{2013}$ / 15

Below is a schematic representation of the raster calculator expression used to calculate the average monthly magnitude rainfall between 1998-2013 (Figure 6). January is used as an example below:

∑

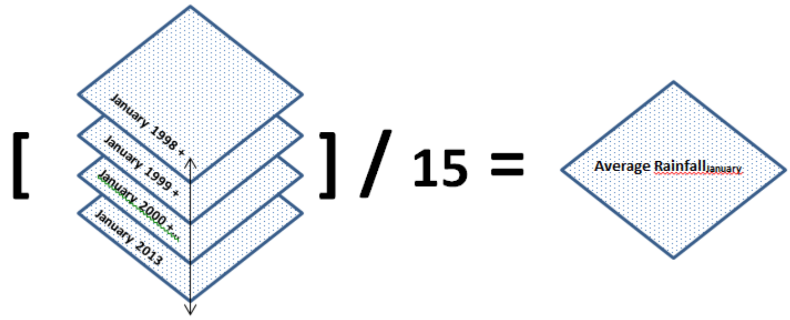


Figure 6: An annotation of the average monthly magnitude rainfall calculation used for this study. The January calculation is used as an example (Created by Relotilwe Maboa, 2014).

3.2.2 Variability:

Rainfall magnitudes in the tropics vary both in space (i.e. within a region) and time (i.e. convective rainfall is episodic in nature). Temporal variability was ascertained by observing regional (pixel) based average monthly magnitudes values across the time series. In this study, *variability* of average monthly magnitudes values across the time series were analysed by calculating the standard deviation for the average monthly magnitudes values across the full 15 years. Standard deviation was determined using the Focal statistics tool in ArcGIS. The standard deviation values provided an assessment for rainfall consistency or inconsistency across the country. Rainfall standard deviation values close to 0mm represented little variability in rainfall magnitudes, and temporally consistent rainfall falling in a specific space, throughout the time series. High standard deviations values represented increased variability in average monthly magnitudes, and temporally inconsistent rainfall falling in a specific space, throughout the time series.

3.2.3 Frequency

The significance of evaluating rainfall frequency is to observe the *frequency* of rainfall events above (measured as peaks) and below (measured as troughs) the long term WorldClim average reference throughout the analysis period. Five rainfall frequency reference points (A-E), along the Botswana rainfall gradient were chosen to determine rainfall frequency (Figure 7). Point A and B represent spatial-temporal rainfall in the northern part (Chobe and Makgadikgadi region) of Botswana, point C represents the central part (Central Kalahari region), and point D and E (Kgalagadi region) represent the southern part. The frequency of the average monthly magnitude rainfall values at point A-E, above and below the long term average was used to determine the rainfall frequency during the 15-year period.

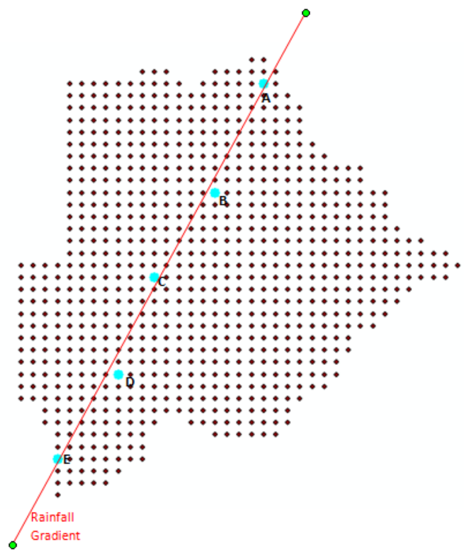


Figure 7: Diagram illustrating the location of the 5 rainfall points (A-E), along Botswana's rainfall gradient, which were chosen for the rainfall frequency analysis. Point A represents the less arid region and point E the more arid region of Botswana (Created by Relotilwe Maboa, 2014).

3.2.4 T-Test

The test investigated the statistical significance of the observed frequency of average monthly magnitude rainfall above and below the long term average reference, for Point A-E respectively. Below is the T-test formula used in this study:

$$t = \frac{X_1 - X_2}{\sqrt{\frac{{S_1}^2}{n_1} + \frac{{S_2}^2}{n_2}}}$$

X_1 = Long term average rainfall

X_2 = Average Monthly magnitudes

S = Standard deviation

n = number of rainfall observations

3.2.5 Spatial analysis

The 180 monthly rainfall total raster maps from 1998 to 2013 were used to perform the spatial analysis of high and low rainfall regions in Botswana. The purpose of the spatial cluster analysis application was to determine the annual spatial persistence of high and low rainfall regions in Botswana. In ArcGIS the Anselin Local Moran's I tool was used to perform the spatial cluster analysis, for each one of the 180 monthly rainfall total raster maps. The tool's output feature class has four main attributes: the Local Moran's I index, z-score, p-value, and cluster/outlier type (COType) fields (Anselin, 1995). This study was interested in the outcome of the COType attribute which indicates features with either, High-High (HH) cluster values or Low-Low (LL) cluster values, as well as spatial outliers. Spatial outliers refer to features that are exceedingly different from the general features. In this study, spatial outliers are indicated by either features with high values surrounded by low value features, which is known as High-Low (HL) or features with low values surrounded by high value features, which is known as Low-High (LH) (Anselin, 1995).

The Reclass tool was used to reclassify outputs from the spatial cluster analysis, as a way of 'classifying clusters' of high and low rainfall in Botswana between 1998-2013. The reclassification included the following: 0 represents insignificant rainfall clusters, 1 represents the LL rainfall clusters, the value 2 represents the LH rainfall clusters, the value 3 represents the HL rainfall clusters, and the value 4 represents HH clusters (Table 1). In ArcGIS insignificant clusters refer to spatial clusters where the p-value is greater than 0.05, and the null hypothesis is rejected. The validity of the reclassification applied here (Table 1) was tested using a transition matrix, where the probability for the persistence of high and low spatial clusters is investigated, throughout the time series, on a year by year basis. The raster calculation expression below was used to determine the annual rainfall clusters, from the monthly cluster outputs. 1998 is used as an example:

$$\textbf{Rainfall Cluster}_{1998} = \sum \textbf{January}_{1998} + \textbf{February}_{1998} + \textbf{March}_{1998} + \ldots\ldots\ldots\ldots \textbf{December}_{1998}$$

The annual rainfall cluster regions were validated using *annual rainfall totals* across the 15-year period'. The annual rainfall totals were calculated according to the following raster calculator expression, using 1998 as an example:

Table1. Reclassification codes used to classify TRMM rainfall clusters during the spatial analysis.

Reclassification	**Raster calculator output (mm)**	**Rainfall cluster**
0	0	Insignificant
1	0>-15	Low rainfall(LL)
2	>15-30	Low-High rainfall (LH)
3	>30-45	High-Low rainfall (HL)
4	>45-60	High rainfall (HH)

$$\textbf{Annual Rainfall Total}_{1998} = \sum \textbf{January}_{1998} + \textbf{February}_{1998} + \textbf{March}_{1998} + \ldots\ldots\ldots\ldots \textbf{December}_{1998}$$

On the whole, the analysis of rainfall magnitudes, variability, frequency and annual spatial cluster provides comprehensive understanding of the rainfall patterns and changes in Botswana.

CHAPTER 4: RESULTS

The analysis of rainfall in Botswana exhibited a rainfall pattern that varied by region, and by season. Figures 8-15 depict the results for the rainfall magnitude, variability, frequency and spatial analysis respectively.

4.1 Magnitude

The average monthly magnitude rainfall results consisted of twelve maps, specific to Botswana, illustrating the amount of rainfall during 1998-2013 (Figure 8). Hereafter, *'rainfall magnitude'* refers to average monthly magnitude rainfall. The pattern of rainfall magnitudes in space and time is described below.

4.1.1 Rainy season: January-March

A spatial difference in rainfall magnitude amounts was evident during the rainy season. January, February and March showed high rainfall magnitudes (96-159mm) in the northern, western and south eastern parts of Botswana (Figure 8). While relatively lower rainfall magnitudes (32-95mm) were evident in the southwest Kgalakgadi region.

4.1.2 Post rainy season: April-August

The persistence of elevated rainfall magnitudes (32-63mm) until April signified the occurrence of late summer rainfall conditions. However, these high rainfall magnitudes were slightly lower than the preceding calendar months (January-March). The Okavango Delta region experienced the highest rainfall magnitudes during this season, with magnitudes on average, up to 10mm higher than surrounding regions. May and June (i.e. seasonally considered the winter months) indicated low rainfall magnitudes (0-32mm) across the landscape, with the exception of the Okavango Delta and south eastern Botswana, which maintained elevated magnitudes (32-63mm). Rainfall magnitudes during July and August were uniformly low (0-31mm) across Botswana, while the Okavango Delta region showed evidence of elevated rainfall magnitudes (32-63mm) during August.

4.1.3 Pre-rainy season: September-October

A gradual increase in rainfall (32-63mm) from western to eastern Botswana was apparent during the September and October months. This increase marked the end of the low rainfall

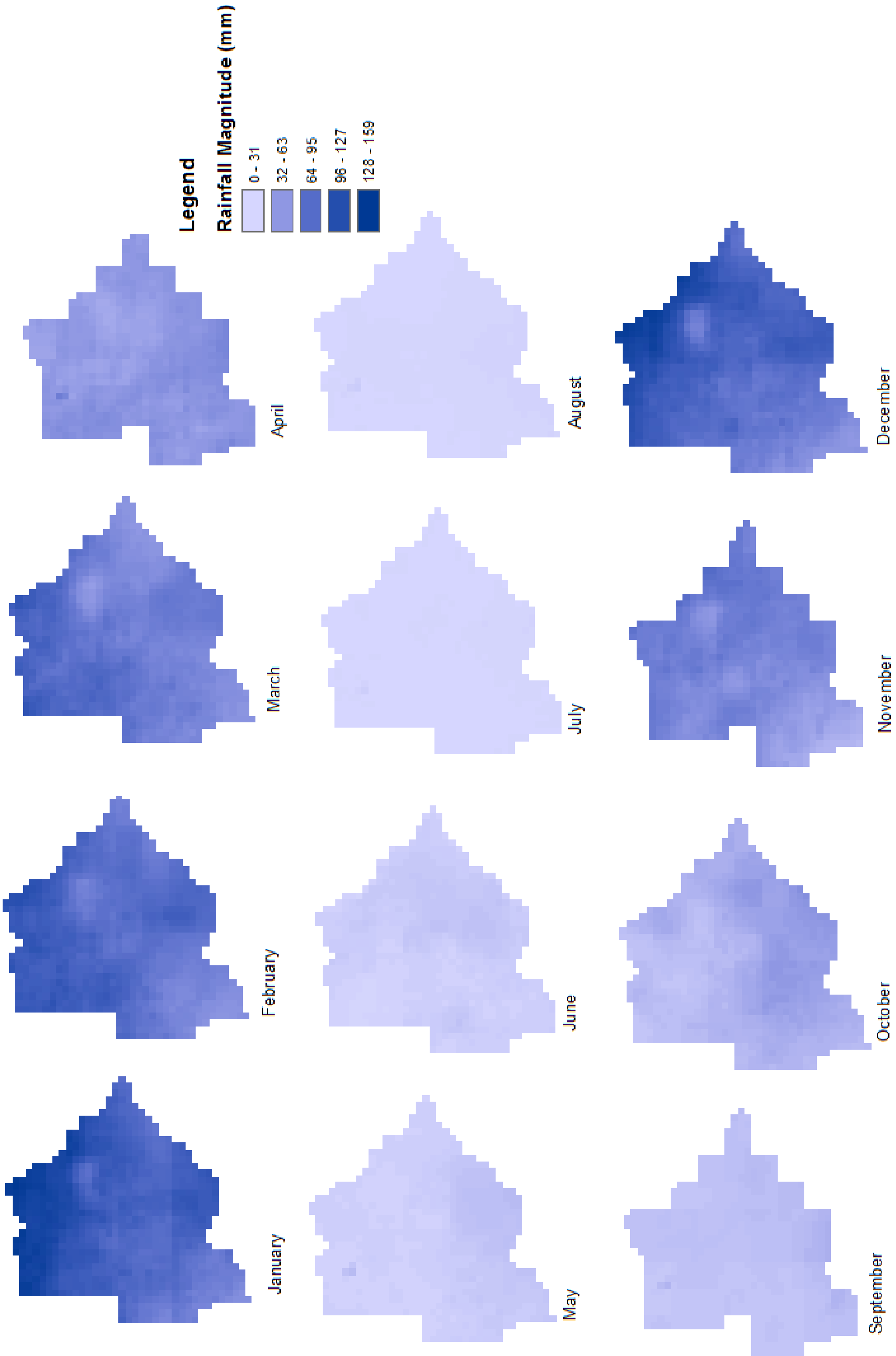


Figure 8: Twelve maps illustrating the average monthly rainfall magnitudes in Botswana from January to December for a period of 15 years (1998-2013) (Created by Relotilwe Maboa, 2015).

season in the north, eastern and south eastern parts of country.

4.1.4 Rainy season: November-December

During November and December northern, central eastern and south eastern Botswana indicated high rainfall magnitudes (96-159mm); while southwestern Botswana indicated relatively lower rainfall (0-63mm). This rainfall trend is similar to rainfall magnitudes during January-March (Figure 7). The Okavango Delta experienced higher rainfall magnitudes (96-127mm) than surrounding region. Surrounding regions like the Makgadikgadi Saltpans experienced relatively lower rainfall magnitudes (96-159mm).

4.2 Rainfall variability

The objective of the rainfall variability analysis was to determine the distribution of the rainfall magnitude in space throughout the time series. The rainfall variability results are illustrated by twelve maps reflecting variability in average monthly rainfall in Botswana, from 1998 to 2013 (Figure 9).

4.2.1 Rainy season: January-March

High rainfall variability (8-19mm) was observed over majority of the Botswana landscape, during January-March. This result coincided with high rainfall magnitudes observed during the same season, months and regions. The highest rainfall variability (16-19mm) was observed in northern, western, eastern and south eastern Botswana.

4.2.2 Post rainy season: April-August

In April low rainfall variability (4-8mm) was experienced in northern, western, eastern and south eastern Botswana. This rainfall variability was relatively lower than rainfall variability experienced during previous months (January-March). The low rainfall variability experienced during April, corresponded with the low rainfall magnitudes observed during the same season, month and regions. The Okavango Delta experienced the highest rainfall variability (8-15mm) in Botswana landscape during this season. A decrease in rainfall variability (0-3mm) was evident across the Botswana landscape during May-August. The Okavango Delta experienced relatively higher rainfall variability (4-7mm) than the rest of the landscape (0-3mm) during May-August.

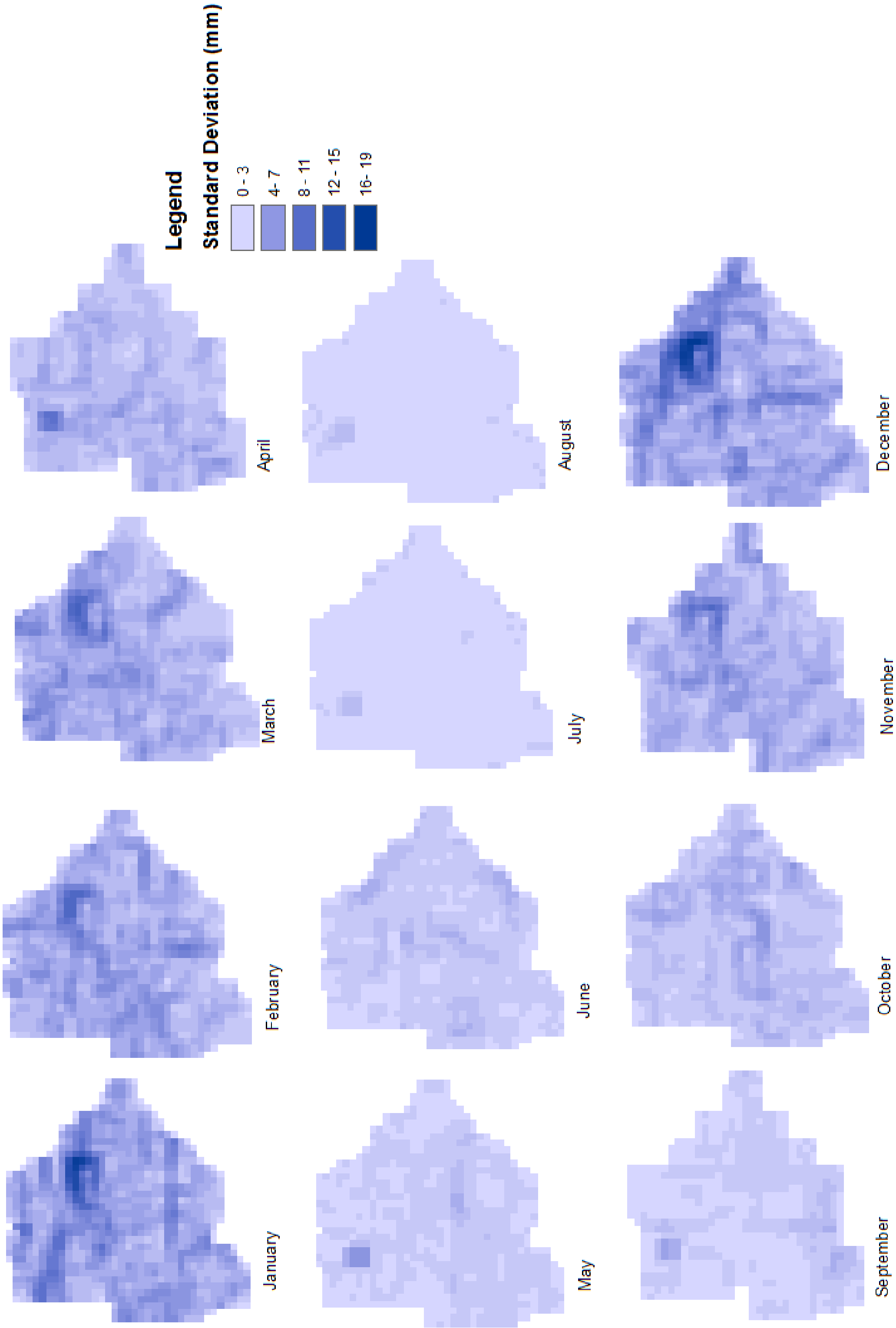


Figure 9: Twelve maps illustrating the rainfall variability in Botswana from January to December for a period of 15 years (1998-2013) (Created by Relotilwe Maboa, 2015).

4.2.3 Pre-rainy season: October-September

An increase in rainfall variability (0-11mm) from western to eastern Botswana was evident in September. This increase coincided with increased rainfall magnitudes observed during the month. In October, an increase in rainfall variability (4-11mm) was evident in eastern, central, south east and western Botswana. This increase corresponded with increased rainfall magnitudes observed during the same during the same time.

4.2.4 Rainy season: November-December

In November, high rainfall variability (8-19mm) in northern, western, eastern and south eastern region of Botswana was observed. Throughout the season, the Okavango Delta experienced higher rainfall (8-19mm) variabilities compared to surrounding regions. Surrounding regions like the Makgadikgadi Saltpans experienced much lower rainfall variability.

4.3 Frequency

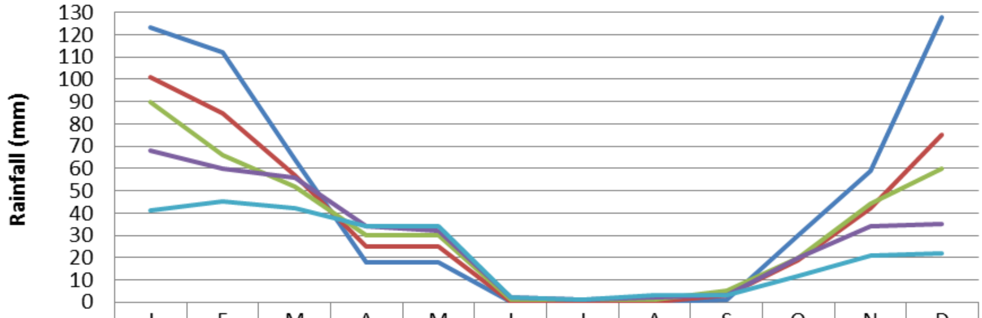
4.3.1 Long term average reference

Long term average rainfall data (1950-2000) were used as a long term average rainfall reference to explore rainfall frequency along Botswana's rainfall gradient, specifically at points A-E (Figure 10). The long term average rainfall dataset was particularly useful for indicating the expected rainfall patterns in Botswana. The long term rainfall dataset exhibited a rainfall trend of the highest rainfall occurrence during the rainy season (November to March), and a gradual decrease in rainfall during the post rainy season (April). A further decrease in rainfall, and a consistent period of low rainfall, was evident between May-August. This was followed by a gradual increase in rainfall during September and October, and an elevated rainfall occurrence between November-December.

4.3.2 Rainfall frequency analysis

4.3.2.1 Rainy season rainfall frequency: January-March

The results (Figure 11) indicated that during the rainy season (January to March) rainfall events at point A were predominantly above the long term average (i.e. more than 50% of rainfall was above the long term average). January showed 11/15 and March 10/15 rainfall events above the long term average. Points B-E indicated rainfall events consistently below



	J	F	M	A	M	J	J	A	S	O	N	D
Point A	123	112	64	18	18	0	0	0	1	30	59	128
Point B	101	85	57	25	25	0	0	0	3	19	42	75
Point C	90	66	52	30	30	1	1	1	5	20	44	60
Point D	68	60	56	34	32	2	1	2	3	20	34	35
Point E	41	45	42	34	34	2	1	3	3	12	21	22

Figure 10: A line graph showing the long term average reference at points A-E in Botswana for a period of years (1950-2000) (Created by Relotilwe Maboa, 2015).

the long term average. At points B and C, both the January and February rainfall events were below the long term reference (8/15 and 9/15). This trend continued at point D and E, with February having shown 11/15 and March 8/15 rainfall events below the long term average. At point E, rainfall was predominantly below the long term average, with February having shown 9/15 and March 10/15 rainfall events. The observation of rainfall events well above the long term average reference at point A, and predominantly below the long term reference at Points B-E is similar to the trend of rainfall along Botswana's rainfall gradient (i.e. spatial 'drying' from northeast towards southwest).

4.3.2.2 Post rainy season rainfall frequency: April-August

During April, rainfall at Point A was predominantly above the long term average, with 8/15 rainfall events above the long term average. At Point B and C, the rainfall frequency was largely below the long term average, with an occurrence of 8/15 rainfall events below the long term average for both points. At Point D and E, the rainfall frequency was largely above the long term average, with 8/15 rainfall events above the long term average at points D and E. The rainfall frequency results during May-August (i.e. the dry rainfall period) indicated that only at Point A were rainfall events above the long term average. At point A June, July and August showed 12/15, 11/15 and 15/15 rainfall events above the long term average. At Point B, rainfall was mostly below the long term average with May, July and August having shown 14/15, 15 /15 and 11/15 rainfall events below the long term average.

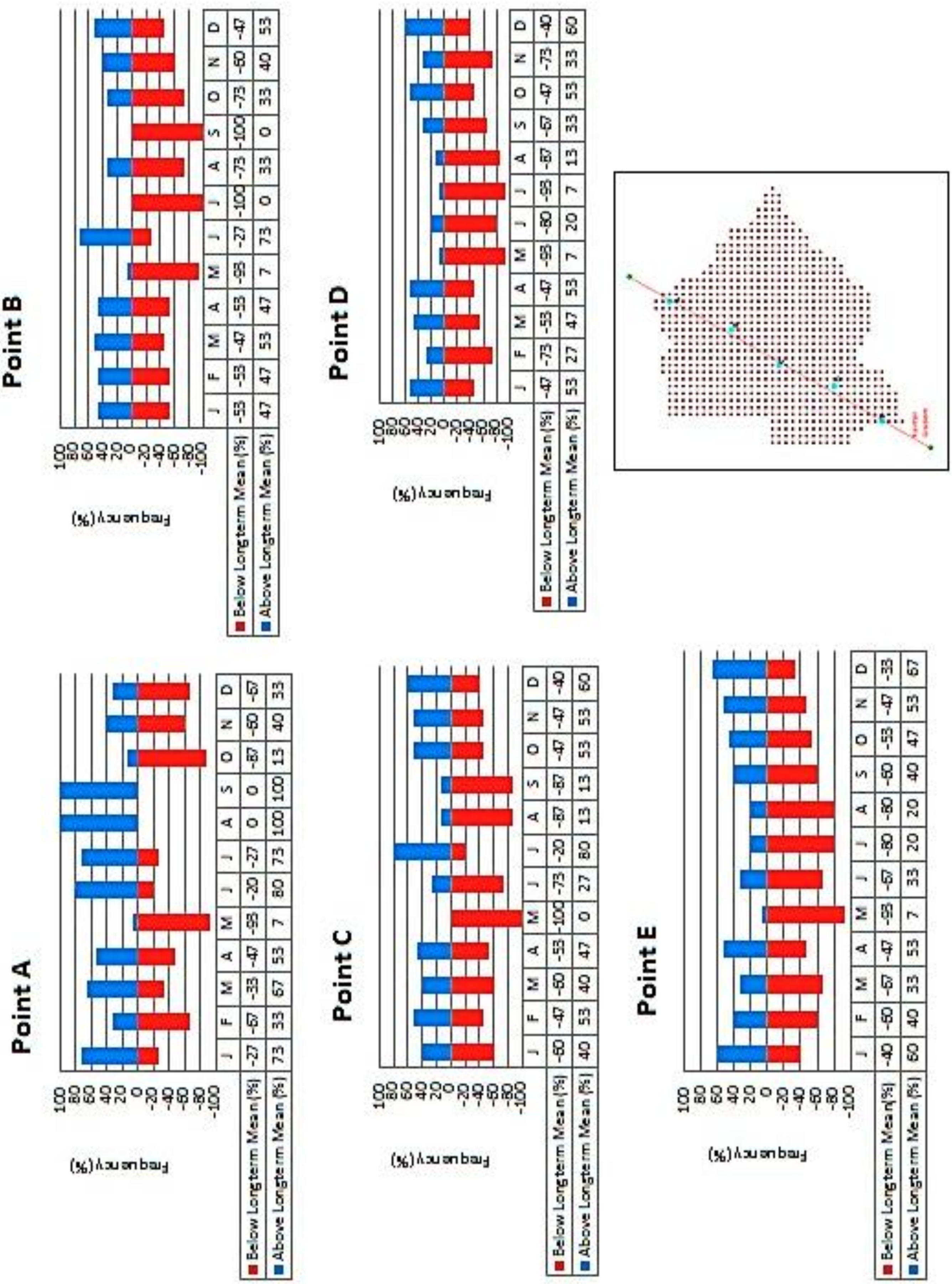


Figure 11: Bar graphs showing the frequency of average monthly magnitude rainfall above and below the long term average rainfall reference, at spatial location points A-E in Botswana, for a period of 15 years (1998-2013) (Created by Relotilwe Maboa, 2015).

At Point C, rainfall was mostly below the long term average with May, June and August showing 15/15, 11/15 and 13/15 rainfall events below the long term average. At Point D, rainfall was mostly below the long term average with May, June, July and August having shown 14/15, 12/15, 14/15 and13/15 rainfall events below the long term average. At Point E, rainfall frequency was mostly below the long term average with May, June, July and August having shown 14/15, 10/15, 12/15 and 12/15 rainfall events below the long term average.

4.3.2.3 Pre-rainy season rainfall frequency: September-October

October signified an exception to Point A's expected rainfall trend of being above the long term average regardless of the season. October showed more than 50% of rainfall events below the long term average (13/15). September showed 100% (15/15) of rainfall events above long term average in September. At Point B, rainfall remained below the long term average during both September (15/15) and October (11/15), yet at Point C rainfall events in October (8/15) were above the long term average. At Point D, rainfall events September were below the long term average across the 15-year analysis period (10/15), and in October more than 8/15 rainfall events were above the long term average. Rainfall events at Point E, remained below the long term average during both September and October, having shown 9/15 and 8/15 rainfall events below the long term average.

4.3.2.4 Rainy season rainfall frequency: November-December

At Point A, November and December showed 9/15 and 10/15 rainfall events below the long term average. At both points B and D, rainfall events were largely below the long term average in November (9/15 and 11/15), while largely above the long term average in December (8/15 and 9/15). At both Point C and E, rainfall events were largely above the long term average for both November (8/15 and 8/15) and December (9/15 and 10/15).

4.3.3 Comparison of rainfall magnitude and long term average rainfall

The t-test results for the comparison of rainfall magnitudes (i.e. average monthly magnitude rainfall) and long term average rainfall (Table 2), specifically at points A- E, indicated that there is no significant difference (i.e. $p>0.05$). Thus, there is no significant difference between the observed rainfall (1998-2013), and the long term average rainfall (1950-2000).

Table 2: T-test results indicating the difference between the TRMM average monthly magnitude rainfall and long term average rainfall, for rainfall points A- E.

Statistics variable	Point A	Point B	Point C	Point D	Point E
Degrees of freedom (df)	22	22	22	22	22
t-value	0.1054	-0.474	0.1809	1.0000	0.3089
P-value	0.9170	0.6400	0.8580	0.3282	0.76.02

4.4 Spatial analysis

The spatial analysis results consisted of 15 maps, for each year in the analysis period, depicting the occurrence and persistence of high and low rainfall clusters in Botswana (Figure 12). In addition, the isolated clusters of HH (i.e. a high rainfall surrounded by a high rainfall region) and LL (a low rainfall surrounded by a low rainfall regions) rainfall are exhibited in Figures 13 and 14, for visualisation purposes. This spatial analysis of rainfall clusters provided an indication of annual variability of rainfall in Botswana (as opposed to the monthly rainfall variability analysis investigated earlier).

4.4.1 Annual rainfall cluster persistence

The rainfall clusters maps in Figure 13 and 14 were used to calculate the percentage persistence of high and low rainfall clusters across Botswana, between 1998-2013 (Table 3).

4.4.1.1 Northern Botswana

The spatial analysis results (Figure 12) showed that, on an annual basis, majority of northern Botswana experienced insignificant rainfall clusters. However, the Okavango Delta and Chobe National Park region showed evidence of HH rainfall clusters. Northern Botswana showed 100% persistence for HH rainfall clusters occurring annually, throughout the analysis period (Table 3). In contrast, there was zero evidence of LL rainfall clusters occurring annually, across the time series.

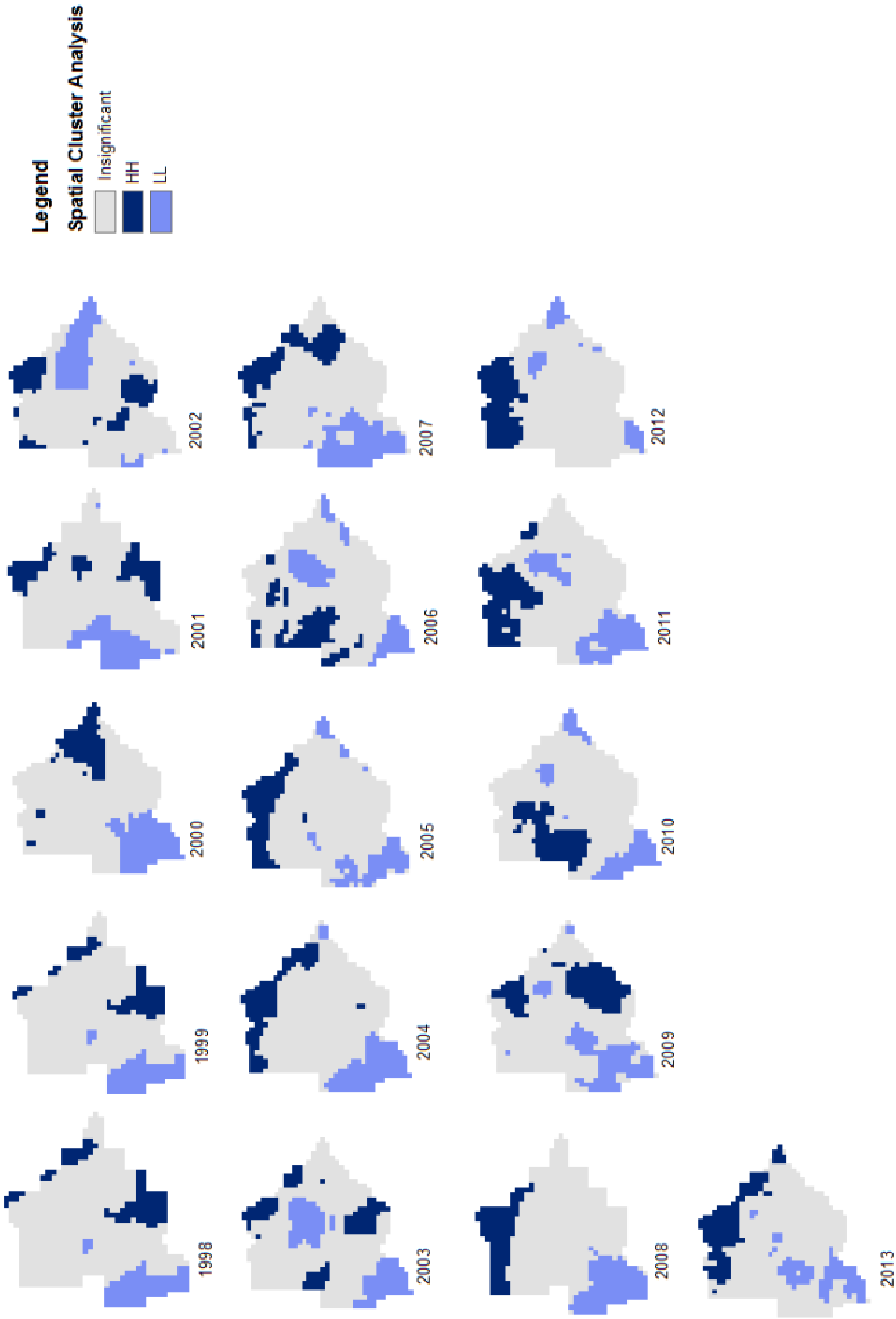


Figure 12: Maps showing annual rainfall clusters between 1998 to 2013 (Created by Relotilwe Maboa, 2015).

Table 3: Percentage persistence of high and low rainfall clusters across the Botswana landscape.

Spatial Region	**Rainfall cluster**			
	HH		**LL**	
	Number of years	**Percentage persistence (%)**	**Number of years**	**Percentage persistence (%)**
Northern Botswana	15	100	0	0
Central Botswana	6	40	9	60
Eastern Botswana	8	53.3	7	46.7
South eastern Botswana	7	46.6	3	20
Southwestern	0	0	15	100

4.4.1.2 Central Botswana

Central Botswana (Central Kalahari region) demonstrated HH rainfall clusters during 2001-2003, 2005, 2006 and 2010. The LL rainfall clusters were prevalent during the more recent analysis years namely, 1998-2006, 2009, 2011 and 2013. Central Botswana indicated a persistence of 40% HH and LL 60% rainfall clusters (Table 3). At the beginning of the time series (1998-2003) central Botswana experienced predominantly high rainfall clusters, while predominantly low rainfall clusters towards the end (2009-2013). This result was suggestive of a progressive drying across the analysis period.

4.4.1.3 Eastern Botswana

Eastern Botswana (Francistown region) demonstrated HH rainfall clusters during 1998-2000, 2003, 2004, 2007, 2009, 2011 and 2013. The LL rainfall clusters were evident during 2001-2006, 2009, 2010 and 2012. Here a similar drying trend to central Botswana was observed in eastern Botswana, where the beginning of the time series experienced predominantly high rainfall clusters, and low rainfall clusters towards the end. This indicated a drying trend across the analysis. Eastern Botswana depicted the persistence of 53.3 % HH and LL 46.7% rainfall cluster throughout the analysis period (Table 3).

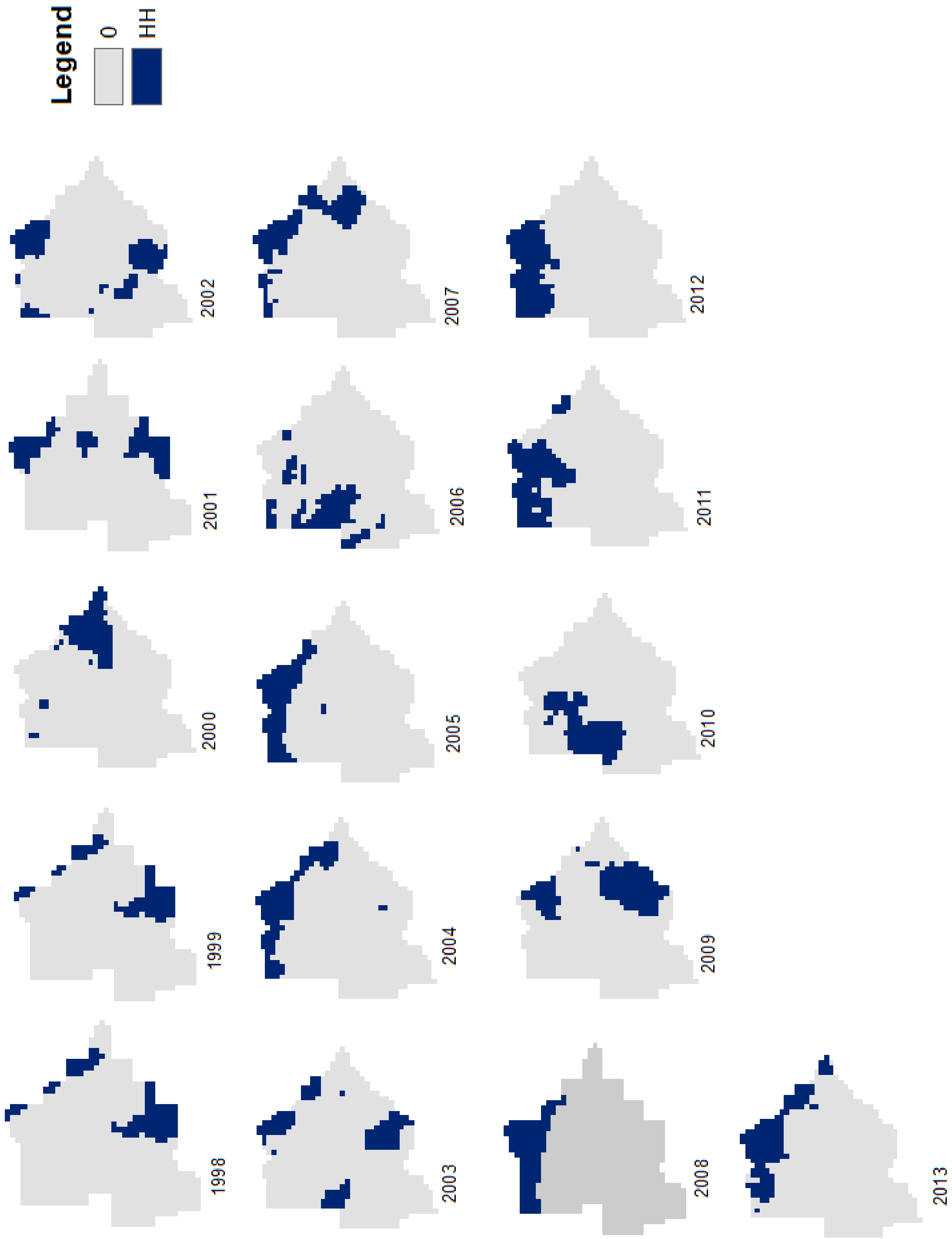


Figure 13: Map showing annual HH rainfall clusters between 1998-2013 (Created by Relotilwe Maboa, 2015).

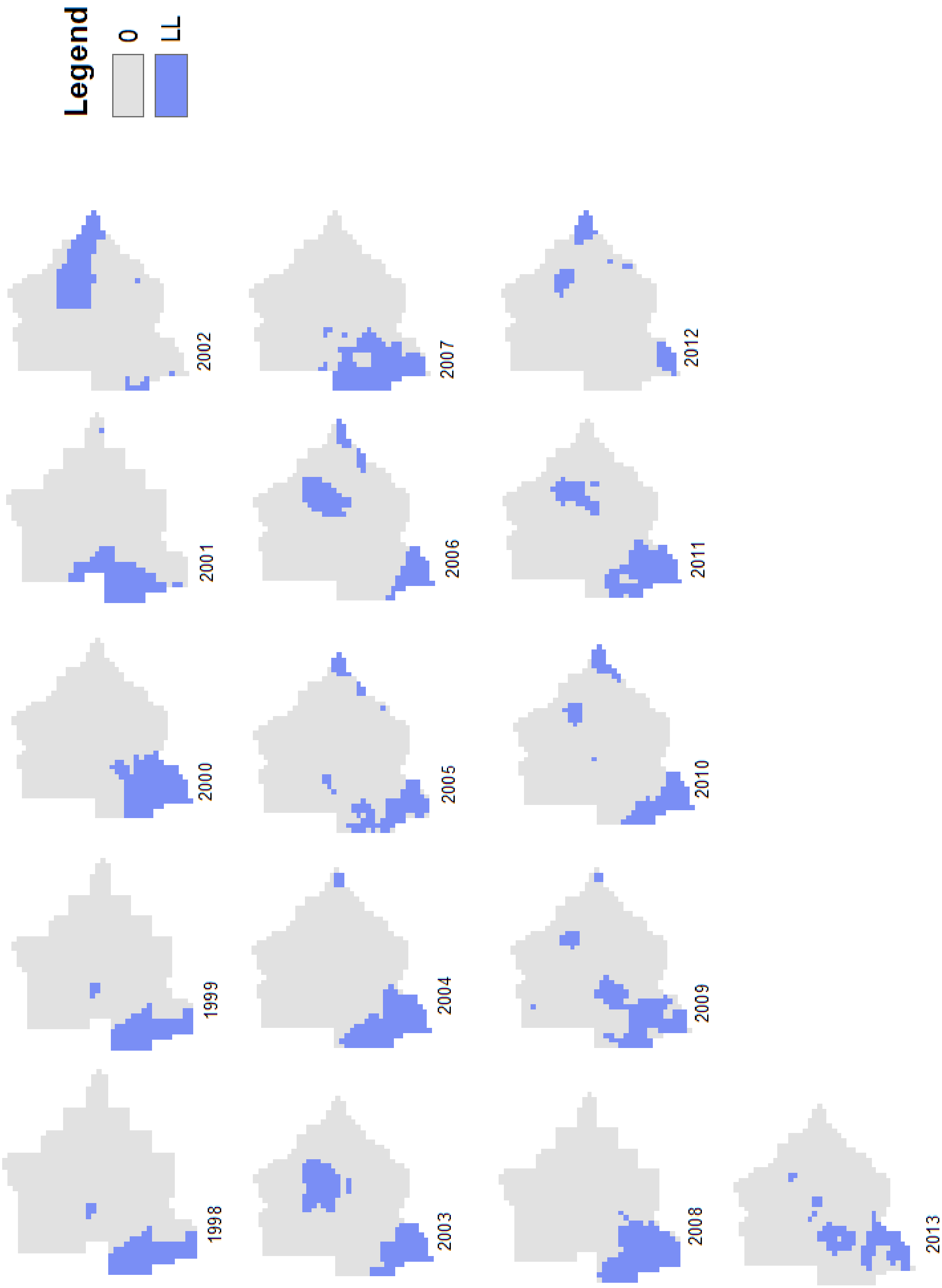


Figure 14: Map showing annual LL rainfall clusters between 1998 to 2013 (Created by Relotilwe Maboa, 2015).

4.4.1.4 South eastern Botswana

South eastern Botswana (Gaborone and Lobatse) showed HH rainfall clusters during 1998-2004 and 2009. The LL rainfall clusters were evident during 2002, 2005 and 2012. A similar drying trend to central and Botswana was observed in south eastern, which was suggestive of a drying trend across the analysis period. The HH rainfall clusters persisted for 46.6% of the analysis period, while LL rainfall clusters persisted 20% (Table 3). The remainder of the rainfall clusters were insignificant for 33.4% of the analysis period, indicating where and when (2000, 2006-2008, 2010-2011 and 2013), there was a low level of confidence for rainfall cluster classification.

4.4.1.5 Southwestern Botswana

Southwestern Botswana, typically considered the driest region, showed zero evidence of HH rainfall clusters, occurring annually, throughout the time series. Southwestern Botswana demonstrated 100% persistence for LL rainfall clusters, occurring annually, between 1998-2013 (Table 3). This result agreed with the expected rainfall conditions along Botswana's rainfall gradient (i.e. the lowest rainfall conditions are experienced in southwest Botswana) (Figure 7).

4.4.2 Annual rainfall totals

The annual rainfall totals values between 1998-2013 are depicted by 15 maps, specific to Botswana (Figure 15). It is evident that across the 15-year analysis the annual rainfall totals ranged between 0-1025mm, which corresponds with the annual rainfall totals observed both in the rainfall literature and historical rainfall records for Botswana (Regenmortel, 1995; Veenendaal, 1996). The annual rainfall totals were used validate the occurrence of high and low rainfall clusters across Botswana. These annual rainfall totals agreed with the observed regions of high and low rainfall clusters, during this rainfall analysis.

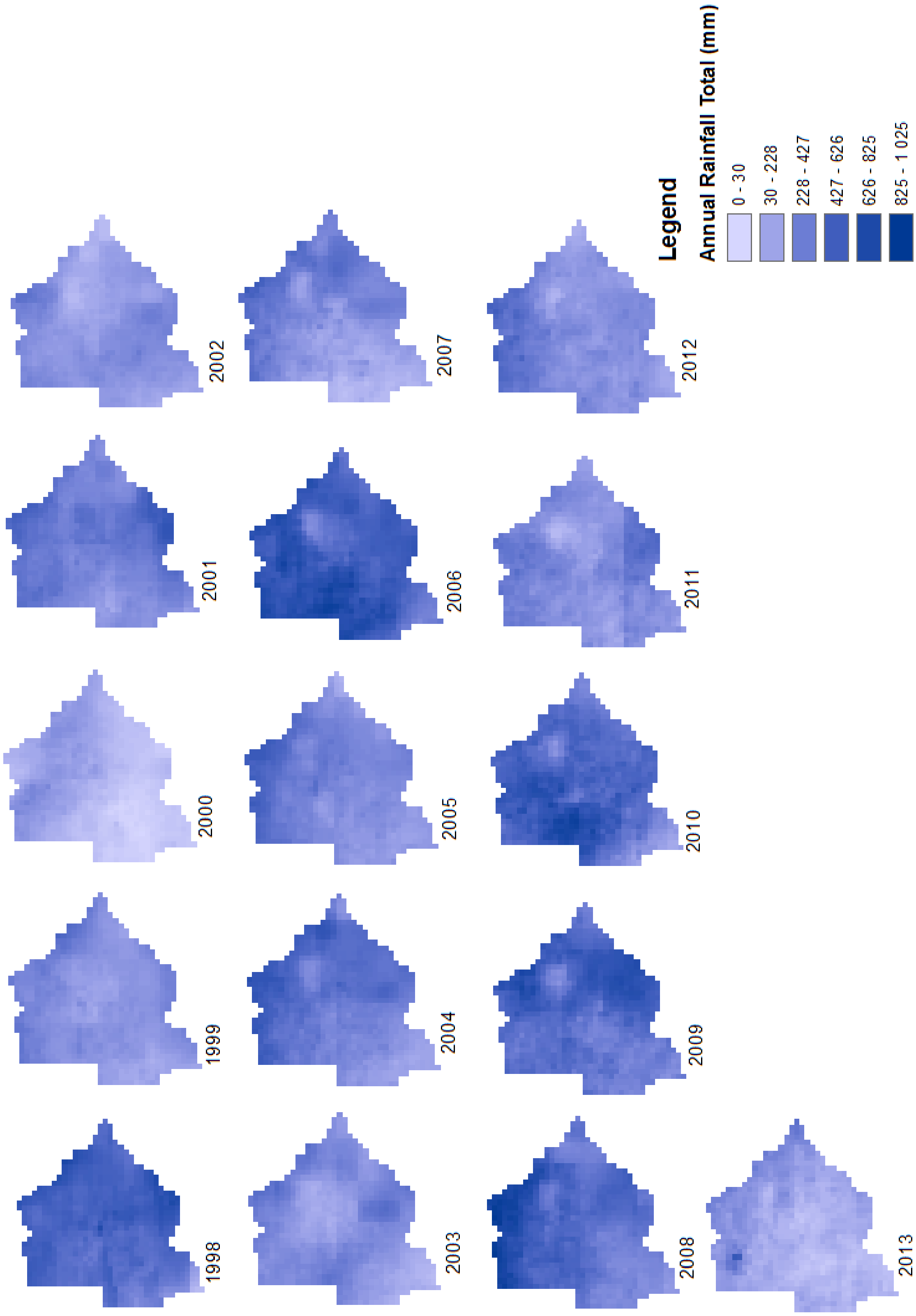


Figure 15: Annual rainfall totals measurements between 1998 to 2013 (Created by Relotilwe Maboa, 2016).

CHAPTER 5: DISCUSSION

Rainfall is a complex subject matter that is most understood by analysing patterns of rainfall in space and time. Semi-arid regions have spatially complex and seasonal rainfall patterns, which contribute towards the nature of climate conditions across semi-arid landscapes Veenendaal, 1996; Batisani and Yarnal, 2010).

5.1 The general rainfall pattern and observed changes

This study has obtained a better understanding of the spatial and temporal rainfall patterns in Botswana. The use of satellite imagery provided a unique analysis approach, and as a result has produced highly detailed rainfall information for conservation authorities in Botswana.

Magnitude: The highest rainfall magnitudes (96-59mm) occurred in the northern, western and south eastern parts of Botswana during the rainy season (January-March and November-December) (Figure 8). These high rainfall magnitude events were likely to promote relatively wet conditions conducive for increased vegetation growth and surface water. The lowest rainfall magnitudes (0-32mm) occurred across majority of Botswana, during May and June (i.e. post rainy season). These low rainfall magnitude events were likely to promote relatively dry conditions, decreased vegetation growth and surface water during May and June. The Okavango Delta remained a region of relatively higher magnitude (32-159mm) compared to surrounding regions throughout the time series. This marks the Okavango Delta region as a spatially reliable location for surface water and vegetation growth, at any point in time (1998-2013). A deviation from the expected rainfall pattern was observed in April where elevated rainfall magnitudes, typical of the rainy season, extended to April throughout the time series. This indicated the occurrence of high rainfall events (i.e. late summer rainfall) until April and an extended period for relatively wet conditions, throughout the analysis period.

Variability: The highest rainfall variability (8-19mm) occurred in the northern, western and south eastern parts of Botswana, during the rainy season (January-March and November-December) (Figure 9). This high rainfall variability is indicative of the most temporally inconsistent rainfall events distributed variably across Botswana. The lowest rainfall variability (0-3mm) occurred across most of the Botswana landscape during May-August (post rainy season). This observation of low rainfall variability is indicative of less temporally inconsistent rainfall events distributed across Botswana.

The increased magnitudes corresponded with increased variability, spatially and temporally. The rainy season (i.e. January-March and November-December) consisted of relatively high rainfall magnitudes and variability; high rainfall magnitude events were inconsistently distributed across Botswana throughout the analysis period. In contrast, the post rainy (May-August) season consisted of relatively lower magnitudes and variability. Low rainfall magnitude events were less inconsistently distributed across Botswana, spatially and temporally. It must be noted that the observed trend of increased magnitudes corresponding with increased variability is not due to a general association of increased magnitudes with increased variability. Rather, it is because of the nature of the rainfall in Botswana, which is strongly seasonal, convective and episodic (i.e. variable timing of rainfall events) in nature. Thus rainfall, particularly during the rainy season, is unlikely to fall consistently in the same place or in same amounts, through time.

Rainfall frequency: The rainy season had a high frequency of rainfall events above the average long term rainfall reference (along rainfall gradient), meaning relatively wetter conditions, than the years preceding this study, were experienced across Botswana. According to the results, Point A was the known ‘wettest’ area in Botswana during the rainfall analysis period. This trend continues until a change in season emerges, with point A remaining wetter than historically documented. The post rainy season consisted of a high frequency of rainfall events below the long term average rainfall reference (along rainfall gradient), suggesting that relatively drier conditions, than the years preceding this study, were experienced across Botswana. Points B-E was consistently drier than previously observed in the post rainy season. The observation of these spatially wetter and drier conditions than the long term average rainfall suggests the steepening slope of the rainfall gradient (Figure 7) in Botswana. This may be an environmental indicator for a changing climate in Botswana. While differences between the rainfall magnitudes (i.e. average monthly rainfall magnitudes) (1998-2013) and the long term average (1950-2000) rainfall exist, statistically there is no significant difference between these rainfall aspects (Table 2).

Spatial analysis: The 100% persistence of annually high rainfall events in northern Botswana means relatively wet conditions persisted in this region, throughout the analysis period. The 100% persistence of annual low rainfall events towards southern Botswana, means relatively dry conditions persisted in southern Botswana, throughout the analysis period. Similar to the rainfall gradient (Figure 7), the persistence of annual, high rainfall events decreased from northeast to southwest. This suggests the likely occurrence of decreasing surface water and vegetation conditions (i.e. if one assumes all rainfall collects as surface flow), from northeast to southwest throughout the analysis period. In addition, it was observed that from central Botswana towards southwestern Botswana high rainfall clusters persist at beginning of the time series (1998-2003), while low rainfall clusters persist towards the end of the time series (2009-2013). This observation is suggestive of a progressive drying across the analysis period. This detected progressive drying trend, indicates relatively increasing drying conditions across the time series, spatially and temporally. This observation may be another environmental indicator for a changing climate in Botswana.

5.2 Rainfall pattern implications

This study found that the observed rainfall patterns largely agree with rainfall literature for Botswana. It is understood that November-March marks the rainy season, April-May is the post rainy season, and September-October is the pre-rainy season. The variability of rainfall patterns by season and region is likely to have had consequences for the climate conditions in Botswana, during the analysis period.

5.2.1 Magnitude and variability

The high rainfall magnitudes and variability during the rainy season (January-March) are suggestive of inconsistent wet conditions during this season. A decrease in rainfall magnitudes and variability during the post rainy season (April-August) indicates less inconsistent, but relatively dry conditions during this season. The rainfall literature supports this finding indicating that rainfall events in Botswana are seasonal, unevenly distributed and prone to drought conditions (Reason et al. 2004).

As discussed in the literature review, the seasonal rainfall patterns over southern African are attributed to the ITCZ phenomenon (Tyson and Crimp, 1998; Reason et al. 2004; Chikoore and Jury, 2010; Collier and Hughes, 2011). Thus, seasonally variable rainfall events observed during this study can be attributed to the ITCZ. The ITCZ causes enhanced convective conditions that are episodic in nature, contributing to the observed variability results (Tyson and Crimp, 1998; Zhou et al. 2005; Collier and Hughes, 2011; Blamely and Reason, 2012).

The ITCZ typically moves south during November-March resulting in intense convective rainfall, cumulus and cumulonimbus clouds, and wet conditions over southern Africa (Collier and Hughes, 2011). This suggests that the rainfall events observed during the rainy season, consisted of intense convective rainfall events (i.e. thunderstorms), and spatially inconsistent wet conditions across Botswana. When the ITCZ moves north during May-October a strong high pressure system is evident over southern Africa. This results in subsidence, minimum cloud cover, little or no rainfall and dry conditions over southern Africa (Tyson and Crimp, 1998; Chikoore and Jury, 2010). Movement of the ITCZ towards the north is likely responsible for the low rainfall variability observed during the post rainy season.

5.2.2 Rainfall frequency

Given the rainfall gradient in Botswana (Figure 7), relatively wet conditions were anticipated in the northern parts of Botswana, and dry conditions in the southern parts. The rainfall frequency results showed that rainfall events during the rainy season (January-March) were predominantly above the long term average rainfall reference, suggesting relatively wetter conditions than in years preceding this study. Rainfall events during the post rainy season (April-August) were predominantly above the long term average rainfall reference, suggesting relatively drier conditions than in years preceding this study. The observation of these spatially wetter and drier conditions compared to the long term average rainfall, suggests the steepening slope of the rainfall gradient in Botswana. This may be considered an environmental indicator for a changing climate in Botswana.

During 2008, flooding activity prompted by a high frequency of rainfall events in Botswana, resulted in the continuous flow of water into the Savuti Channel, the Boteti River, and the Makgadikgadi pans. The point of interest is that these water resources (Savuti Channel and Boteti River) do not typically flow throughout the year (McCarthy et al. 2003). This suggested an elevated frequency of rainfall events in 2008, compared to previous years. The flooding during 2008 may be related to the observation of a larger spatial extent of HH rainfall clusters across northern Botswana, during this year. This particular extent was spatially larger than the previous (i.e. 2006 and 2007) and subsequent (i.e. 2009-2010) years. The flooding may also be attributed to the observation of high frequency values for months July to September, at point A. This suggests relatively wetter conditions, than historically documented in the literature, were experienced during this analysis period. Similar flooding conditions may have been apparent during 2004-2005 and 2011-2012, due to the observation of i) the larger spatial extent of HH rainfall clusters across northern, and ii) high frequency values for months July to September at point A. McCarthy et al. (2003) conducted a study on flooding patterns in the Okavango Delta Wetland in Botswana, which explains that flooding is influenced by the frequency of rainfall events in time and space. The Okavango Delta is one of Africa’s largest wetlands, and the floodplain forms a gentle slope in the shape an alluvial fan. It takes flood waters approximately four months to reach the southern part of the delta, and peak flooding is known to occur in the month of July or August, well after the rainy season (McCarthy et al. 2003; McCarthy, 2006). These flood waters ultimately discharge into the Thamalakane River which flows along the scarp of the Delta, discharging into the Boteti River (McCarthy et al. 2003; McCarthy, 2006).

The literature also indicates that flooding in Botswana is known to be influenced by the arrival of flood waters from the Angolan Highlands. After 3-4 months of leaving the Angolan Highlands, the flood waters arrive (i.e. August-September) at the Okavango Delta (McCarthy et al. 2003). This may explain the availability of water and greener vegetation at the Okavango Delta during the dry season. The velocity of the flood water is contingent on factors such as the quantity of the local rainfall, and water table height when the flood water arrives. Therefore, it is understood that a large component of flooding and water availability in northern Botswana is to a large extent affected by precipitation originating from beyond Botswana’s borders, i.e. rainfall events in the Angolan Highlands.

5.2.3 Spatial analysis

It is clear from the spatial cluster analysis that annual rainfall events were spatially and temporally variable from year-to-year. Northern Botswana experienced the persistence of HH rainfall clusters throughout the rainfall season, while southern Botswana experienced the persistence of LL rainfall clusters. The literature indicates that ENSO has an effect on annual and regional rainfall patterns in southern Africa and may account for rainfall variability during certain years (Tyson and Crimp, 1998; Reason et al. 2004; Reason et al. 2006). Thus, the observed progressive drying trend could be attributed to ENSO. Richard et al. (2000) conducted a study investigating the modification of southern African rainfall variability by ENSO, which is related to the emergence of dry climate conditions to ENSO. According to Nicholson et al. (2001), ENSO events have the capacity to strongly influence rainfall patterns, in relation to rainfall magnitude, timing and duration, ultimately causing variable rainfall events.

5.2.4 Climate change signals

This study has detected two environmental indicators which may be indicative of a changing climate in Botswana. Due to the length of the analysis period it cannot be proven conclusively whether the observation of relatively wetter and drier conditions during this analysis; as well as the observed progressive drying trend across the time series, is indeed indicative of a changing climate in Botswana. However, this drying trend supports the climate projections of a decrease in rainfall events and increased rainfall variability in future (Batisani and Yarnal, 2010; Conway et al. 2015). Whether this drying trend will continue beyond this 15-year analysis period, is uncertain. Regenmortel (1995) conducted a study on the regionalisation of Botswana rainfall, which found that rainfall events in Botswana are spatially variable, and convectional in nature, and even in good rainfall years certain parts of the country experience below normal rainfall events. Thus, an extended rainfall analysis period is required to determine whether this drying trend is indicative of a changing climate in Botswana.

5.2.5 Conservation in Botswana

This study fits into a bigger research project that is focused on herbivore conservation in Botswana. Rainfall is known to have a direct influence on water, vegetation, and food resources throughout Africa, as well as an indirect influence on herbivore movement.

5.2.5.1 Surface water and vegetation resources

The seasonal nature of rainfall events in Botswana results in a variable quality of surface water and vegetation resources, between seasons (Brooks and Harris, 2008). It is clear from the analysis that rainfall in Botswana varies by season and by region. The rainy season (November-March) consisted of relatively wetter conditions than historically documented, which may have been conducive to an increased quantity of surface water and vegetation resources in Botswana, during this season. Beyond the rainy season, a relative decrease in wet conditions was evident. The post rainy (April-August) season consisted of relatively drier conditions, than historically documented, which may have been conducive to a decreased quantity of surface water and vegetation resources during this season. According to Mwafulirwa (1999), understanding rainfall variability and predictability is important for surface water, vegetation and wildlife conservation management in southern Africa. Given that the objective of this study was to provide an analysis of recent spatial and temporal rainfall patterns in Botswana, the observed trends can be used to predict the occurrence of surface water, vegetation, and also indirectly, predict conditions likely to promote herbivore movement in Botswana.

From a vegetation cover perspective, the occurrence of vegetation cover in Botswana is based on the rainfall gradient (Figure 7), which produces dense vegetation cover in the northeast and less dense vegetation cover towards the southwest (Figure 3) (Nicholson and Fairar, 1994; Weare and Yalala, 2009; Chikoore and Jury, 2010). This study has exhibited evidence of relatively seasonally wetter and drier conditions than historically documented. This suggests the occurrence of denser or less dense vegetation in Botswana, than the years preceding this study, between seasons. The extension of rainy season conditions to April throughout the time series suggests dense and or denser vegetation conditions, occurring until April (i.e. later than previously expected). Similarly, the drying trend towards the end of the time series may have implications for vegetation, like a progressive trend of decreasing vegetation quality and quantity in Botswana in future.

5.2.5.2 Animal movement and conservation

The literature indicates that animal movement is usually prompted by the need for an environment that is conducive for survival (i.e. being in close proximity to surface water and vegetation resources) (Cushman et al. 2005; Owen-Smith et al. 2010). Regions of permanent surface water are known to be home to large amounts of wildlife (Child, 1970; Campbell, 1973). Northern and Central Botswana are considered the natural habitats for surface water loving species such as hippopotamus *(Hippopotamus amphibious)*, crocodile *(Crocodylus niloticus)*, elephants *(Loxodonta Africana)* and wildebeest *(Connochaetes taurinus)*. The Okavango delta in Botswana is a permanent surface water point for wildlife throughout the year (Child, 1970). Southwest Botswana is home to species which survive with little access to surface water such as gemsbok *(Oryx gazelle)* and springbok *(Antidorcas marsupialis)* (Campbell, 1973; Cushman et al. 2005).

The observations of relatively wetter conditions than historically documented during the rainy season, suggests that animals were likely exposed to sufficient surface water and vegetation resources. The consequences of these wetter conditions may be increased forage quantity and a longer period of forage persistence, compared to preceding years. In turn, these conditions could have prompted a delay or reduction in animal movement, which may be a change from the expected animal movement during the rainy season. In contrast, the relatively drier conditions than historically documented during the post rainy season, suggest that animals were exposed to relatively less surface water and vegetation resources, compared to the rainy season. The consequences of these drier conditions may be decreased forage quantity and a shorter period of forage persistence, compared to the years preceding this study. In turn these conditions could have prompted increased and or earlier animal movement than expected, due to the animals need for suitable forage resources given the drier conditions. Furthermore, based on the rainfall trends observed during this study, it may be predicted that water and or plant dependent animals are likely to migrate towards northern Botswana during dry seasons (i.e. post rainy season).

The extension of rainy season conditions to April means that the period of relatively wet conditions was extended. The consequence of an extended period of wet conditions is that forage may have lasted longer, beyond the typical rainy season. In turn, this may have prompted a change from the expected animal migration during April, i.e. a delay in animal movement until the emergence of drier conditions in the following month (i.e. May). In addition, the progressive drying trend may result in a change in the availability of forage and water resources, as well as a progressive decrease in forage quantity and surface water resources through time. This may prompt increased and or earlier animal migration than expected, between seasons.

This study has conducted a comprehensive rainfall analysis for the full extent of Botswana, providing valuable information for conservation authorities. Conservation authorities, prior to this study, had developed national parks and reserves areas (Figure 4) for protecting wildlife in the country. The Botswanan Government recognises the value of wildlife and its contribution to the national economy, and thus it is committed to ensuring that wildlife is adequately managed (Child, 1970; Mwafulirwa, 1999). Wildlife management in Botswana includes maintenance of the national parks and game reserves, as well as controlling and improving recreational hunting activities and facilities (Child, 1970). An important component of conservation and management of wildlife is ensuring that surface water resources are available for water dependent animals, and vegetation resources available for plant dependent animals.

The progressive drying trend detected during this analysis could create a challenge for conservation authorities in Botswana, due to the associated reduction in surface water and vegetation resources. This finding requires the attention of conservation authorities in order for them to establish a comprehensive response plan or strategy that would help sustain current conservation priorities in the country. Updated conservation or animal migration plans and strategies may be required in Botswana. These improved plans would help ensure that given the expected drying trend, the national parks and game reserves fencing does not hinder or prevent access to surface water and vegetation resources. A lack of adequate conservation planning against this drying trend could result in wildlife deaths from dehydration and starvation (Mbaiwa and Mbaiwa, 2006). However, there is uncertainty, whether this drying trend will continue beyond this 15-year analysis period.

CHAPTER 6: CONCLUSION

Rainfall in Botswana is notably variable by season and by region, and is a contributing factor to surface water and vegetation availability. This study has documented and described rainfall patterns in Botswana from 1998 to 2013, using TRMM satellite data. The analysis revealed that spatial and temporal rainfall patterns in Botswana, in recent years, are similar to the literature. However, there are notable shifts observed in the 15-year analysis period.

6.1 Summary

In summary, the highest rainfall magnitudes occurred in northern Botswana, during the rainy season. While the lowest rainfall magnitudes occurred in southern Botswana, during the post rainy season. High rainfall magnitudes corresponded with high rainfall variability, indicating regions of inconsistent rainfall events distributed variably. Low rainfall magnitudes corresponded with low rainfall variability, indicating regions of less inconsistent rainfall events. The occurrence and persistence of rainy season conditions (i.e. elevated rainfall magnitudes and variability) until April is a change from the expected rainfall pattern, which indicated an extended period of wet conditions. In terms of rainfall frequency, rainfall during the rainy season consisted of a high frequency of rainfall events above the long term average rainfall reference. This indicated relatively wetter conditions, than in the years preceding this study, during the rainy season. In contrast, the post rainy season consisted of a high frequency of rainfall events below the long term average rainfall reference, indicating relatively drier conditions, than the years preceding this study. These spatially wetter and drier conditions compared to the long term average rainfall may be an environmental indicator for a changing climate in Botswana.

Based on the spatial analysis, annual high rainfall clusters persisted in northern Botswana, indicating the annual persistence of wet conditions. Low rainfall clusters persisted in southern Botswana, indicating the annual persistence dry conditions. A deviation from the expected annual rainfall pattern, was the observation of a progressive drying trend towards the end of the time series, which may indicate a signal of a changing climate in Botswana. An extended period of rainfall analysis is required to confirm this climate change trend, and the associated consequences thereof. The observed drying trend during analysis period can be considered an important environmental indicator for conservationists in Botswana. This finding requires the attention of conservation authorities in Botswana in order for them to establish a comprehensive response strategy that would support conservation under changing rainfall patterns in future.

6.2 Rainfall gradient adjustment

The observed rainfall patterns in Botswana are not changing dramatically in time and space. The spatially wet and dry conditions remain in the same place, and are similar to that reported by the literature. It was observed that northern Botswana became relatively wetter and wetter, compared to historical records, while areas from central towards southwest Botswana got relatively drier and drier. This suggests that although the rainfall gradient remains in the same position (i.e. from northeast and southwest Botswana); it has become steeper in terms of the observed rainfall pattern. This steepening is accompanied by greater contrasts between traditionally ‘wet’ and ‘dry’ areas. This may be considered as another signal of a changing climate in Botswana.

6.3 Conservation in Botswana

This study contributes towards the overarching conservation project in Botswana. The contribution made by this study entails the ability to suggest spatial regions where vegetation growth is likely to occur, and as such, associated herbivore migration, in response to rainfall. The findings will be compared with those obtained by other students observing vegetation and herbivore movements in time and space in Botswana. Together, these studies will collectively enable protected areas authorities to better manage herbivore migration, improving conservation in Botswana over time. Based on the 15-year analysis of rainfall, the results predict that water and plant dependent animals are prone to move towards northern Botswana during the dry season. This prediction should be complimented by further studies related to this subject matter.

6.4 Considerations for other TRMM users

Accurate rainfall measurement at different temporal and spatial scales is a pertinent aspect for rainfall studies. The objective of TRMM is to provide accurate rainfall measurements over the tropics (Oki and Sumi, 1994; Habib and Krajewski, 2001). The accuracy of TRMM data are calibrated and validated by comparing TRMM rainfall measurements with rainfall measurements from surface sensors, precipitation radar and rain gauge data (Habib and Krajewsk, 2001; Adeyewa et al. 2003; Nicholson et al. 2003; Javanmard et al. 2010). This process is instrumental for providing an adequate level of confidence for use of TRMM measurements. As a point of interest, Almazroui (2010) conducted a calibration study for TRMM rainfall climatology over Saudi Arabia during 1998-2009, focusing on annual and seasonal rainfall patterns. This calibration study found that TRMM overestimated rainfall measurements during certain years, seasons and within certain regions in Saudi Arabia, a semi-arid region with a largely flat landscape. According to Oke et al. (2009), who conducted a TRMM satellite predictor study in Australia, a poor relationship between rain gauge data and TRMM data can lead to large errors. The fact that TRMM has i) a significant positive bias for inland elevated altitudes, and ii) does not capture orographic effects at the low spatial resolution of TRMM at 0.25 (i.e. localised storms and rain shadow) contributes to a weak relationship between rain gauge and TRMM data, which leads to error in rainfall measurements (Oke et al. 2009). Therefore, although TRMM is considered as one of the satellites producing some of the best available rainfall measurements in tropical regions, the literature indicates there are certain issues related to TRMM.

6.4.1 Issues associated with TRMM

The error of overestimation is a relevant issue, which has been supported by the literature and anecdotal evidence in discussions with other TRMM users. There are several possible reasons for rainfall overestimation from TRMM products. These reasons are most frequently related to i) quality of TRMM composite rainfall estimation, ii) sensitivity to rain droplet size, iii) TRMM sensitivity to frontal rainfall, and iv) the size of the confidence interval between ground-based data and TRMM satellite data (i.e. comparison between ground-based data and satellite data). Below, these factors have been expanded upon:

TRMM composite rainfall estimation: The TRMM composite Climatology (TCC) is a TRMM product which provides annual average rainfall data over a period of time. This product is made up of the merging of various TRMM rainfall products, over both the land and the ocean, providing an accurate composite rainfall measurement. TRMM products over the ocean include TRMM Microwave Imager (TMI) 2A12, Precipitator Radar (PR) 2A25, and TMI-PR 2B31 (http://www.disc.gsfc.nasa.gov). TRMM products over land consist of the TRMM Multi-satellite Precipitation Analysis product (TMPA 3B43) (http://www.disc.gsfc.nasa.gov).

Nicholson et al. (2003) conducted a study on the validation TRMM rainfall product estimations with gauge data in West Africa. The study found that the TRMM merged products were associated with rainfall overestimation. According to Adler (2008) different

TRMM products produce rainfall measurements with biases towards certain regions or surfaces, such as towards land or elevated altitudes. Gebremichael and Romilly (2010) conducted a study on satellite derived rainfall measurements over Ethiopian river basins. The study detected that a bias in satellite rainfall measurements existed in relation to elevation, and the rainfall regime. Additionally, the Ethiopian study found that at low elevations TRMM overestimated rainfall, while producing relatively accurate rainfall measurements at higher elevations.

TRMM sensitivity to frontal rain: There are limited studies surrounding TRMM satellite sensitivity to mid-latitude rainfall. Nonetheless, frontal rain is known to provide more consistent and concentrated TRMM rainfall measurements (Vaughn, 1986). Han et al. (2009) conducted a study on mid-latitude rainfall variability using TRMM, which found that TRMM satellite sensitivity was elevated for regions experiencing frontal rain. However, according to the literature there are certain discrepancies or inconsistences (i.e. rainfall overestimation), surrounding TRMM rainfall measurements in convective rainfall regions. It is deduced that TRMM may perform better in frontal rain regions, compared to convective rainfall regions.

Sensitivity to droplet size: Variation in rainfall droplet size influences scattering and absorption of clouds, for instance large rainfall droplets are associated with short wave absorption (Wetzel, 1990). Large rainfall droplets often lead to the establishment of atmospheric instability, promoting rainfall formation. Understanding Rainfall Droplet Size Distribution (DSD) is an important aspect of rainfall measurement, because variability in rainfall droplet size can be a source of inaccuracy for rainfall measurement. A study sampling the rainfall in China found that, increased convection rainfall rates are related to increased rain droplet size and concentration, which can result in rainfall overestimation (Liu et al. 2010). This means droplet size may be a physical issue influencing rainfall measurement in the tropics.

Confidence interval between ground-based data and TRMM satellite data: Both ground-based data and TRMM satellite data have been associated with rainfall measurement errors. Ground-based data errors are considered to be smaller than TRMM satellite data (Nicholson et al. 2003). With regards to rainfall measurement accuracy, this creates a trade-off between ground-based data accuracy and comprehensive TRMM satellite spatial coverage. Rain gauge data consists of spatially limited measurements for rainfall, and also a lack of spatial consistency for rainfall measurements. In contrast, TRMM provides more consistent and spatially continuous rainfall measurements.

A study evaluating TRMM rainfall measurements using ground-based rainfall measurements over Central Florida, found that at high rainfall rates ground-based rainfall measurements and TRMM rainfall measurements are more likely to differ (Wang and Wolf, 2011). This may result in less precise rainfall measurements. While at low rainfall rates the ground-based rainfall measurements and TRMM rainfall measurements are less likely to differ (Wang and Wolf, 2011). At high rainfall rates the possibility of TRMM rainfall overestimation increases and the confidence interval between ground and TRMM rainfall measurements also increases. This places emphasis on the importance of understanding the relationship between ground-based rainfall data and TRMM rainfall data, in order to avoid less precise rainfall measurements or overestimation.

6.5 Further research directions

This study is one of the first rainfall studies in Botswana conducted using TRMM 3B43 monthly rainfall data. This 15-year rainfall analysis, in addition to other studies on vegetation and herbivore migration, has used satellite data to explore spatial and temporal patterns in Botswana. I argue that the observed rainfall trends are credible and justify the conclusions made. The methods and approach used in this study, are considered feasible, and are in line with appropriate scientific methodology required for a detailed rainfall study. Ultimately, this study is a building block for ensuring accurate use of TRMM data over semi-arid regions going forward, and the implementation of increasingly effective conservation planning and management in Botswana. Yet, there is still scope for future research across southern Africa and within Botswana. The key areas for further research include:

- The use of TRMM rainfall measurements in this study has allowed for the comprehensive spatial analysis of rainfall in Botswana. The TRMM satellite's ability to provide spatially consistent rainfall data has been illustrated in this study, addressing the typical historical limitations associated with ground-based rainfall measurements. However, the use of satellite data does not replace ground-based data, and it is not this study's intention to suggest this. Rather, satellite data as shown by this study might be considered a useful complement to ground-based rainfall measurements, particularly in areas where rain gauge measurements are scarce. Based on the anecdotal evidence in discussions with other TRMM users regarding TRMM overestimation, it is recommended that increased local validation of TRMM is conducted subsequent to TRMM calibration. This will assist with the rectification of TRMM overestimation in convective rainfall regions.

- The determination of localised spatial rainfall patterns and changes beyond Botswana, i.e. Angola, particularly with reference to climate change is a point of interest. A study of this nature would provide more recent information, regarding the consequences of climate change for countries neighbouring Botswana.
- The TRMM satellite dataset used in this study did not include detailed information about the conditions of the landscape, for which each rainfall measurement was recorded. This made it difficult to predict, with great certainty, how the observed rainfall patterns impacted Botswana on the surface (ground level). Consequently, further studies investigating the impact of these rainfall patterns at ground level are required nonetheless. TRMM satellite data combined with various other statistical methods could be highly valuable, in predicting the spatial and temporal response of vegetation and surface water resources, as well as herbivores migration in Botswana.
- An extension of the time series for this rainfall analysis to 30 years, would confirm whether the observed drying trend is indeed a signal of a changing climate in Botswana. An extended time series would be valuable for making long term predictions regarding the response of surface water and vegetation resources, as well as animal migration.
- Although TRMM was developed for rainfall measurement in the global tropics at a spatial resolution of 0.25 x 0.25, it might be a point of interest to assess how TRMM satellite responds to non-tropical regions, and measurements at different spatial resolutions (Lunetta et al. 1991).
- A hydrological analysis concerning two big rivers in Botswana (i.e. Boteti and Savuti rivers) may be valuable for comprehending the effect of the variable rainfall frequency events, on surface water bodies in the country. Both the Boteti and Savuti rivers derive their flow from the Okavango Delta (McCarthy et al. 2003; McCarthy, 2006). The river flows are seasonal and influence the abundance of surface water

resources and vegetation cover in Botswana. Assessing the hydrology in Botswana is a sustainable way of indirectly, but continuously monitoring rainfall patterns in the country.

- An assessment on the performance of TRMM with other satellites or remote sensing products (NOAA and STAR satellite rainfall estimates) also used for rainfall measurement, is recommended. This assessment will provide more recent information regarding quality and reliability of the TRMM product on a broader scale. The standard of the TRMM compared other satellites should be indicated, and areas of improvement for TRMM products highlighted.

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