**PAN AFRICAN UNIVERSITY**

Institute of Water and Energy Sciences (Including Climate Change)

# Rainwater harvesting for irrigation in the wake of climate change: A model-based design

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### 1.1.1. DECLARATION

I Ronny Gorata Matenge hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics. It is being submitted for the Master of Science in Water Engineering at Pan African University Institute of Water and Energy Sciences (Including Climate Change). It has not been submitted before for any degree or examination at any other University.

Signed: ........................................ 22 September 2018

Name Date

### 1.1.2. DEDICATION

This thesis is dedicated to the memory of the my late auntie and grandfather, Babani Theni and Theni Setlhako, who rejoiced with me when I got the scholarship to undertake this study, but went to be with the Lord during the thesis research period, and was not there to see the fulfilment and completion.

ABSTRACT: Water is a fundamental element in the attainment of food security and socio economic development any country. Spatiotemporal variation in rainfall and lack of scientific research in water resource utilization and management greatly affect conventional agricultural production. Rainfall is very important for the economic growth and development of any nation; hence there is dire need to study the monthly and annual trends. Rainfall in Botswana is highly variable characterized by frequent droughts and flash floods. In addition to that understanding the rainfall variability in a catchment is essential in policy formulation regarding for integrated water management and monitoring. Consistent water shortage of water call for the need to study the hydrological processes in order to plan for the limited resource. Descriptive statistical techniques like time series analysis, mean and standard deviation were employed to depict the temporal distribution of rainfall over the area. The main objective of this study is to model rainwater harvesting for irrigation taking into account spatio-temporal variations of rainfall, its influences on streamflows, basin yield and their relationships with climate change. The results of rainfall analysis reveals that Francistown catchment has high rainfall variability as indicated by regression analysis R2, Skewness, and Kurtosis coefficients of respectively. There is a shift in the rainy season onset and cessation coupled with recurrent droughts and floods. These are clear indicators of that climate is changing. The rainfall distribution is also highly variable with space and time which confirms that the catchment is situated in a semi-arid climate. Findings of these model and rainfall analysis are useful planning for activities such as irrigable farming, agricultural processing industries which strongly relies on year-to-year climatic variations.

**Key words**: model, climate variation, rainfall, Botswana, analysis

### 1.1.3. RÉSUMÉ

L'eau est un élément fondamental de la sécurité alimentaire et du développement socioéconomique de tout pays. La variation spatio-temporelle des précipitations et le manque de recherche scientifique sur l'utilisation et la gestion des ressources en eau affectent grandement la production agricole conventionnelle. Les précipitations sont très importantes pour la croissance économique et le développement de toute nation; Il est donc urgent d'étudier les tendances mensuelles et annuelles. Les précipitations au Botswana sont très variables et se caractérisent par de fréquentes sécheresses et des crues éclair. En plus de cette compréhension, la variabilité des précipitations dans un bassin versant est essentielle dans la formulation des politiques concernant la gestion et le suivi intégrés de l'eau. La pénurie d'eau constante nécessite d'étudier les processus hydrologiques afin de planifier la ressource limitée. Des techniques statistiques telles que l'analyse des séries chronologiques, la moyenne et l'écart type ont été utilisées pour décrire la répartition temporelle des précipitations sur la zone. L'objectif principal de cette étude est de modéliser la récolte des eaux de pluie pour l'irrigation en tenant compte des variations spatio-temporelles des précipitations, ses influences sur l'écoulement fluvial, le rendement du bassin et de leurs relations avec les changements climatiques. La décharge générée a ensuite été utilisée pour estimer la capacité de stockage d'un réservoir. Les résultats de la variabilité des précipitations montrent qu'il ya une diminution de la quantité de précipitations et en nombre de jours de pluie, ce qui est une indication claire que le climat est en train de changer. La distribution des précipitations est également très variable avec l'espace et le temps qui confirme que le bassin est situé dans un climat semi-aride. Les résultats de ces analyses de modèles et de précipitations constituent une planification utile pour des activités telles que l'agriculture irrigable, les industries de transformation agricoles qui dépendent fortement des variations climatiques d'une année sur l'autre.

### 1.1.4. ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my supervisor, Prof. Joseph Adelegan for his untiring guidance, and patience throughout this study.

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# LIST OF ABBREVIATIONS

HEC-HMS: Hydrologic Engineering Center-the Hydrologic Modelling System

IQR: Interquartile Range

DEM: Digital Elevation Model

SSTs: Sea-Surface Temperatures

ENSO: Pacific El Ni˜no-Southern Oscillation

GIS: Geographical Information System

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# 2. CHAPTER 1

## 2.1.1. INTRODUCTION

Botswana is a semi-arid country facing a challenge of freshwater scarcity and effect of climate change is expected to worsen the current state of water stress. The population depend mainly on rainfed agriculture hence variation of rainfall in time and space can highly influence agricultural yields (Abbam, Johnson, Dash, & Padmadas, 2018). Botswana's economic development particularly the irrigation sector is constrained by water shortage and climatic variability. In order to achieve sustainable economic development, there in need to invest in water resources infrastructure planning and management (Strzepek, McCluskey, Boehlert, Jacobsen, & IV, 2011). To meet this increasing demand efficiently, there is need for sustainable, effective policy formulation and implementation (Setlhogile & Harvey, 2000). Optimizing catchment water yield by harvesting rainwater is essential element in water resource management (Jovanovic & Clercq, 2012) to meeting increasing demand from competing uses.

Water is a vital element that influence and affect the livelihood of people and the socio-economic activity of a society. Climatic variation is a threat to agricultural production since the livelihood of the poor and the marginalized depends entirely on rainfed agriculture. Irrigation is the single most largest user of world's freshwater accounting for 70% of total water use (Sato, Qadir, & Yamamoto, 2013). Since in Botswana water is a scarce resource, agriculture accounts for only 42% of the total water use hence low agricultural productivity (Kwashirai et al., 2016). Water resources development and management for agriculture has been key more especially in the eastern part of Botswana where most river streams are flowing. This is crucial since over 80% of the population depends on subsistence agriculture for its livelihood. According to Food and Agriculture Organization FAO, (2016) the el-Niño effect causing a shift in weather patterns due to climate change has led to late rains in Southern Africa. These changes in rainfall onset has affected dry land farmers especially in Botswana by delaying the planting season which normally in October and ends in January. In most areas, the cropping season has shifted to November/December since they would not have received enough rainfall by then. This effect has resulted in very little ploughing and planting hence low production.

The economic growth and development of any society is dependent on rainfall, hence there is a great need to study, analyze the monthly and annual trends (Chibuike, Kunda, Eze Johnson, & Adekunle, 2014). Traditional knowledge to predict rainfall is no longer relevant due to changing climate. This factor has increased the vulnerability of local farmers to the impacts of spatio-temporal variation of climate(Abbam et al., 2018). Development of Sustainable water resources for agriculture requires in-depth analysis and understanding of catchment and its hydrologic processes. Understanding water flows particularly the water quantity is essential to decision makers and policy makers. To achieve such development and policy implementation it is important to understand water resource availability and spatial distribution in the catchment.

Hydrological data is key in water resource management. However, in developing countries like Botswana most catchment are ungauged with only few years of available data. This issue has led limited hydrological studies in Botswana. Limited observed data does not only affect the hydrological studies, it also slows hydrological development in the catchment (Abouabdillah, 2009). Water management problem solving requires an integrated approach. Over the years hydrological assessment tools have been developed to curb the issue of insufficient data, both quality and quantity. Hydrological models are effective tools in catchment management and solving hydrological problems (Psomas, Panagopoulos, Konsta, & Mimikou, 2016) especially in areas of limited data. The concept of hydrological modelling is brought about by the challenge of increasing pressure on water resources as a result of rapid increase in competing use (Rochester, 2010). The pressure exerted on water resources by increased populated growth, drought, floods and pollution exacerbate rapid industrialization and water for irrigation further. Hydrological models are then applied to address these challenges on water resources. Hydrological models are now adopted in numerous tasks in hydrology (Patil & Stieglitz, 2012) for academic purposes and also to solve practical engineering problems. Models generate various hydrological data, which can be used for decision-making, strategic planning, design and management.

Models have been applied in a wide range of tasks, which include prediction of: streamflow forecasting infiltration into soils, percolation into aquifers (Beek & Loucks, 2005), flood estimation, water quality estimation and assess how changes in landuse and climate affect catchments (Patil & Stieglitz, 2012). A variety of hydrological models have been developed and implemented in catchments over the years. They are categorically be classified into: 1) conceptual mechanistic models and 2) data driven models. Conceptual models are created based on the profound understanding of the physical system while data-driven models create a relationship between input and output parameters without considering the intrinsic physical process (Parasuraman, 2007). Conceptual models are developed at a certain scale of interest with a baseline of assumptions. However models are prone to difficulties in providing realistic estimates, these shortcomings are taken care of by calibration process. Hydrological models can also be described as either deterministic or stochastic. In stochastic models one or more mathematical variable cannot be predicted over time while in deterministic model variables are free from random variation. Another classification of models is either as event based models or continuous time models. For event based models, they estimate runoff for a storm happening in a short period of time ranging from an hour to some few days. A continuous time based watershed model determines runoff over a sequential period of time and it includes components of evapotranspiration and subsurface components which are not included in the later. The last categorization of models is either as umped or distributed or a mix of both. Lumped models does not they varying features of a watershed, it assumes a homogenous nature in a catchment. Distributed models are sensitive to varying feature such as topography, land cover and soil type in a catchment when estimating runoff (Beek & Loucks, 2005).

Rainfall runoff models requires observed streamflow data for calibration of model parameters in order to estimate streamflow. To estimate streamflow and catchment discharge a certain procedure must be developed which involves using streamflow of gauged catchments to calibrate model parameters (Patil & Stieglitz, 2012). Remote Sensing (RS) and Geographical Information System GIS) have been applied in integration with hydrologic models to produce substantial results (Gangodagamage., 2001).

Probability distribution models for rainfall can be very effective tools in providing the policy makers, designers, planners and decision makers with useful information for to guard against rainfall anomalies. Developing rainfall models for frequency distribution and statistical analysis requires historical data. Best fitted model are then applied in water resource planning, design and development initiatives like water harvesting systems, irrigation projects, floods and drought mitigation (Al-suhili & Khanbilvardi, 2014).

Over the years, different distribution models have been used to find out the probability distribution function parameters for rainfall data. Some of these models include Weibull, Normal, Exponential, Log-normal, Log-Pearson III, Two parameters Gamma type and others (Al-suhili & Khanbilvardi, 2014) while e Kolmogorov-Smirnov, Chi-Square and Anderson-Darlin tests have been used to test the goodness of fit.

In a changing climate, hydrological response of a catchment is also affected. Challenge of missing and data shortage is a challenge for scientific researchers and decision makers. Use of models rainwater harvesting is still an enchanted field of research that needs exploration. Currently no research have yet modeled spatio-temporal patterns of daily rainfalls, climatic variables and their relationship with streamflow variations in to determine catchment. This research will are expand our understanding of rainfall variability in Botswana's hydrology.

### 2.1.2. BACKGROUND

### 2.1.3. Agriculture and climate change

Climate change is predicted to reduce rainfall by 10%-20% (Phillipa & Tamer, 2012). The effect of climate change is a constraint to Botswana's agriculture and food security. Concerns from the global climate change projections shows that there is likelihood of increase in prolonged droughts, shortened planting season and increased evaporation rates due to increased temperatures leading to complete crop failure. Rainfall events going to be short and intense causing flash flooding. Persistence underperformance of the agricultural sector is also influenced by harsh agro-ecological conditions, low soil fertility and high reliance on low, unreliable rainfall (Policy-Brief, 2013) (Gases, 2012).

Water scarcity has led shortage of food. The country import 90% of all its grains, 45% of vegetables (Utiang Ugbe, 2013) and other agricultural products worth US$632 million in 2014 (Nguema & Esterhuizen, 2015). Rise in food prices and high dependence on food imports has attributed to persistent poverty and food security in Botswana. Most of food supplies comes from South Arica hence any threat in South Africa's climatic patterns will affect the livelihood of Botswana's food security. The poor and the marginalized households cannot access food even if it is available due to low income and high food prices (Moseley, 2016). In addition the rural households are insufficient in food production hence rely on food highly priced food which keeps fluctuating in prices. Climate change will add a burden to the existing stress if adaptive measures are not taken into consideration.

### 2.1.4. Economic Outlook

Botswana is considered a middle income country having a GDP per capita of $7,505 and GDP of $15.8 billion in 2014 (Nguema & Esterhuizen, 2015). The country has sustained a stable economic growth due to its attractive tourism sites, large mineral deposits, good governance and political stability (Wingqvist & Dahlberg, 2008). The population is growing at a rate of 1.9% and it is currently estimated to be 2,235,533 (Country-Watch, 2017). Contrary to other African economies, Botswana's agricultural sectors contribution to the GDP has been growing at a slow of 0.5% annually between 1974 and 2011 (Jefferis, Kenewendo, Sigwele, Tlali, & Moyo, 2012). Over the years, the contribution of agriculture to

GDP has decline from 40% prior independence to 1.9% in 2008 (Moseley, 2016) (Pholele, Moakofhi, & Phiri, 2017) (Gases, 2012).

Despite a noble vision of a diversified economy and poverty free society by 2016, the country remains excessively diamond driven economy ("A STRATEGY FOR ECONOMIC DIVERSIFICATION AND SUSTAINABLE GROWTH BUSINESS AND ECONOMIC ADVISORY COUNCIL GABORONE SEPTEMBER 2006," 2006). The poverty and economic hardship is more prominent in rural areas were 14.5% of the population compared to 5.2% of urban households living under poverty datum line of $1.25 per day in 2009/10 (Mosha, 2015). Rural urban migration from has increased from 5% in 1966 to 64% in 2011 since the sources of income in rural areas are minimal. Poverty is more profound in rural areas and female-headed families bears the brunt mainly due to low income and lack of alternative income producing opportunities(Malema, 2012).

### 2.1.5. Botswana water profile

More than 70% of area is the unproductive Kalahari Desert. The country has harsh climatic conditions with prolonged droughts, low unreliable rainfall ranging between 250mm and 650mm which is unevenly distributed (Manthe, 2014), (Matenge, 2017). This uneven distribution has increased pressure on the limited water resources affect socio-economic development across the country. Deep sandy soils of the Kalahari Desert and low rainfall has led to few surface water resources. The nation is highly dependent on internationally shared trans-boundary water resources. Botswana has five major perennial drainage systems namely: Limpopo river basin occupying 14 percent of the countries surface area; Makgadikgadi is the largest covering 63 percent of the entire country; Okavango delta which originate in Angola occupies 9 percent in the north west; Orange-Senqu River basin occupies about 12 percent in the southern part and Zambezi occupies only 2 percent. All these basins are shared (Botswana Ministry of Minerals Energy and Water, 2012). These perennial river system however do not coincide with population density (Segosebe & Parida, 2006).

The population is more concentrated in the eastern side of the country were soil is more fertile. This un-coinciding distribution of population coupled with rapid economic and population growth has resulted exploitation of slowly replenishing underground fossils water. Extreme evaporation rates reaching 2,000mm/year combined with an low aquifer recharge rates of 3mm annually worsens the country's valuably vulnerable scarce resource. Aquifers are under threat of overexploitation for irrigation and human consumption.

Groundwater is unevenly distributed in terms of both quality and quantity estimated to be around 100 billion $m^3$ with recharge of approximately 1,600$Mm^3$ annually. The depth of groundwater varies from 20m in the northern to 100m in the north western Botswana. Over the years water demand has increased to 195$Mm^3$ in 2013/14 from 150$Mm^3$ in 1990 and it is projected to increase to 285.8$Mm^3$ in 2030. The effort of this project is explore and harness potential water alternatives despite the challenges of low rainfall, flat topography and high evaporation rates especially for irrigation purposes. Given the fact that climate change effects is going to decrease the inflow of Limpopo and Orange rivers by 10% to 35% there is likelihood of having shortfall in water.

In order to overcome the challenges of increased water demand to due to increasing population and economic activity there is need to explore water potential. Optimization of wastewater use will decrease the pressure on boreholes which will allow them recuperate and serve as backup water resource.

### 2.1.6. Rainwater Harvesting

Rainwater harvesting is a measure of water security by providing sustainable water relief in times of water scarcity. Harvested rainwater can be used to boost vegetable production through irrigation (Samuel & Mathew, 2008). Botswana has the lowest per capita water storage capacity in southern Africa. Assessment by University of Notre Dame's Global Adaptation Index (ND-GAIN), found out that Botswana is the most vulnerable country in readiness to respond to climate change. Major reasons attributing to that are: Botswana depends entirely on food imports, has limited agricultural production capacity and it has the smallest dam capacities (Crawford, 2016). My study was driven by the need to increase dam capacities in Botswana to harvest rainwater to boost agricultural production; this will reduce the dependence on food importation. There research therefore if implemented by policy and relevant stakeholders will lessen the vulnerability of climate change in our country.

### 2.1.7. PROBLEM STATEMENT

The biggest challenge facing Botswana, is water resource management is centralized and there is lack of stakeholder participation (Setlhogile & Harvey, 2000). Botswana as a semi-arid country, with frequent recurrent droughts coupled with unreliable varied rainfall. It has 70% of its surface area covered with a desert. This alone indicates the magnitude of water scarcity the country is facing. Another challenge is the population growth rate of 2.4% annually in a water stressed landscape. The hydrography is characterized by deep sandy soils of the Kalahari Desert, flat topography, high evaporation rates reaching 200mm/year, low aquifer recharges and low surface runoff (Segosebe & Parida, 2006). In addition the country does not have perennial rivers, hence more pressure is put on underground water resources of which the of aquifer recharge is barely 3mm per annum.

The current water stringent conditions, rainfall variation and the expected changes in the rainfall distribution, rainfall onset and cessation, and amount of rainfall are considered to be the main key measures of vulnerability for Botswana water sector from now hence forth. The demand of water use from industries, residences, commercial and agriculture in increasing while rainfall and groundwater recharge is decreasing (Crawford, 2016). These challenges are putting significant pressure on the country's water resources. The strong hold of the country's economy, the mining sector is continuously growing as a result will lead to increased demand for water resources. Reduction in rainfall amount will lead to reduced streamflow for up to 13% and cereal production will decline by 19% in 2050.

Irrigation is still relatively small industry with an average area ranging between 1,500ha to 1,800ha (United-Nations-World Water-Assessment-Programme, 2016). Botswana has a potential to irrigate 13,000ha, 2000ha is equipped for irrigation and only 85% of the equipped land is utilized for irrigation. Production is mainly vegetables and citrus fruits just for the local market. Farmers use between 2.5Mm$^3$ to 7.5Mm$^3$ per year per hector which is way less than 18Mm$^3$ assumed water use per hector per year by National Water Master Plan. According to Accounting for Water in Botswana ("Accounting for Water in Botswana," 2014) 60.2% of irrigation farmers use groundwater, 34% use rivers water while 5.8% use surface and wastewater largely because of water scarcity. In its bid to improve the horticultural sector, the government has established irrigation schemes at Glenn Valley to irrigate 203ha with treated wastewater and 60 ha at Dikabeya using dam water. These efforts however could not meet the agricultural demand of the country. There is an urgent need to increase the efficiency of water use amongst competing users especially in agriculture which is the largest consumer of water.

Botswana's economy is highly dependent on minerals particularly the diamond but projections shows that diamond production will cease in 2030. This calls for the need to diversify the non-diamond particularly the agricultural sector that is interlinked. However, this sector is underpinned by water scarcity. Water scarcity has led to other socio-economic hardship like high poverty rate (14.5%), high employment rate (19%) and urban migration from (64%). Mining is the strong hold and the backbone of Botswana's economy. At maximum production diamond and coal production is estimated to use at least 5.7Mm$^3$ of water a year. Fear is increasing to the fact that the mines are already overexploiting the limited ground water resources. There is limited policy on water management, monitoring and abstraction mainly because of limited scientific research on this valuable resource.

Lack of climate and hydrological data causes uncertainty in the assessment, management, planning and design of water resources. Lack of information on water distribution is a constraint to socio-economic development including the agricultural sector. In this study, modelling techniques will help develop the knowledge and understanding of water resources. The knowledge gained here will help alleviate the challenge of water scarcity in Botswana. To address these challenges this study is going to explore the potential of harvesting rainwater and recycling of wastewater to increase agricultural production under irrigation in the wake of climate. This will reduce the countries dependency on rain fed agriculture. There is need to improve the irrigation sector to close the importation gap of food products. This is a clear indication of high risk food insecurity.

Francistown is in the eastern part of the country that receives a significant amount of rainfall compared to other parts of Botswana. This area contributes to the 6% of total surface area that is suitable for agricultural production. However, the region is extremely susceptible to the current and anticipated negative effects of climate change and vulnerability (Wamukoya & Kinyangi, 2015). The global economic crises coupled with the global food crisis in the 2000s exposed the country's deficiencies in food security and agricultural development. The current state of highly variable rainfall intensity, duration, onset and cessation, the devastating impacts of weather extremes like recurrent droughts, frequent floods and heat waves calls for drastic innovative strategies to alleviate farmers from weather and climate repercussion. Developing the agricultural sector especially the irrigation sector will stimulate economic growth for and sustain the livelihood of the people for a country heavily dependent on agricultural produce import (80%).

This research is aligned with the Country Climate Smart Agriculture (CSA) program (2015-2030) which aims at addressing the challenges of Botswana's agricultural development and growth in a changing climate. The strategies include improving resilience and climate change adaptation, research and development, seasonal weather forecast, and dissemination of climate smart agricultural practices. To achieve such a kind of a program and related initiatives there is great need of probable rainfall quantities that an area can receive. This paper serves as a contribution by providing an estimation of future rainfall events probability. The results will be useful for policy makers, planners, stakeholders, decision makers and developers.

### 2.1.8. THESIS ORGANIZATION

This thesis will examine the spatio-temporal variations of rainfall; model the interrelationship of the hydrological processes of Francistown, Botswana in order to determine the catchment yield for rainwater harvesting. The interannual variability of climate and streamflows are key in designing a sustainable reservoir capacity. The study is divided into ten chapters with the aim of achieving three main objectives. Chapter 1 introduces the entire study, chapter 2 will present rationale for study, the objectives the study is covered in chapter 3, the study area is described in chapter 4. Chapter 5 is literature review while the data sets will be described in chapter 6. Chapter 7 outlines materials and methods, chapter 8 analysis the findings, chapter 9 discusses the finding of the research. Lastly, reservoir and irrigation design and conclusion will be covered in chapter 10 and 11 respectively.

# 3. CHAPTER 2

## 3.1.1. RATIONALE FOR STUDY

Chapter 1 clearly indicates that there is great need to increase the water resource capacity of Botswana that will address the challenge of food security. This however requires in-depth analysis of the climatological and hydrological variation in order to achieve environmental sustainable and economical sound decision on rainwater harvesting. Great effort is required to model and understand the hydrological process of a catchment in the wake of climate change. This chapter presents key questions that will help in issues that are being addressed by this research.

There are currently no or little hydrological information on Francistown Basin contributing to sustainable watershed management and rainwater harvesting. The purpose of this study is to assist decision makers and stakeholders with a detailed framework for water resource planning and development. The knowledge acquired in this study will be applied to other catchments in Botswana in an attempt to contribute to vision 2036 of Botswana and the Millennium Development Goals (MDGs) by diversifying the economy and reducing pressure on water resources. This section present a set of questions pertaining to rainfall variability, variation in stimulated flow, interrelationship between climate variability, streamflow and catchment yield. Changes in landuse and soil are also key factors that needs detail analysis since they influence the hydrological process and reservoir capacity.

Although rainfall amounts and distribution is being studied all over the country, less attention is being given to in-depth details in day-to-day, monthly and seasonal variation especially at a sub-basin level. Some questions remain unanswered by the available research. The purpose of this study then is to address the following questions in rainfall analysis: What is the spatiotemporal rainfall variation at a sub-basin level?; How does the number of rainfall events vary from season to season?; How does climate change influence rainfall variations?

A rainy season is difficult to define. This is mainly due to the spatiotemporal variability in the onset and cessation of rainfall. This study will analyze daily and monthly rainfall to determine the beginning and end of rainy season. The following question will be addressed: Can rainy season be defined after analyzing the dry and wet days?, What is what is the sequence, variability and distribution and of rainy season in the catchment in terms of onset and cassation?

Streamflow variation is dependent on rainfall variation coupled landuse patterns and human interference. Decrease in landcover increases high flows in rivers and increased abstraction decrease inflows into river streams. This research must be capable of answering questions such as: what are the changes in seasonal variability within season and interannual patterns of streamflow over the years? Suitability of a catchment for rainwater harvesting in not only dependent on rainfall and streamflow variation but also geographical, landuse and environmental changes over time. The study will answer the following questions: Is the catchment suitable for rainwater harvesting?; How will soil type, soil erosion, slope and other factors affect the hydrological process of the catchment?, Is the project environmentally compatible? At the end of this study, the, the research should come up with solutions to the suitable capacity and design of reservoir for rainwater harvesting.

### 3.1.2. RESEARCH GAPS

The research has identified some research gaps that this study will attempt to bridge. Use of models rainwater harvesting is still an enchanted field of research that needs exploration. Currently no research have yet modeled spatio-temporal patterns of daily rainfalls, climatic variables and their relationship with streamflow variations in Botswana to determine catchment. Rainwater harvesting is limited only to small scale like rooftop harvesting, well and farrows in farming fields. This research will are expand our understanding of variability in Botswana's hydrology.

The country has great initiatives live vision 2036, which aims at increasing food production and diversifying the economy but less attention, is given to hydrological studies, rainwater harvesting and irrigation for sustainable food production other than relying solely on rainfed agriculture. Limited information on the potentiality of harvesting rainwater for irrigation is hampering policy makers, practitioners and researchers to make informed decisions that will help boost food production and increase food security that has negatively affected Botswana's socio economy. This study will provide information and necessary data required for strategic decision-making.

# 4. CHAPTER 3

### 4.1.1. OBJECTIVES

The main objective of this study is to determine if model based water balance monitoring system can be used to access the potential of harvesting water for irrigation taking into account spatio-temporal variations of rainfall, its influences on streamflows, basin yield and their relationships with climate change. The main objective will be achieved by the fulfillment of the following four specific objectives:

OBJECTIVE 1: RAINFALL VARIABILITY ANALYSIS

To reach this objective this paper will:

1. Will investigate rainfall variability and distribution of rainfall of Francistown on monthly and annually bases
2. Investigate the results for any sign of climate change by analyzing the descriptive statistical parameters
3. Define the rainfall season of Francistown by establishing the onset and cessation of rainfall
4. To explore the policy implications for climate adaptation.

OBJECTIVE 2: DEVELOP A HYDROLOGICAL MODEL OF THE CATCHMENT

This is the fundamental objective of this study is to model the hydrological processes of Francistown catchment by:

- Investigating the suitability of the catchment for rainwater harvesting
- Establish the interrelationship between rainfall, streamflow and landuse
- Forecast outlet discharge

### 4.1.2. WORKING HYPOTHESIS:

H0: There is no significant difference in the mean annual rainfall in Francistown over the period of thirty-five years.

H1: there is significant difference in the mean annual rainfall in Francistown over the period of thirty-five years.

# 5. CHAPTER 4

## 5.1.1. STUDY AREA

### 5.1.2. Background of the study area

The Francistown catchment forms part of Limpopo catchment located in the North East part of Botswana. Area is located approximately 436 km North of Gaborone (the capital) city by road. The area shares part of the boarder with Zimbabwe. The basin has a population of 98,961 according to the last population sensors in 2011. The catchment is medium size, covering an area of 20 000ha. Francistown is situated in a flat plateau with an elevation of 915 m. The catchment receives a localized rainfall that ranges between 250mm and 400mm. Factors that influence the hydrological process of the catchment that are typical to Francistown will be discussed here in brief.


Figure 4.1: A map of Botswana showing the location of Francistown (https://yourbotswana.com/index.php/category/lifestyle/page/6/

### 5.1.3. Agriculture

Rainfed dryland farming under rainfed conditions is found mainly in Francistown catchment. The crops are predominantly cereals: maize, millet, sorghum and sweet reeds. The farming practice primarily include crop rotation with food legumes such as groundnuts, cowpeas, lentil and forage legumes. The major constraints in both regions to crop production are low soil fertility, insecure rainfall, low-productive genotypes, low adoption of improved soil and crop management practices, and lack of appropriate institutional support.

#### 5.1.4. Topography, soils and geology

The Digital Elevation Model (DEM) map was obtained from USGS website at a resolution of 90m and the Catchment map delineated using GIS tools. The area is relatively flat with an elevation ranging from 780m to 950m above sea level. the soil composition is mainly alluvial and decomposed granites. The geology of the catchment consist of granitic gneiss and meta sedimentary/meta lavas.

#### 5.1.5. Climate

Francistown falls under the semi-arid type of climate. The climate is characterized by great variation in temperatures and rainfall between summer and winter. The area receives a unimodal type of rainy season between October and April; the mean annual rainfall in the Francistown catchment is over the last 30 years is 415mm. the catchment is prone to extreme events like heat wave, drought and floods. The mean annual maximum temperature is 33°c in January and a minimum of 5°c in June. Maximum prevailing wind speed in the catchment ranges from 16 Km/h and 22 Km/h in august and September respectively.

#### 5.1.6. Vegetation

A canopy forest consisting of Mopane woodland *(Colophospermum mopane)* and Acacia tree savanna are more prominent in the catchment with tall grasses and bushes and trees. Mopane trees are a host of a nutritious phane worn which is economically harvested for sale locally and regionally.

#### 5.1.7. River streams

The rivers in the Francistown catchment are mostly seasonal which are prone to flash floods, with the exception of Limpopo River which is perennial. The catchment is at the confluence of the Tati and Inchwe rivers, and near the Shashe River, which is a tributary to the Limpopo River. Tati River is a tributary of the Shashe River.

# 6. CHAPTER 5

LITERATURE REVIEW

### 6.1.1. RAINFALL VARIABILITY ANALYSIS

### 6.1.2. Rainfall variability in Africa and Globally

Throughout the world semi-arid regions are well-known for their unpredictable precipitation (Barbe, LEBEL, & TAPSOBA, 2002). Semi-arid climate is very complex, the spatio-temporal variation and distribution of rainfall within catchments is unpredictable, is highly variable from year to year, with a year and even during a rainfall event. This has a large impact in assessing and predicting how climate is changing. The Sahel is predominantly semi-arid climate region with high climatic variation and irregular/unpredictable rainfall ranging between 200-600mm per annum (Chibuike et al., 2014).

Rain-fed agriculture is still the main source of food production and the livelihood of many Sub-Saharan Africans depends on it (Cooper, Dimes, Rao, & Shapiro, 2008) (Abbam et al., 2018). Poorly developed countries are however limited to the subsistence rainfed agriculture despite the spatio-temporal variation without irrigation infrastructure. However rainfall variability mainly driven by climate change has a great likelihood of affecting the already fragile agricultural production. Rapid population growth ends an alarm to the already limited water resource supply. To address these challenges there is need to develop strategies that can enhance our understanding of the highly limited, variable unpredictable resource. Developing models and tools that can predict the variability of climate variables will allow farmers and stakeholders to plan for adaptive and mitigation measures. Understanding the variability of rainfall is important for optimum management and utilization amidst increasing and conflicting demands (Nyatuame, et. al, 2014).

To mitigate the impacts of food security and household poverty it is important to analyze the spatio-temporal variation of climate (Abbam et al., 2018). High-spatial resolution data in Ghana was used to examine the spatiotemporal variations in rainfall and temperature in order to establish suitable areas for stable food production. A non parametric regression test was used to analyze how substantial are the changes of rainfall and temperature. The findings of the research reviled that the changes in climate pattern are heterogeneous hence there is a need for developing an adaptation policy (Abbam et al., 2018).

A study in western equatorial Africa to analyze the interannual variability of rainfall and how it is related to sea-surface temperatures (SSTs) proved to be complicated due to some governing parameters. Some of the factors that govern rainfall variability include sea-surface temperatures (SST) anomalies along the Benguela Coast, warming and cooling of tropic oceans, changes in sea-surface temperatures between Atlantic and Indian Oceans, and lastly the Pacific El Ni˜no-Southern Oscillation (ENSO). These governing factors changes constantly from season to season. The study found out that there are many assumptions conclusions regarding the connection between SSTs and continental rainfall. Some of the conclusions are that the influence of the three oceans and impact of a specific SST anomaly are seasonally dependent. They can either enhance rainfall in some season and reduce it in the subsequent season (Toggweiler, Key, & N. Balas, 2007).

Chibuike et al., (2014) conducted a mathematical study of monthly and annual rainfall trends in Nasarawa State, Nigeria using a 20 year period data to analyze temporal distribution of rainfall. The results showed that there is shift in the starting and ending of rainy season. Another research conducted by (Barbe et al., 2002) to analyze rainfall variability in West Africa made used 300 daily rain gauges to characterize the rainfall regimes of West Africa at hydrological scales. The study did an analysis of the average number of rainfall events for a particular time period (nT) and cumulative average rainfall per event (h) which makes it possible to understand the rainfall variation on seasonal bases and annually. The results indicates that the number of rainfall period at a particular time correlate well with the decline in mean interannual rainfall. In addition the results shows that in the south there has been a shift in time for dry period for the second rainy season. All these factors will have serious consequences concerning agricultural production and water resources management.

### 6.1.3. Rainfall variability in Botswana

Semi-arid climates like Botswana are characterized by high rainfall variability and the likelihood of climate change is bound to worsen the variability in such regions (Batisani & Yarnal, 2010). Rainfall data and distribution is a key element in quantification of catchment's yield. In addition to that understanding the rainfall variability in a catchment is essential in policy formulation regarding for integrated water management and monitoring. Since Botswana is situated in a semi-arid region, all precipitation is in the form of rainfall (Jovanovic & Clercq, 2012). The rainy season is unimodal occurring between September and April. The rainfall is characterized by low intensity long duration coupled with high intensity short duration storm. The major determining factor that influence climate across the southern Africa region include altitude (where Botswana is on a relatively flat land, with an altitude of 1,000m on average); is the warm Indian and cool South Atlantic oceans and the shift of the Inter-Tropical Convergence Zone. These factors mainly dictates the onset, cessation of summer rains; and the location of dominant atmospheric high- and low-pressure systems (Crawford, 2016). A combination of these factors causes rainfall variability in the country make it difficult to predict future rainfall.

Botswana's population is highly reliant on rainfed agriculture; this variable rainfall has made agricultural production a daunting task. The variability brings with it extreme events such as drought and floods causing famine, food scarcity and increase the spread of diseases. These extreme events have been reported to increase the likelihood of climate change (Batisani & Yarnal, 2010). Botswana is more vulnerable to climate change because of the fragile climate (Wingqvist & Dahlberg, 2008). Climate warming projected an changes in both temperature and rainfall, this change has a likelihood of producing severe negative impacts in the agricultural sector which is mainly based on water use (Nkemelang, 2018). Studies shows that Botswana is one of the worst countries to be hardly hit by the impacts of changing climate with serious consequences more pronounced in the agricultural sector, reducing yield significantly. Both extremes will negatively the agricultural sector, rainfall below average will cause water stress and reduce yields significantly while damage crops. Research agrees with the objective of this study which aims at increasing water availability through rainwater harvesting (Wingqvist & Dahlberg, 2008).

In a study conducted by (Batisani & Yarnal, 2010) to assess the rainfall variability in Botswana they applied the Mann–Kendall test (MK) is used to find out annual rainfall patterns, monthly rainfall pattern, and trends in rainy days per annum. They also used the standardized statistical test (Z) is used, a positive Z valve shows increasing trends and negative Z values shows decreasing trends. When testing either increasing or decreasing monotonic trends at a *p* significance level, the null hypothesis is rejected for absolute values of Z >Z1-p/2, found from standard normal cumulative distribution tables. For their research the standard significance levels of p = 0.05 and 0.10 are applied. Their study also assessed the variation (R2) of the correlation between yearly rainfall and number of rainy days per annum. The reason to assessing is to check whether a station's rainfall is explained more by the total number of rainy day or either rain individual large rainfall events. They found out that mean annual rainfall is low in the south western part of Botswana while in the northern part it was extreme. The standard deviations proved to be relatively small ranging between 137.4 mm and 195.6mm. their research proved to be correlating with studies done in the western Mediterranean and south Africa. The study conclude that rainfall has been decreasing both annually and on monthly bases.

A study conducted by Maboa, (2016) investigated rainfall by using satellite imagery in Botswana by analyzing whether there are any spatial and temporal changes in patterns from 1998 to 2013. For his methodology Tropical Rainfall Measuring Mission (TRMM) 3B43 dataset (1998-2013) was applied to abstract monthly rainfall data on magnitude and variability for a period over 15 years. The study also incorporated the application of GIS spatial analysis and the Anselin Local Moran's I tool to determine changes of rainfall conditions on annual bases for the entire study. Findings of the study revealed that comparatively, the rainy season is made up of considerably high rainfall variability and magnitudes, whereas post rainy season is made up of considerably low rainfall magnitudes and variability country wide. Rainfall with high magnitude was recorded in April mostly, despite the fact that April is the end of rainy season. The finding also amach with a research done by (Batisani & Yarnal, 2010) where they found out that the northern part of Botswana receives a relatively high amount of rainfall compared to other parts of the country despite the rainy season. The study also discovered that the frequency of rainfall events is high on rainy season above the long-term WorldClim average, while any other season is associated with low rainfall events below the long term WorldClim average. The findings also reveals that Botswana has experienced both wetter conditions and drier conditions compared to the historical documented record within the 15-year period. The trend discovered by Maboa, (2016) matches the conclusion made by Nkemelang, (2018) that there is a significant drying progressing over the years which could be a sign that climate is changing, however due to limited, documented data such observation it cannot be proven plainly as climate change.

Jain, Prakash, & Lungu, (2006) applied ARIMA technique which has long been used to analyze time-series of hydrological data. In their study, they assessed the deterministic and stochastic behavior extremum temperatures, solar irradiation, rainfall, and sunshine duration for some parts of Botswana. They found out that the pattern for temperatures is more deterministic from year to year, while rainfall follow a more stochastic pattern.

Climatic variability of a particular area is determined mainly by long-term precipitation and temperature variations. Climate variability research in the southern zone of Tigray regional state, Ethiopia by Hayelom et.al., (2017) was conducted to determine trends variation in climatic elements of temperature and precipitation. The station is mainly used to study the climatic records for detecting probable trends in the region. For analysis records of the daily, monthly and annual precipitation totals and temperature obtained from korem meteorological station were used for the period of 1981-2010 and 1985 – 2010 for Precipitation; and minimum and maximum temperature respectively. The results of the study of descriptive statistics and Mann Kendall test methods demonstrated an increasing trend; however, minimum temperature displayed a decreasing trend. As for rainfall analysis for 30 years period (1981-2010) the results indicated a coefficient of variation ranging between 33.77 – 233 %. This is an indication that variance of precipitation is not normal with a great margin from year to year (Hayelom et al., 2017).

Al-suhili & Khanbilvardi, (2014) conducted a study with different frequency distributions models at Sulaimania region, north Iraq using monthly rainfall data. The data was fitted into 3 different distributions models which are Normal, Log-normal, Wiebull, Exponential and Two parameters Gamma type, while the Kolmogorov-Smirnov test was used to estimate the goodness of fit. The findings revealed that, Gamma distributions had highest percent of best fit and the analysis (Al-suhili & Khanbilvardi, 2014). Some of the distribution models are described below:

1. Weibull Distribution Model

Weibull distribution in 1937 named after him in 1951 invented the Weibull distribution model and since then it is most commonly applied lifetime statistical distribution model for data analysis (H.Bainbridge et al., 2011). It has been used in many applications including weather forecasting and fitting all kinds of data in reliability engineering. It is used to test the mean time between the failures.

2. Lognormal Distribution Model

The lognormal distribution is commonly used to model the lives of units whose failure modes are of a fatigue-stress nature.

3. Normal Distribution Model/ Gaussian Distribution

The normal/Gaussian distribution, is one of the most commonly-used lifetime distributions model for reliability and life data analysis. Normal pdf has a bell shape and it does not change. It is influenced by standard deviation, which is the scale parameter. An increase in $\sigma_T$ spreads pdft away from the mean while a decrease in $\sigma_T$ pushes the pdf toward the mean. Random errors often follow normal distribution. The standard normal distribution is a Gaussian distribution with mean = 0 and variance = 1.

4. Exponential Distribution Model

This exponential distribution is used to model the time between successive events and behavior of units that have a constant failure rate.

5. Goodness of fit
    a. The Chi-square test

The Chi-square is a non-parametric test of significance that determines whether value are distributed across the distribution as expected.

To design and operate water resources systems are there is need for baseline hydrological assumption. Availability of profound pattern of distribution data for analysis is important in determining hydrological assumptions. These assumption can be used to bases in assessing, designing and operating hydrological systems (Kizza, Rodhe, Xu, Ntale, & Halldin, 2009). This chapter serves, as a foundation for hydrological modeling since data trends needs analysis, coming up with assumptions needed for designing and operating hydrological systems.

### 6.1.4. HYDROLOGICAL MODELING

Models are the most important tools in water resources assessment for key decision making in catchment water balance. They vary in complexity depending on data availability and levels of accuracy. Hydrological models seek to stimulate how watershed and river basins react as rainfall is transformed to runoff. These tools are however, limited by field data shortage. These tool are becoming useful in analyzing stream flow quality and quantity, catchment characteristics analysis for effective management and distribution of water resources for various use and activities (Holman, 2005). Over the years they have been used to solve hydrological problems by stimulating catchment behavior.

Over the years models have been applied in several experiments in catchments to support decision making and policy making on water resources. Models are classified into three categories which are: (i) physically based models, (ii) conceptual models, and (iii) data-driven models. Physically based models are relatively complex since they apply mathematical principles to describe physical processes of mass balance and energy conservation. They have been used in the analysis of environmental and water resources problems (Munyaneza, 2014). Data driven models also involve mathematical equations within limited boundaries by analyzing input-output time series. The conceptual models are the mostly used models. They make use of both field and calibrated data.

Conceptual models have been applied to many catchments in Africa and the results shows great correlation in the relationship between rainfall-runoff processes. There are various reasons why hydrological stimulation is being done, they include: determining the input and output of existing catchments; estimating runoff of catchments; predicting how catchments respond to changes in landuse and climate change.

Jovanovic et al. (2012) conducted a study using in South Africa using J2000 model that is used to stimulate water balance in a spatially distributed manner for large catchments. The J2000 model focuses on three main processes which are: temporal climate data distribution, runoff generation and flood routing. The model incorporates the use of GIS to input basin characteristics data (slope, soil, geology, elevation and landuse). Daily input data used by the model include precipitation, minimum and maximum temperature, sunshine duration, wind speed and relative humidity. The objective of the study was to separate hydrograph and identify streamflow contributors. The findings of Jovanovic et al. (2012) reveal that streamflow is more reliant on rainfall distribution in time than annual average rainfall.

A research conducted by Gangodagamage (2001) developed a hydrological model for Bita River Basin in India using ILWIS, ERDAS and AutoCAD Map software. The model proved to be effective in forecasting the runoff of a given rainfall event. In a study done by Tamalew & Kemal, (2016) to find out the model parameters. Using trial and error for sensitivity analysis, the HBV-96 model proved to be good in estimating discharge for catchment by regional method. HEC-HMS was applied in an oil palm catchment and the results shows that peakflow and stormflow are correlating well with rainfall (Yusop, Chan, & Katimon, 2007).

Botswana is a country with a scarce water resource as vast amount of its land coverage is a desert (Kalahari) which is approximately 70%. Despite this water deficient condition, over 80% of its population is dependent on subsistence rained agriculture. This condition makes the subject of water availability very important. Increased understanding and knowledge of water resources is the foundation for effective management and policy formulation (Munyaneza, 2014).

Management, assessment and monitoring of water resources requires hydro-climatological data which is often a challenge in most African countries. Increased competition of water use from population growth, industries and agriculture possess a threat to the already poorly monitored, quantified, assessed precious resource. It is then very important to increase our knowledge of the hydrological cycle and the spatio-temporal distribution of water resources for its effective use and management. The rational method is most widely applied technique for estimating discharge in small catchment since the mid-19th century. The rational method has a concept of time of concentration which is defined as the time it take for a drop of rain to contribute to runoff at the outlet of a catchment. The objective of this chapter is to estimate peak flow in the catchment. Peak flow is influenced by land use, land cover and soil type hence runoff coefficients has to be determined.

Water for agriculture is the stronghold for any country for it to progress in terms of socio-economic development. Over the years the value of water has increased and it shall continue becoming more precious in decades to come. For these reasons it is important to focus more research and resources in sustainable water resources management and development. Water for irrigation should be in the forefront in water resources availability especially for Botswana, a country which its livelihood is mainly depending on rainfed agriculture in such unreliable weather and changing climate conditions.

In assessing water availability, there is need to delve deeper into the hydrological process in order to understand the basis needed for sustainable catchment management. To understand rainfall processes and catchment properties calls for hydrological modelling which plays an important role in water resource and catchment. However, such studies are affected by lack of rainfall distribution and stream flow data which are required in the calibration and validation processes. Findings of this study will not only add up to the knowledge base, but also contribute to sound decision making in water resource planning and development for the Francistown catchment.

# 7. CHAPTER 6

## 7.1.1. DATA SETS

### 7.1.2. Data quality assessment

The efficiency and conclusions drawn from hydrological models is determined by the quality of the data. Data in Botswana like most African countries is collected and recorded manually. Data handled by different hands over years in different locations is bound to have problems of quality (Kasei, 2009). Errors usually occurs during reading/observation, recording/typing and in digitizing data from sheets. The data was verified by comparing data with neighboring weather stations which have the same squall lines, visually observing the data and picking out doubtful data that differ greatly from normal values based on personal knowledge of the area. And lastly, through regression with long-term data of the same station.

### 7.1.3. Meteorological Station

The Department of Meteorological Services (DMS) is the provider of meteorological data that has been used for this research. This department is responsible for measuring and monitoring rainfall around the country. The monthly rainfall data was for 35 years from 1980-2015 from Francistown Airport weather stations.

### 7.1.4. Hydrological data

In pursuit to understanding the hydrologic nature of the Francistown catchment, historical data is needed to calibrate, validate a hydrological model. This will helps us in attaining one objective which is to assess the hydrological changes and possible impacts of climate change in the basin if there is any. The annual rainfall amount was calculated by averaging the rainfall amount of the rain gauge. The monthly rainfall data was obtained from Department of Meteorological Services (DMS) in Gaborone.

**Meteorological stations in the catchment**

| **Station** | **Elevation** | **Latitude** | **Longitude** |
|---|---|---|---|
| Francistown Airport | 1000 Metres | 21 Deg 09 Min S | 27 Deg 29 Min E |

### 7.1.5. Streamflow

Water Affairs department is responsible for management, recording and monitoring of streamflow, catchment reservoirs, aquifers and its data dissemination. This data is essential for model calibration and validation to imitate water balance of the catchment. For this research river discharge records measured manually from 1970 to 2007 from Tati river were used. The continuously using a 120° V-notch weir.

# 8. CHAPTER 7

### 8.1.1. MATERIALS AND METHODS

Monthly rainfall data set for Francistown for a period of 35 years (1980-2015) was obtained from The Department of Meteorological Services (DMS). For this research, reliable gauging stations with consistent data which are representative of the entire catchment were selected for analysis and modeling. The gauges are located strategically at representative elevations within the catchment.

For this research time series analysis of the monthly and annual rainfall data were applied to demonstrate the trend in the performance of rainfall and in approximating periodic variation. Linear regression analysis was used Microsoft Excel statistical tool and it was very effective in examining the rainfall variability (Chibuike et al., 2014). Basic descriptive statistics was used to calculate and analyze rainfall variability in the Francistown catchment using spreadsheet. These statistics include annual minimum rainfall, annual maximum rainfall, annual mean rainfall, Standard Error, Median, Standard Deviation, Sample Variance, coefficient of kurtosis, Skewness, Range, Coefficient of variance and Confidence Level (95.0%) precipitation were determined. Statistical analysis determines the measure of central tendency (mean, range, etc.) and dispersion. (S.D., CV, etc.). Below are some of the formulas applied in Descriptive Statistical Analysis:

I. Mean: Is the sum of all the scores divided by the number of scores for a measure.
Mean $\mu = \frac{\sum x}{N} = \frac{x_1 + x_2 + x_3 + \cdots + x_N}{N}$

II. Mean Absolute Deviation $MAD = \frac{\sum |x-\mu|}{N}$

III. Population Variance $\sigma^2 = \frac{\sum (x-\mu)^2}{N}$

IV. Population Standard Deviation $\sigma = \sqrt{\frac{\sum (x-\mu)^2}{N}}$

V. Sample Variance $s^2 = \frac{\sum (x-\overline{x})^2}{n-1}$

VI. Population Mean $\mu = \frac{\sum x}{N} = \frac{x_1 + x_2 + x_3 + \cdots + x_N}{N}$

VII. Sample Mean $\overline{x} = \frac{\sum x}{n} = \frac{x_1 + x_2 + x_3 + \cdots + x_n}{n}$

VIII. Interquartile Range $= Q_3 - Q_1$

IX. Sum of Deviations from the Arithmetic Mean is Always Zero $\sum (x-\mu) = 0$

X. Mean Absolute Deviation $MAD = \frac{\sum|x-\mu|}{N}$

XI. Empirical Rule*

a. Distance from the Mean — Values within the Distance

| Distance from the Mean | Values within the Distance |
|---|---|
| i. $\mu \pm 1\sigma$ | 68% |
| ii. $\mu \pm 2\sigma$ | 95% |
| iii. $\mu \pm 3\sigma$ | 99.7% |

XII. Chebyshev's Theorem

a. Within $k$ standard deviations of the mean, $\mu \pm k\sigma$, lie at least

b. $1 - \frac{1}{k^2}$ proportion of the values. Assumption: $k > 1$

XIII. Coefficient of Skewness $s_k = \frac{3(\mu - M_d)}{\sigma}$

i. where:

ii. $s_k$ = coefficient of skewness

iii. $M_d$ = median

XIV. Coefficient of Variation $cv = \frac{\sigma}{\mu}(100)$

XV. Sample Standard Deviation $s = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}}$

XVI. Computational Formulas for Population Variance and Standard Deviation

a. $\sigma^2 = \frac{\sum x^2 - \frac{(\sum x)^2}{N}}{N}$

b. $\sigma = \sqrt{\sigma^2}$

XVII. Computational Formulas for Sample Variance and Standard Deviation

a. $s^2 = \frac{\sum x^2 - \frac{(\sum x)^2}{n}}{n-1}$

b. $s = \sqrt{s^2}$

XVIII. Regression Line: is a that summaries the relationship between the variables in a scatter plot drawn through the points that are being studied.

XIX. The probability (P value) is the significance of the slope. The regression analysis, value of $R$-square ($R^2$) was used to show the relationship between the variables $X$ and and the strength of correlation which is a fraction between 0.0 and 1.0. If An $R^2$ value is 1.0 it means that there is a correlation whereas a $R^2$ value of 0.0 means that there is no linear relationship and correlation between $X$ and $Y$ (Nyatuame et al., 2014).

### 8.1.2. FREQUENCY ANALYSIS

Probability density function (PDF) are mathematical model that are used to estimate values of rainfall probabilities. Here are some of the few selected mathematical description:

1. Weibull Distribution Model

$$f(T) = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}} \quad f(T) \geq 0,\ T \geq 0 \text{ or } \gamma,\ \beta > 0,\ \eta > 0,\ -\infty < \gamma < \infty,$$

Where: η = scale parameter which reflect the size of units which the variable t, is measured, β = shape parameter (or slope) and γ = location parameter.

2. Lognormal Distribution Model

$$f(T) = \frac{f(T')}{T},$$

$$f(T) = \frac{1}{T \bullet \sigma_{T'} \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln(T)-\mu'}{\sigma_{T'}}\right)^2}$$

$$f(T) \geq 0,\ T > 0,\ -\infty < \mu' < \infty,\ \sigma_{T'} > 0$$

3. Normal Distribution Model

The normal distribution is described by the following formula:

$$f(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad -\infty < x < \infty$$

where the function f(x) defines the probability density associated with X = x.

4. Exponential Distribution

$$f(x) = \frac{1}{\beta} e^{-x/\beta}, x \geq 0. \qquad \mu = \beta, \sigma^2 = \beta^2$$

5. The Chi-square test

$$X^2 = \sum \frac{(O - E)^2}{E}$$

Where: O = Observed frequencies

E = Expected frequencies

8.1.3. MODELING

8.1.1. HYDROLOGICAL PARAMETERS

**8.1.2. Mean annual runoff**

Mean annual runoff measure the amount of surface water available in a catchment.

**8.1.3. Basin Yield**

Basin yield is the most fundamental element in reservoir storage capacity. It measure the amount of water available for storage in a given year until it is needed for use. A time series curve is normally used to estimate the amount of catchment yield on monthly and annual bases.

**8.1.4. Annual Low Flow (q90)**

The Botswana National Water Policy of 2012 regard water as an essential element of life, sustaining environment and long term development if it sustainably used as a limited resources (Botswana Ministry of Minerals Energy and Water, 2012).

8.1.5. HYDROLOGICAL PROCESS

It is important to understand the hydrological process as it provides the foundation to hydrological modelling (Munyaneza, 2014). There are many factors that influence surface runoff, some of the major factors are rainfall amount and its intensity, landuse/land cover, topography, soil type and geology.

### 8.1.6. CLIMATE FACTORS

### 8.1.7. Temperature

Botswana is a semi arid climate country, which influence the high temperatures. The temperatures are extreme in the north eastern and south western region. Minimum average temperature 2.1°c was recorded in Tsabong 2016 July and the highest was recorded in Shakawe 37.3°c in October (Botswana Statistics Botswana, 2013).

### 8.1.8. Rainfall

Rainfall in Botswana is highly erratic and variable in space and time. The rainfall ranges from 650mm in north east and 250mm in the south west making an average of 450mm per annum (Botswana Statistics Botswana, 2013). The rainfall fall below average during El Nino and rises above average in La Nina.

### 8.1.9. Wind speed

The Department of Meteorological Services (DMS) records the wind speed across the country and our country lies between westerlies and the trade winds, which are 30 and 35 degrees north and south. The highest average speed was recorded in Goodhope with a monthly average of 3.9m/s.

### 8.1.10. WATER BALANCE

Rainfall is most important input component in the hydrological cycle, which is transformed into dependent variables including streamflow, evaporation, water storage and evapotranspiration. Simplified mathematical computations have been used to determine water balance in a catchment (Jovanovic & Clercq, 2012). There are various formats used to express the water balance equation. Below is the commonly used form:

$$P - E_a - SS = Q$$

where:

P is the precipitation,

$E_a$ the actual evaporation, SS the soil storage and

Q the streamflow.

SCS method is another method used to forecast runoff and discharge estimate at the outlet. This method establishes a relationship between land cover, hydrological soil group and curve number. Curve number signifies the possibility of runoff depending on hydrological soil cover. (Gangodagamage., 2001) This method applies the following equation:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)}$$

Where:

Q-Direct runoff

$I_a$-Initial Abstraction

P-Precipitation

S-Maximum Potential Retention

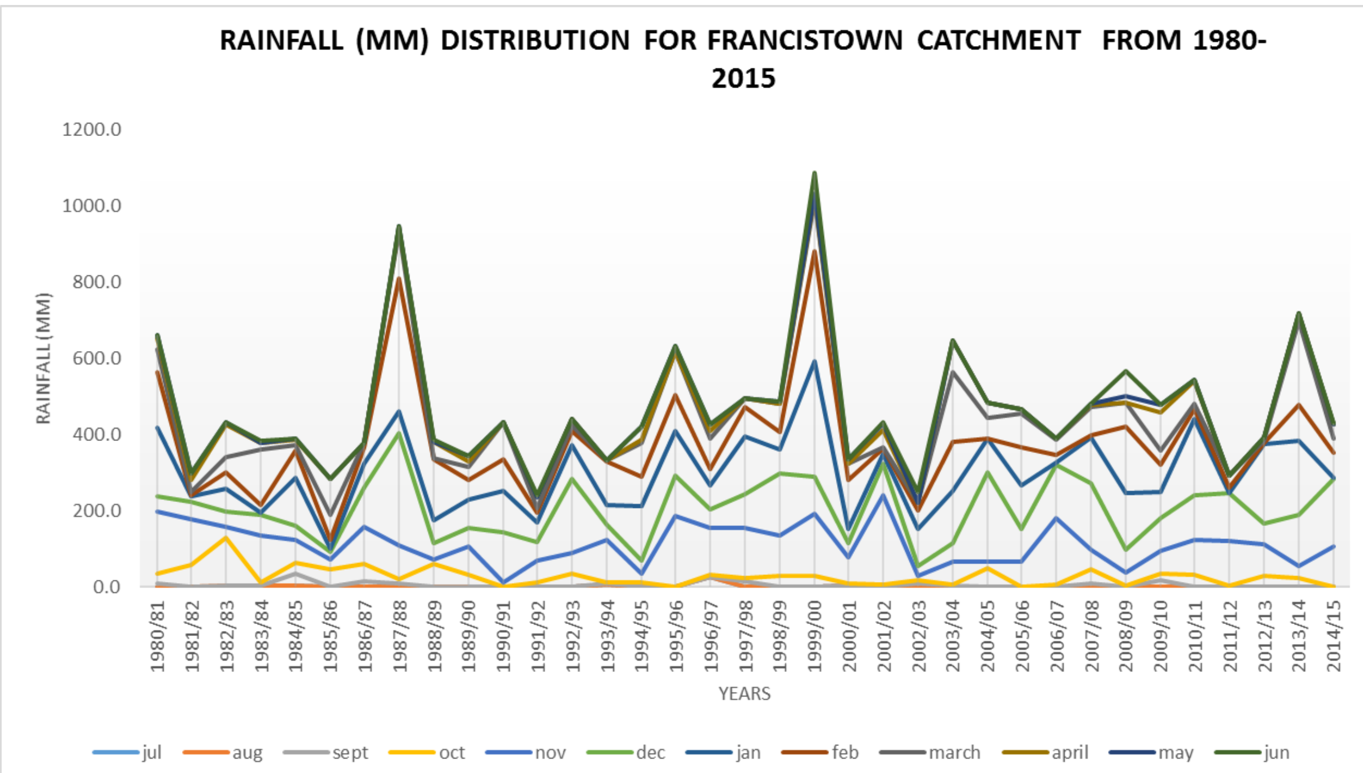
The complexity in water balance calculation is dependent on availability of hydrological data. Since precipitation is the fundamental, the data has to be complete, reliable and representative of the entire catchment.

# 9. CHAPTER 8

### 9.1.1. FINDINGS

### 9.1.2. RESULTS OF ANNUAL RAINFALL VARIABILITY ANALYSIS

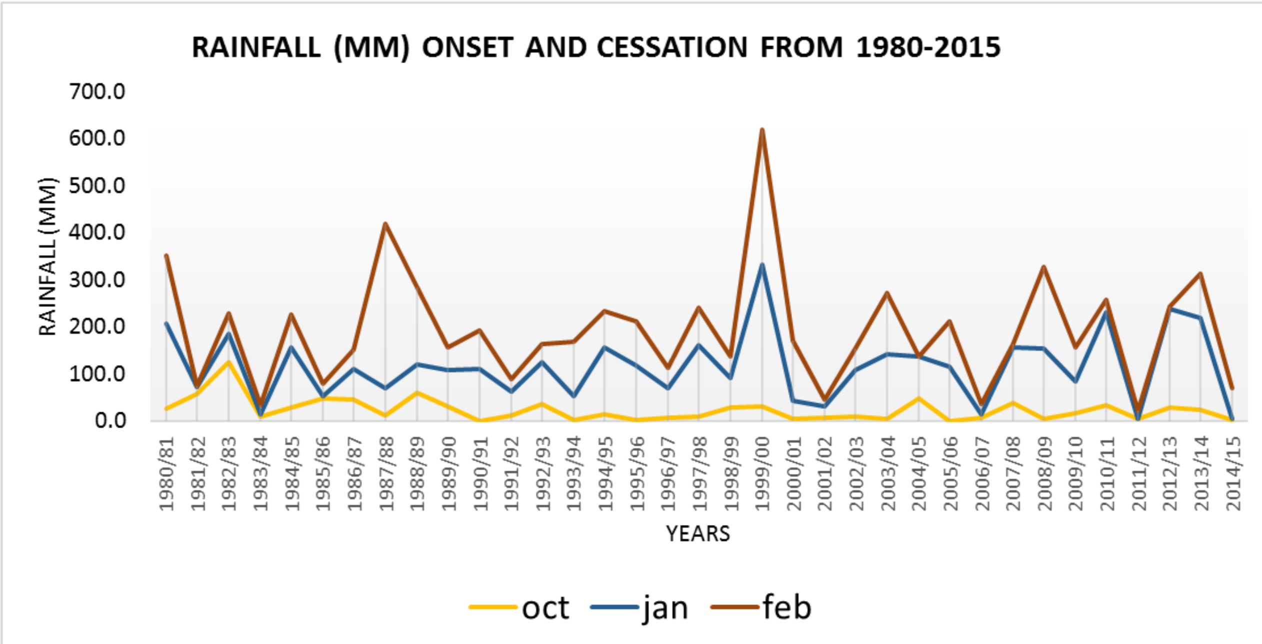
Rainfall distribution of Francistown catchment is shown in Graph 1 below. There are two peaks which seem to be outliers in the distribution. These peaks recorded the highest rainfall in the trend for the entire distribution period from 1980-2015. The highest recoded rainfall was 1086.4mm on February 1999/2000. According to the trend most of the precipitation lies in between the ranges of 200mm and 400mm. The graph shows that some years suffered water scarcity particularly 1982–1987, 1991–1992, 2001-2004, 2007-2008, and from.2011-2013. However some years like 1995/96 received above average rainfall. The rainfall is variable distributed for the entire period which is an expected kind of distribution. It is notable that the rainfall is distributed between September and April.

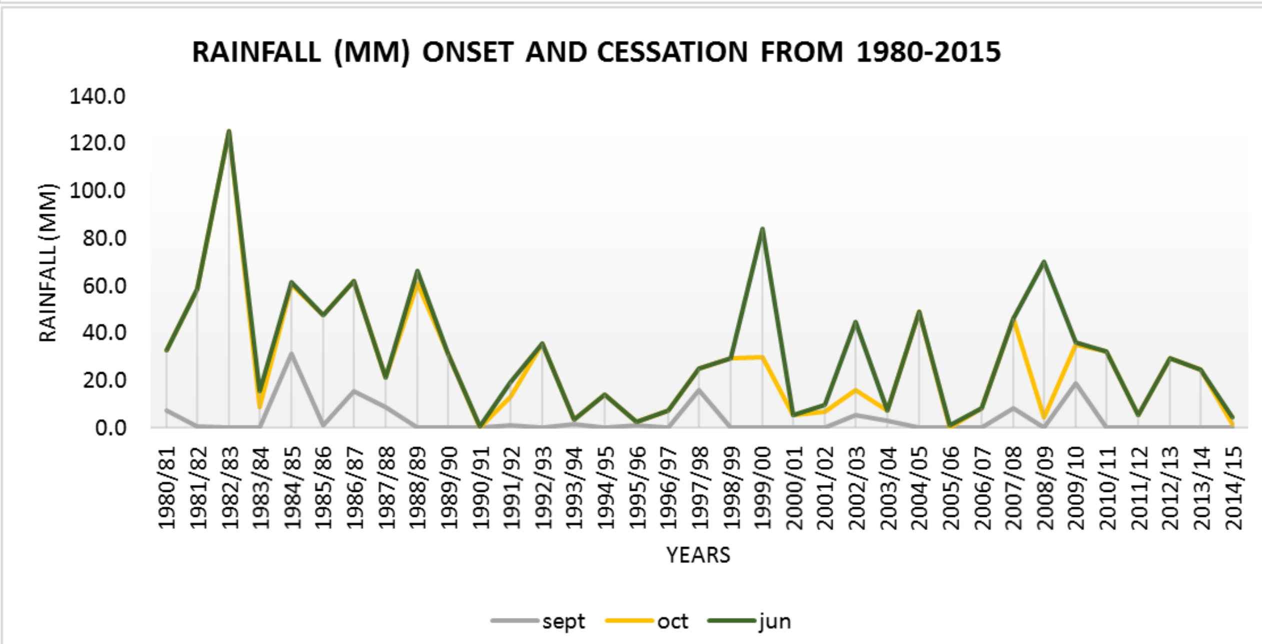



Graph 1: Overall rainfall distribution from 1980-2015

Graph 2 below present rainfall onset and cessation. The results shows that onset of rainfall is variable from year to year. The earliest time rainy season has started was on September, that too at great variation with light showers, a maximum of 35.1mm. Onset of rainfall is more significant in October however, the precipitation has been decreasing over time with from the highest record of 125mm in 18982/83 and to the lowest of 00mm in 2006/05. After onset, the rainfall increases in magnitude through to February were it reaches its peak.

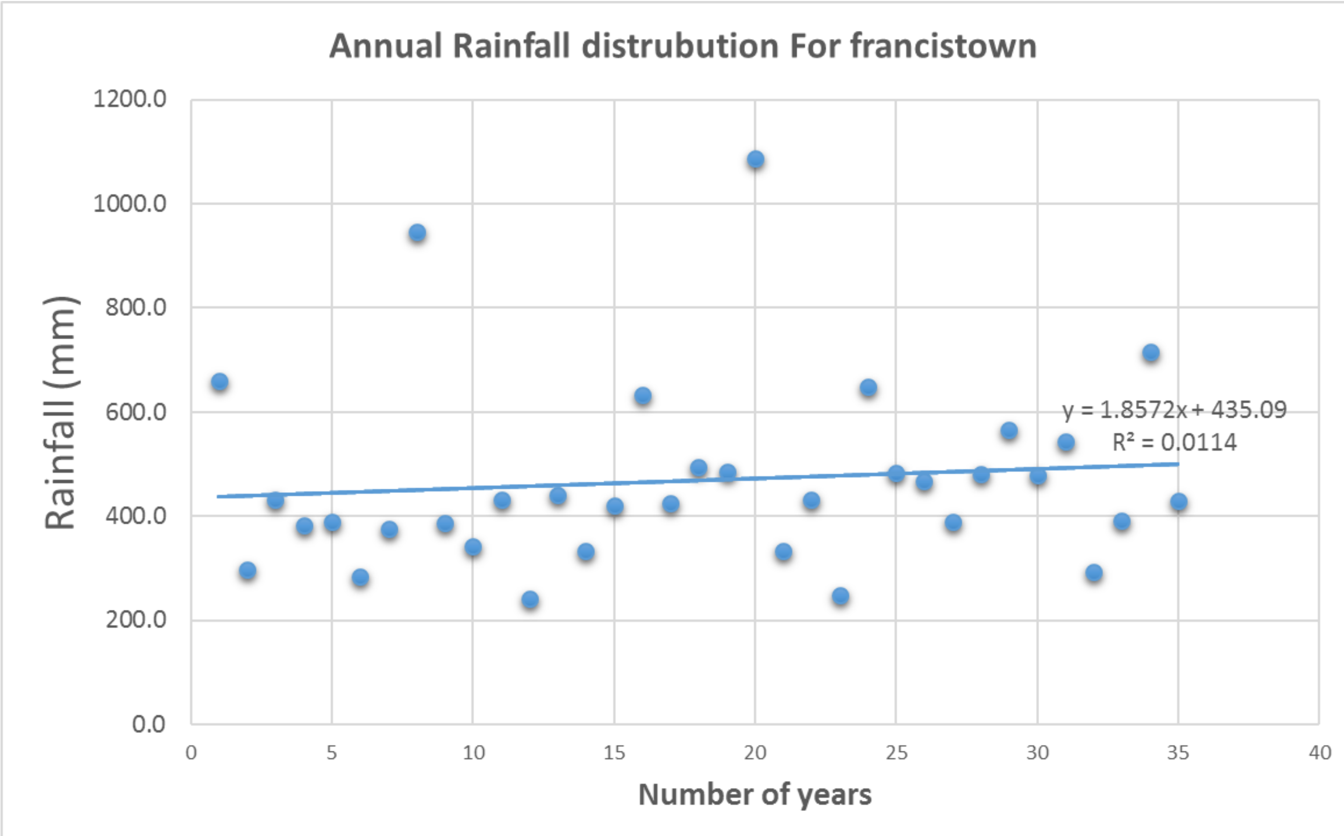
From February through to march the rainy season approaches cessation. According to the trend, many years do have any record in precipitation while some receives only light showers. The distribution however, from onset to cessation depicts a great variation throughout the trend. Changes in onset negatively affect the dryland farmers who depends entirely on onset and cessation of rainy season.



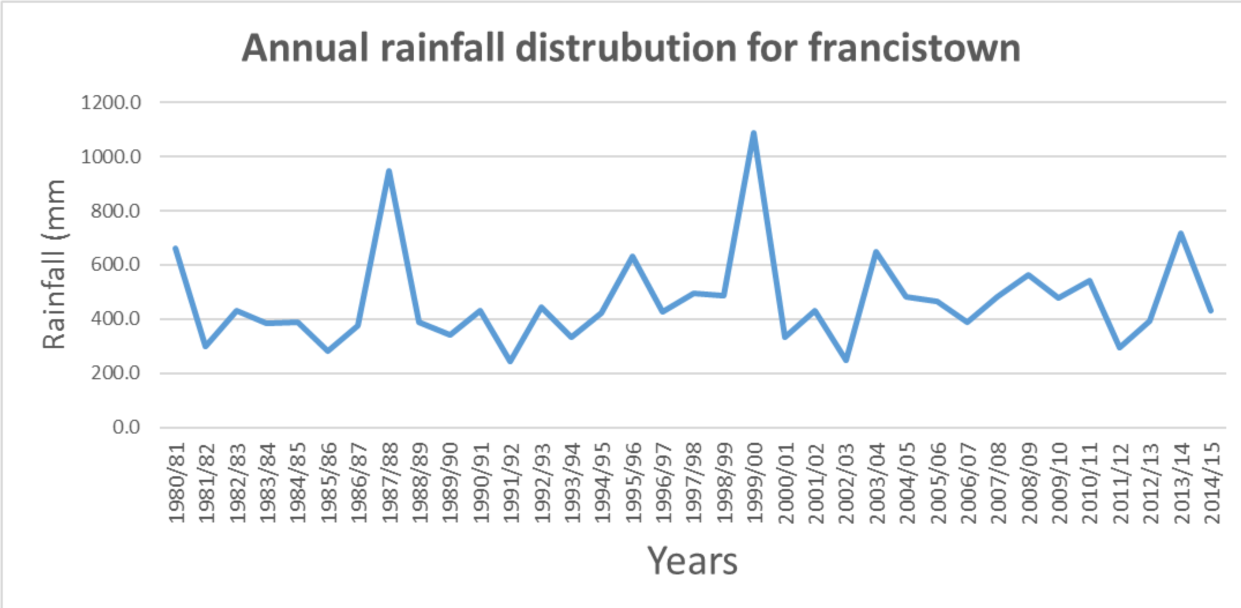

Graph 2: Rainfall onset and cessation 1980-2015

The trend of Francistown rainfall in Graph 3 shows a more pronounced variation it total rainfall for the 35 years. Rainfall in Francistown is slightly over the years. The regression analysis $R^2$, is relatively small which shows that rainfall is unevenly distributed, the rainfall is not distributed around the mean.



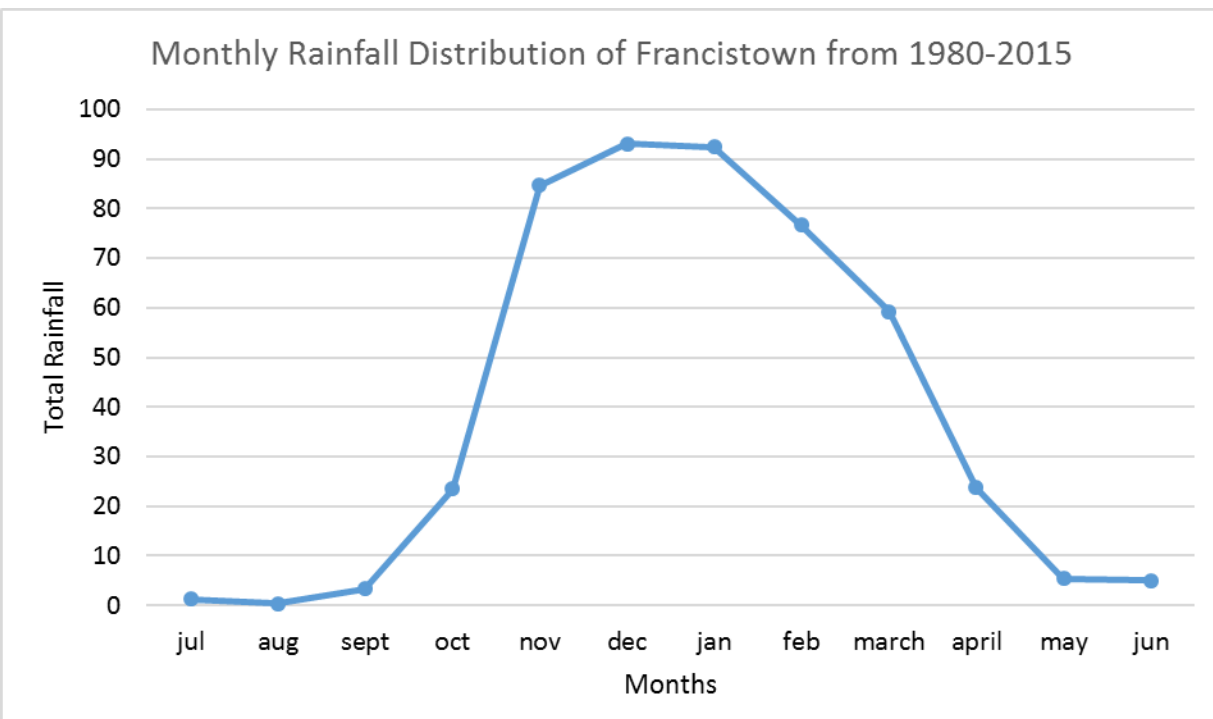

Graph 3: Regression of Total Annual Rainfall distribution from 1980-2015

Total rainfall distribution of Francistown in graph 4 below is showing a substantial increase in the overall mean over time. After the year 1995 total average rainfall was way above 400mm. This notable change is a wakeup call both for hydrologist, stakeholders and policy makers. The observation could be a sign of either inter decadal variation or climate change.




Graph 4: Total Annual Rainfall distribution from 1980-2015

Months that have the highest amount of rainfall are November, December and January as observed in graph 5 below. Between September and October rainfall is on the increasing trend while February to May the rainfall is on the decreasing state. Between June and August it is a dry season, there are no rainfall records.



Graph 5: Monthly rainfall distribution from 1980-2015

The average annual rainfall of the 35-year period is 468.52mm as recorded in table 1 below. Rainfall in the catchment is highly variable, variance of 31769.1516 with a coefficient of variation of 0.3804. The quartile ranges for 25%, 50%, 75% and interquartile range are 431.3, 548.06, 490.75 and 110.4 respectively. The cumulative rainfall for the entire 35 year period is 16 398.2mm, the highest ever recorded annual bases is 1086.40mm in 1999/2000 while the least ever recorded was 241.80mm in 1991/92.

Since Kurtosis measures the amount of probability in the tails or the peakedness of a distribution with a value of 3, the analysis from the study found the value of Kurtosis to be 4.15, value is greater than 3. This means therefore that the data sets has heavier tails than a normal distribution, which is very true because the data great number of outliers in both extremes. The distribution varies considerably a minimum of 241.80mm in 1991/92 to a high of 1088.40mm in 1990/00.
Skewness measures how symmetrical the data is. The data is symmetrical if skewness is between -0.5 and 0.5, If the skewness is between -1 and – 0.5 or between 0.5 and 1, the data are moderately skewed, then data highly skewed if the skewness is less than -1 or greater than 1. From this study the skewness is 1.81, it therefore means that the data is highly skewed. There is no symmetry in the distribution. The results of the various statistical tests showed that the coefficients of skewness and kurtosis for the rainfall series for the period were not normally distributed. It correlates with regression analysis R2 that is very small indicating that the rainfall is not normally distributed around the average mean.
Statistical analysis gives us 95% confidence that the true mean lies between 407.292751 -529.747249 which a confidence interval of 61.2272

**Annual average rainfall from 1980-2015**

**Measures of Central tendency**

| | | | | | |
|---|---|---|---|---|---|
| **Mean** | 468.52 | **Median** | 431.3 | **Mode** | #N/A |

**Measures of Dispersion**

| | If the data is of a | | | |
|---|---|---|---|---|
| | **Sample** | **Population** | | |
| **Variance** | 31769.1516 | 30861.4616 | **Range** | 844.6 |
| **St. Dev.** | 178.23903 | 175.674305 | **IQR** | 110.4 |

**Skewness and Kurtosis**

| | If the data is of a | |
|---|---|---|
| | **Sample** | **Population** |
| **Skewness** | 1.81314769 | 1.73449735 |
| **(Relative) Kurtosis** | 4.15517225 | 3.41818782 |

**Percentile and Percentile Rank Calculations**

| **x** | **x-th Percentile** | **y** | **Percentile rank of y** |
|---|---|---|---|
| 50 | 431.3 | 431.3 | 50 |
| 80 | 548.06 | 548.06 | 80 |
| 90 | 654.92 | 654.92 | 90 |

**Quartiles**

| | | | |
|---|---|---|---|
| **1st Quartile** | 380.35 | | |
| **Median** | 431.3 | **IQR** | 110.4 |
| **3rd Quartile** | 490.75 | | |

**Other Statistics**

| | |
|---|---|
| **Sum** | 16398.2 |
| **Size** | 35 |
| **Maximum** | 1086.4 |
| **Minimum** | 241.8 |

**Chebyshev's Theorem observation**

| | | | |
|---|---|---|---|
| **Data points within** | 1.5 | **Std. Devns from mean** | 33 |
| | | **out of** | 35 |
| | | **which is** | 94.29% |
| | | **Minimum predicted by Chebyshev's Theorem** | 55.56% |
| | | **Minimum predicted by Empirical Rule** | 86.64% |

| | | **Rainfall** |
|---|---|---|
| 1980/81 | 1 | 659.60 |
| 1981/82 | 2 | 297.80 |
| 1982/83 | 3 | 432.30 |
| 1983/84 | 4 | 383.70 |
| 1984/85 | 5 | 389.40 |
| 1985/86 | 6 | 284.00 |
| 1986/87 | 7 | 377.00 |
| 1987/88 | 8 | 946.20 |
| 1988/89 | 9 | 387.80 |
| 1989/90 | 10 | 342.70 |
| 1990/91 | 11 | 432.20 |
| 1991/92 | 12 | 241.80 |
| 1992/93 | 13 | 442.00 |
| 1993/94 | 14 | 332.70 |
| 1994/95 | 15 | 421.10 |
| 1995/96 | 16 | 632.30 |
| 1996/97 | 17 | 425.50 |
| 1997/98 | 18 | 495.00 |
| 1998/99 | 19 | 486.50 |
| 1999/00 | 20 | 1086.40 |
| 2000/01 | 21 | 334.20 |
| 2001/02 | 22 | 431.30 |
| 2002/03 | 23 | 248.90 |
| 2003/04 | 24 | 647.90 |
| 2004/05 | 25 | 482.50 |
| 2005/06 | 26 | 467.00 |
| 2006/07 | 27 | 389.90 |
| 2007/08 | 28 | 480.70 |
| 2008/09 | 29 | 565.50 |
| 2009/10 | 30 | 478.40 |
| 2010/11 | 31 | 543.70 |
| 2011/12 | 32 | 293.30 |
| 2012/13 | 33 | 391.40 |
| 2013/14 | 34 | 716.70 |
| 2014/15 | 35 | 430.80 |

Table 1: Annual statistical analysis of rainfall data from 1980-2015

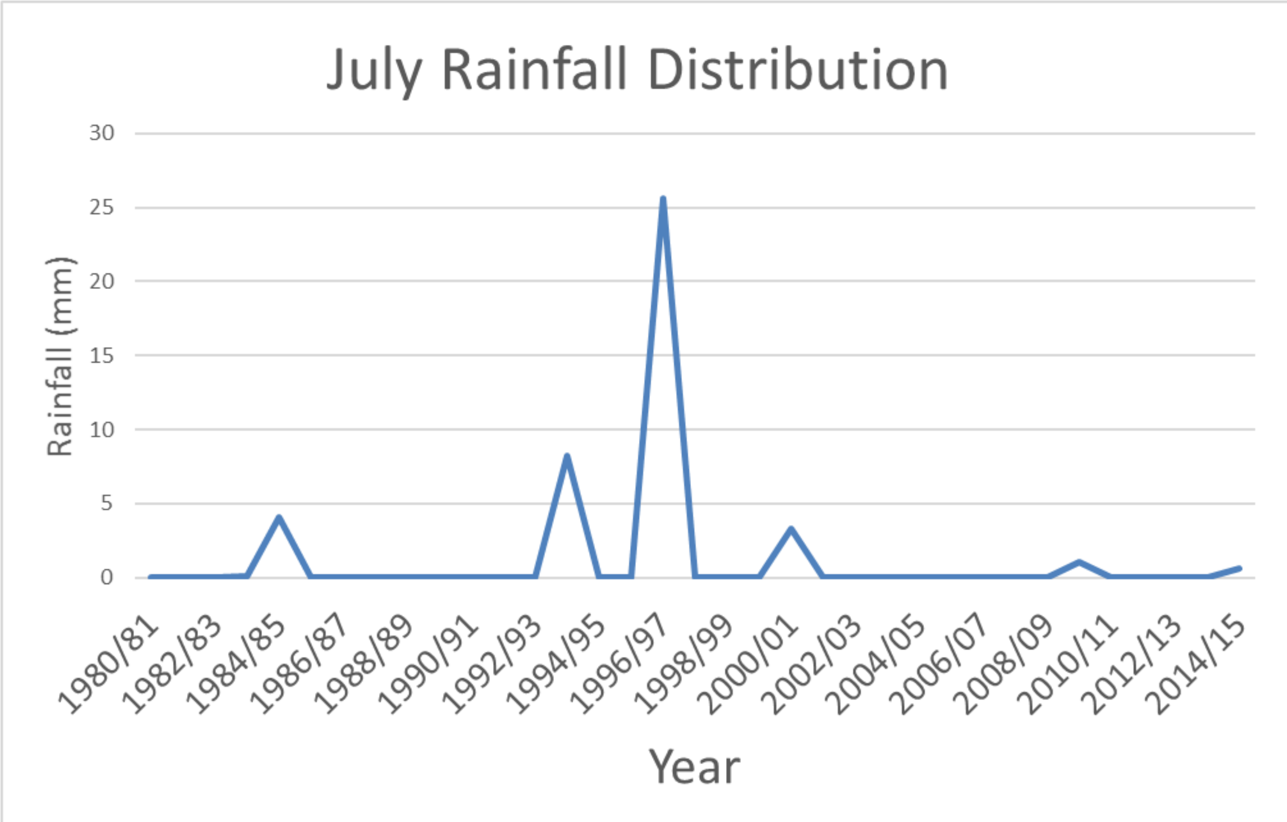
| **Year** | **Rainfall** | **sample size (N):** | **35** |
|---|---|---|---|
| 1980/81 | 659.6 | | |
| 1981/82 | 297.8 | **arithmetic mean:** | 468.52 |
| 1982/83 | 432.3 | **geometric mean:** | 442.301203 |
| 1983/84 | 383.7 | **harmonic mean:** | 420.579533 |
| 1984/85 | 389.4 | **median:** | 431.3 |
| 1985/86 | 284 | **mode:** | #N/A |
| 1986/87 | 377 | | |
| 1987/88 | 946.2 | **range:** | 844.6 |
| 1988/89 | 387.8 | **variance:** | 31769.1516 |
| 1989/90 | 342.7 | **standard deviation:** | 178.239 |
| 1990/91 | 432.2 | **coefficient of variation:** | 0.3804 |
| 1991/92 | 241.8 | | |
| 1992/93 | 442 | **standard error of the mean:** | 30.1279 |
| 1993/94 | 332.7 | **95% confidence interval:** | 61.2272 |
| 1994/95 | 421.1 | **upper 95% confidence limit:** | 529.747249 |
| 1995/96 | 632.3 | **lower 95% confidence limit:** | 407.292751 |
| 1996/97 | 425.5 | | |
| 1997/98 | 495 | | |
| 1998/99 | 486.5 | | |
| 1999/00 | 1086.4 | | |
| 2000/01 | 334.2 | | |
| 2001/02 | 431.3 | | |
| 2002/03 | 248.9 | | |
| 2003/04 | 647.9 | | |
| 2004/05 | 482.5 | | |
| 2005/06 | 467 | | |

| | | |
|---|---|---|
| 2006/07 | 389.9 | |
| 2007/08 | 480.7 | |
| 2008/09 | 565.5 | |
| 2009/10 | 478.4 | |
| 2010/11 | 543.7 | |
| 2011/12 | 293.3 | |
| 2012/13 | 391.4 | |
| 2013/14 | 716.7 | |
| 2014/15 | 430.8 | |

Table 2: Trends of annual rainfall data from 1980-2015

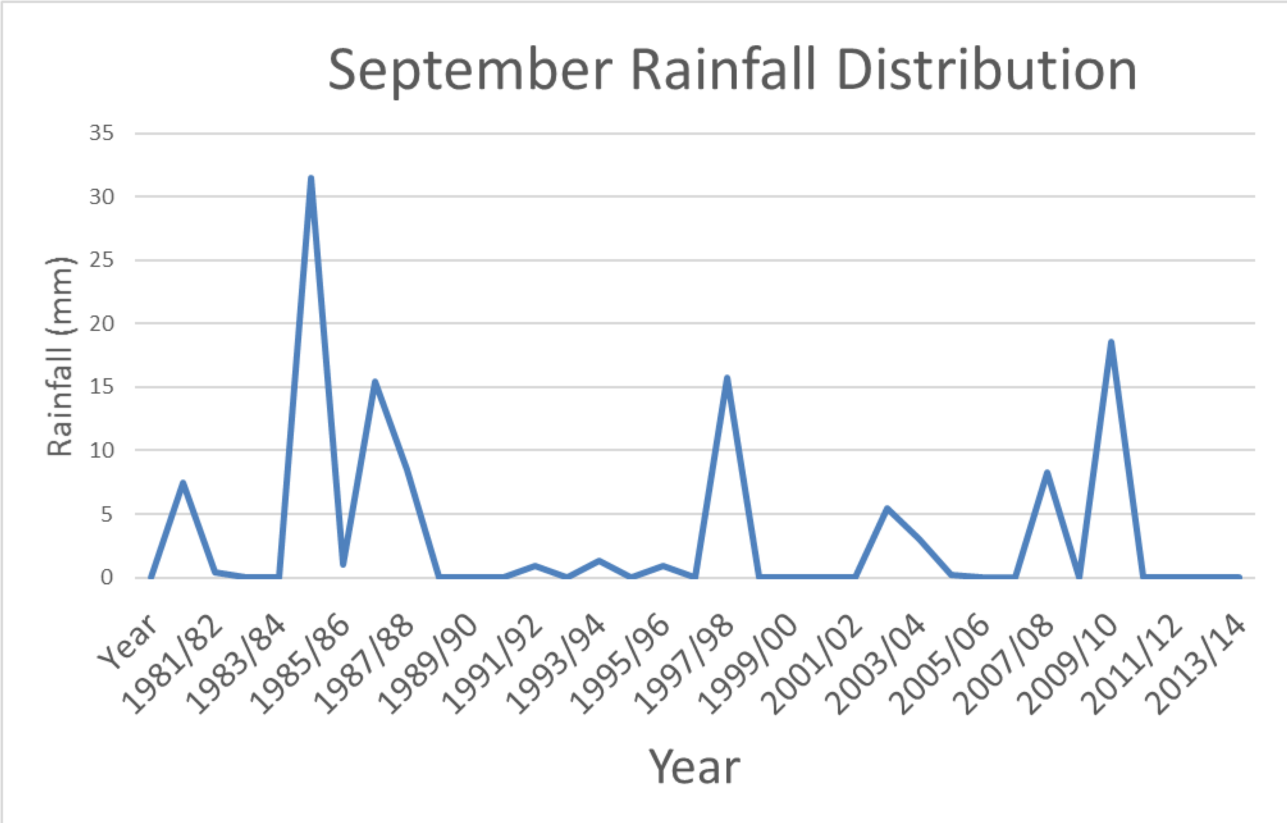
### 9.1.3. RESULTS OF ANNUAL RAINFALL VARIABILITY ANALYSIS

July is dry winter month; no rainfall is expected during this month. However, because of semi aridity of Botswana climate with its high unreliable and unpredictability of rainfall sometimes rainfall is received during this month. This rarely happens, as in this case it happened 5 times in 35 years as indicated on graph below.



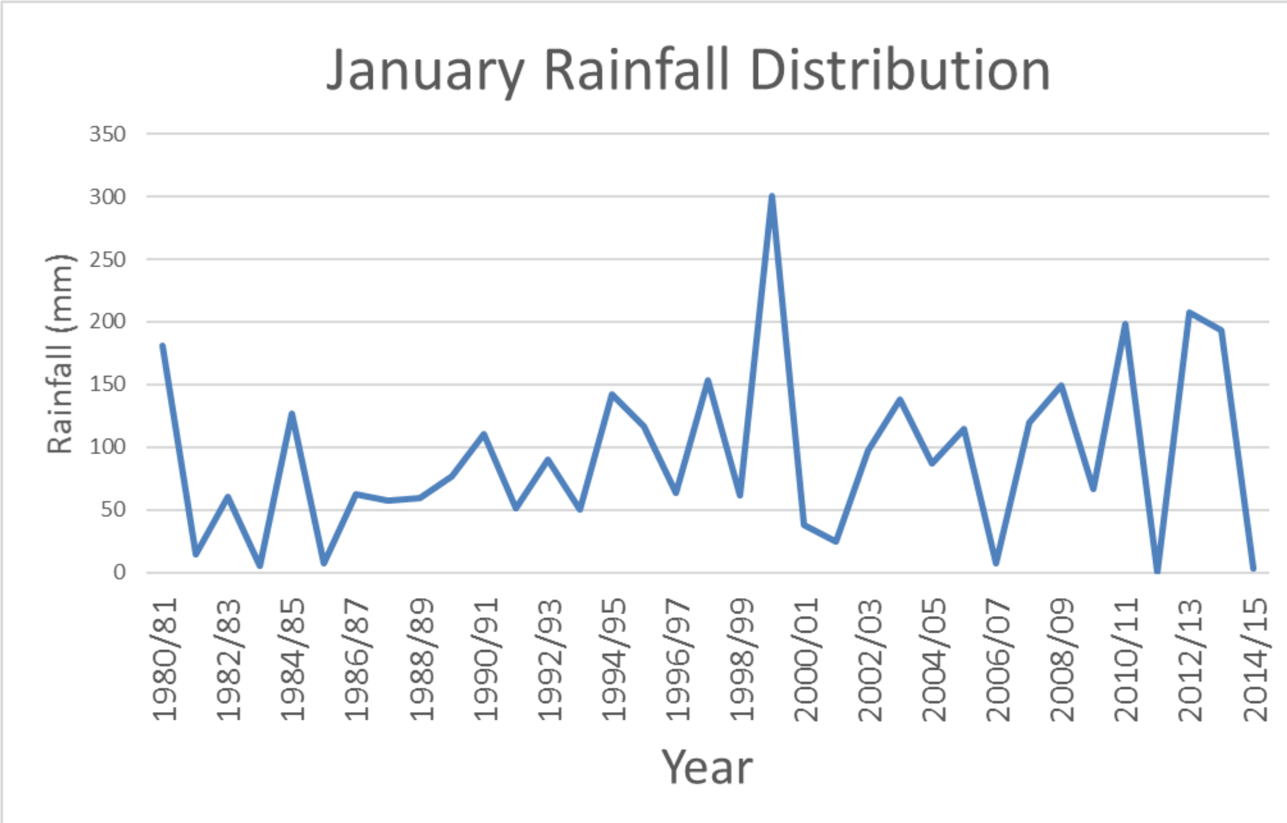

Graph 6: July Rainfall Distribution

September month, is the onset of rainy season, during this month rainfall is however less in magnitude, only light showers are received. Peak rainfall recorded is just a little above 30mm. The distribution is however not consistent over the years as shown in graph 7 below.



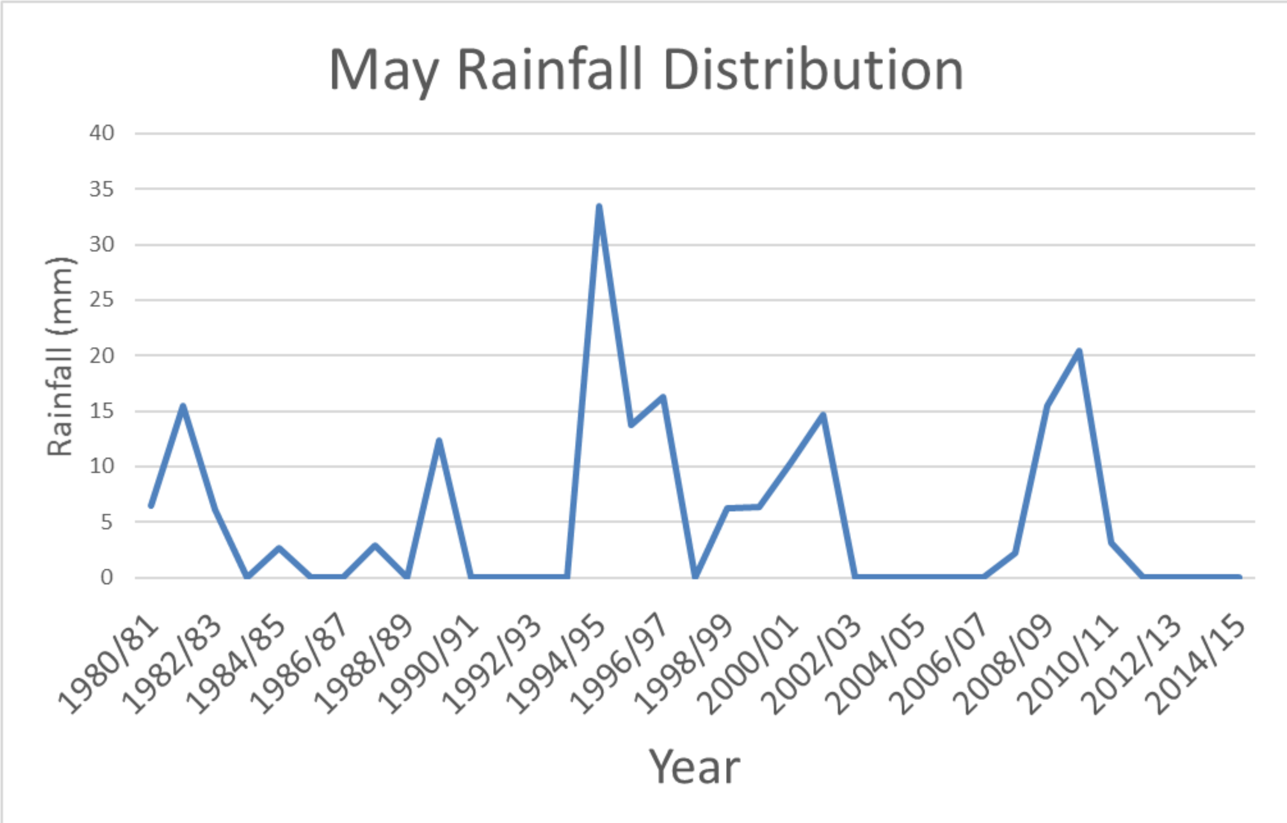

Graph 7: September Rainfall Distribution

During the January month, rainfall reaches the optimum peak in the rainy season. The distribution nonetheless is not consistent over the years as indicated in graph 8 below. January has recorded extremes in the trend, some years has ho rainfall while others like 1999/2000 has recorded over 300mm.



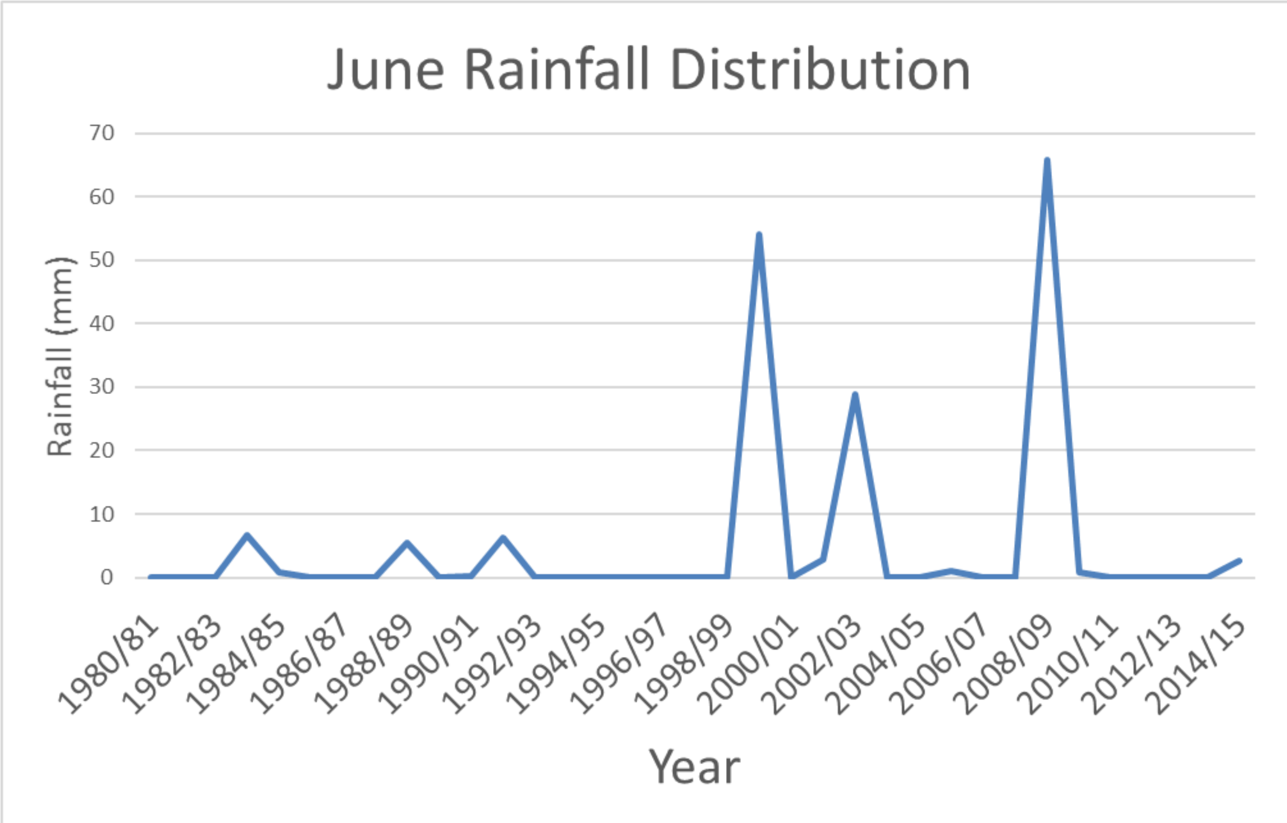

Graph 8: January Rainfall Distribution

May month is a period rainfall cessation; graph 9 below indicates a decrease in the magnitude of rainfall. For some years there is no rainfall recorded. The rainfall distribution in variable.



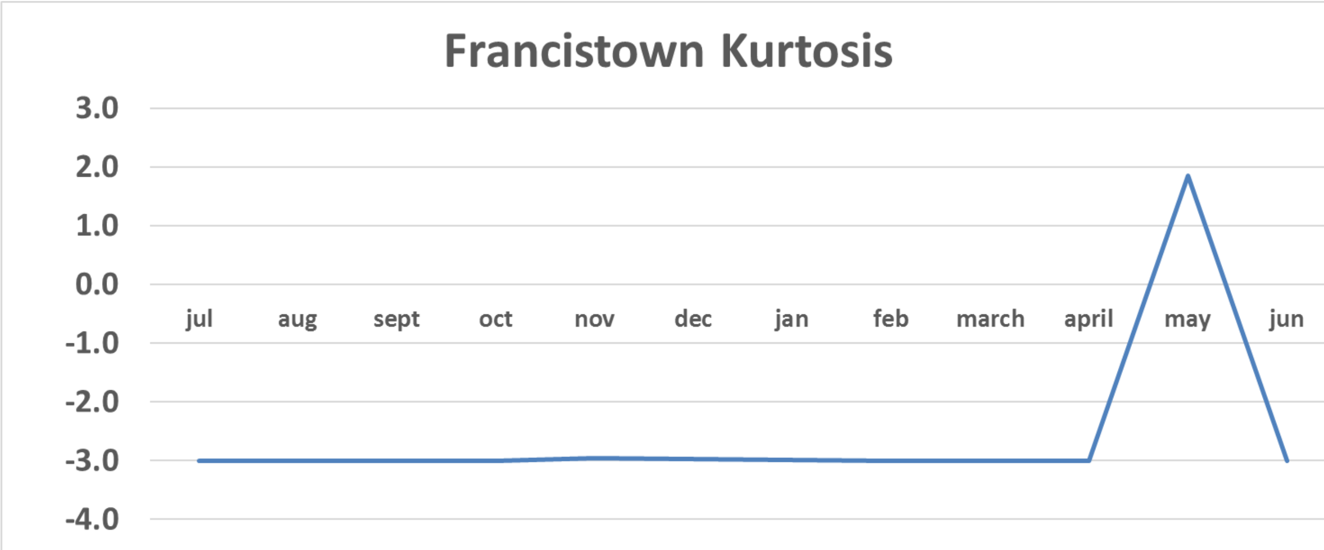

Graph 9: May Rainfall Distribution

June is dry winter season, under normal circumstances no rainfall is usually recorded during this time. Graph 10 below shows a significant amount of rainfall recorded between 1998 and 2010/11. This magnitude is significantly high compared to some years during rainy season.




Graph 10: June Rainfall Distribution

The monthly distribution of kurtosis coefficient for Francistown catchment is negative, this indicates that the distribution is less than the normal distribution curve with the same mean and standard deviation. It is a challenge to have a kurtosis of 3 in a highly variable semi-arid climate, with unpredictable rainfall. The coefficient of skewness however reveals that the curve is almost normally distributed since it is within the bounder limit.




Graph 11: June Rainfall Distribution

| Monthly Statistical analysis of rainfall data from 1980-2015 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Jul** | **Aug** | **Sept** | **Oct** | **Nov** | **Dec** | **Jan** | **Feb** | **March** | **April** | **May** | **Jun** |
| **Mean** | 1.2 | 0.3 | 3.4 | 23.5 | 84.6 | 93.1 | 92.4 | 76.7 | 59.2 | 23.7 | 5.4 | 5.0 |
| **Variance** | 20.0 | 0.9 | 47.5 | 598.8 | 2944.3 | 4013.8 | 4678.0 | 5694.0 | 2797.1 | 812.2 | 60.7 | 209.6 |
| **St.Dev** | 4.5 | 0.9 | 6.9 | 24.5 | 54.3 | 63.4 | 68.4 | 75.5 | 52.9 | 28.5 | 7.8 | 14.5 |
| **Skewenss** | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -0.0012 |
| **Kurtosis** | -3.0 | -3.0 | -3.0 | -3.0 | -2.9 | -3.0 | -3.0 | -3.0 | -3.0 | -3.0 | 1.9 | 3.0 |
| **1st Quartile** | 0.0 | 0.0 | 0.0 | 6.2 | 42.5 | 44.6 | 50.8 | 24.5 | 15.1 | 0.5 | 0.0 | 0.0 |
| **2nd Quartile** | 0.0 | 0.0 | 0.0 | 13.8 | 76.3 | 83.6 | 76.3 | 49.7 | 42.4 | 12.6 | 0.0 | 0.0 |
| **3rd Quartile** | 0.0 | 0.0 | 2.2 | 31.8 | 116.8 | 127.1 | 132.4 | 96.5 | 85.1 | 35.8 | 8.5 | 1.0 |
| **IQR** | 0.0 | 0.0 | 2.2 | 25.6 | 74.3 | 82.6 | 81.6 | 72.0 | 70.0 | 35.3 | 8.5 | 1.0 |
| **Coefficient Of variation:** | 3.7 | 2.9 | 2.1 | 1.1 | 0.7 | 0.7 | 0.8 | 1.0 | 0.9 | 1.2 | 1.5 | 2.9 |
| **Standard Error Of The Mean:** | 0.8 | 0.2 | 1.2 | 4.2 | 9.3 | 10.6 | 11.7 | 12.9 | 9.1 | 4.9 | 1.3 | 2.5 |
| **95% Confidence Interval:** | 1.6 | 0.3 | 2.4 | 8.5 | 18.9 | 21.4 | 23.8 | 26.3 | 18.4 | 9.9 | 2.7 | 5.0 |
| **Upper 95% Confidence Limit:** | 2.8 | 0.7 | 5.8 | 32.0 | 103.5 | 114.9 | 116.2 | 103.0 | 77.6 | 33.7 | 8.1 | 10.1 |
| **Lower 95% Confidence Limit:** | -0.3 | 0.0 | 1.0 | 14.9 | 65.7 | 72.0 | 68.5 | 50.4 | 40.8 | 13.8 | 2.7 | 0.0 |

Table 3: Monthly Statistical analysis of rainfall data from 1980-2015

**Chi-Square Goodness of Fit Test (Assuming Equal Expected)**

| Items | Observed | Expected | Chi Square |
|---|---|---|---|
| 1980/81 | 660 | **465.63** | **80.80** |
| 1981/82 | 298 | **465.63** | **60.49** |
| 1982/83 | 432 | **465.63** | **2.39** |
| 1983/84 | 384 | **465.63** | **14.42** |
| 1984/85 | 389 | **465.63** | **12.48** |
| 1985/86 | 284 | **465.63** | **70.85** |
| 1986/87 | 377 | **465.63** | **16.87** |
| 1987/88 | 946 | **465.63** | **495.98** |
| 1988/89 | 388 | **465.63** | **13.01** |
| 1989/90 | 343 | **465.63** | **32.46** |
| 1990/91 | 432 | **465.63** | **2.40** |
| 1991/92 | 242 | **465.63** | **107.60** |
| 1992/93 | 442 | **465.63** | **1.20** |
| 1993/94 | 333 | **465.63** | **37.95** |
| 1994/95 | 421 | **465.63** | **4.26** |
| 1995/96 | 632 | **465.63** | **59.66** |
| 1996/97 | 426 | **465.63** | **3.46** |
| 1997/98 | 495 | **465.63** | **1.85** |
| 1998/99 | 487 | **465.63** | **0.94** |
| 1999/00 | 1,086 | **465.63** | **827.59** |
| 2000/01 | 334 | **465.63** | **37.10** |
| 2001/02 | 431 | **465.63** | **2.53** |
| 2002/03 | 249 | **465.63** | **100.88** |
| 2003/04 | 648 | **465.63** | **71.35** |
| 2004/05 | 483 | **465.63** | **0.61** |

| **Data** |
|---|
| Level of Significance |
| Degrees of Freedom |

| **Results** |
|---|
| Critical Value |
| Chi-Square Test Statistic |
| *p*-Value |
| **Reject the null hypothesis** |

***This tests the null hypothesis that the distribution is equal across all categories. It also tests if there is a difference in the frequencies of the categories / items. Rejecting the null implies a difference in the categories / items.***

Table 4: Monthly Statistical analysis of rainfall data from 1980-2015

| Enter the number of cycles | Rank | Median Rank | ln(ln(1/(1-median rank)) | ln(cycles) |
|---|---|---|---|---|
| 660 | 32 | 0.895480226 | 0.8146473 | 6.491633591 |
| 298 | 5 | 0.132768362 | -1.948770076 | 5.69642212 |
| 432 | 20 | 0.556497175 | -0.206961308 | 6.069119792 |
| 384 | 10 | 0.274011299 | -1.138744433 | 5.949860997 |
| 389 | 12 | 0.330508475 | -0.913203572 | 5.964607093 |
| 284 | 3 | 0.076271186 | -2.534053926 | 5.648974238 |
| 377 | 9 | 0.245762712 | -1.265677107 | 5.932245187 |
| 946 | 34 | 0.951977401 | 1.110568385 | 6.852453963 |
| 388 | 11 | 0.302259887 | -1.021905234 | 5.960489743 |
| 343 | 8 | 0.217514124 | -1.405357282 | 5.836855429 |
| 432 | 19 | 0.528248588 | -0.285946112 | 6.068888444 |
| 242 | 1 | 0.019774011 | -3.913417318 | 5.488110938 |
| 442 | 21 | 0.584745763 | -0.129124743 | 6.091309882 |
| 333 | 6 | 0.161016949 | -1.73974722 | 5.807241183 |
| 421 | 15 | 0.415254237 | -0.622543117 | 6.042870335 |
| 632 | 30 | 0.838983051 | 0.6022623 | 6.449363965 |
| 426 | 16 | 0.443502825 | -0.534276484 | 6.053264948 |
| 495 | 27 | 0.754237288 | 0.338889879 | 6.204557763 |
| 487 | 26 | 0.725988701 | 0.258190902 | 6.187236902 |
| 1,086 | 35 | 0.980225989 | 1.366955251 | 6.990624757 |
| 334 | 7 | 0.189265537 | -1.561530531 | 5.811739616 |
| 431 | 18 | 0.5 | -0.366512921 | 6.066803904 |
| 249 | 2 | 0.048022599 | -3.011577493 | 5.517051209 |
| 648 | 31 | 0.867231638 | 0.70267629 | 6.473736363 |
| 483 | 25 | 0.697740113 | 0.179373949 | 6.178980921 |
| 467 | 22 | 0.61299435 | -0.052013567 | 6.146329258 |
| 390 | 13 | 0.358757062 | -0.811149725 | 5.965890296 |
| 481 | 24 | 0.669491525 | 0.101764739 | 6.175243375 |
| 566 | 29 | 0.810734463 | 0.509587434 | 6.337710296 |
| 478 | 23 | 0.641242938 | 0.024799755 | 6.170447203 |
| 544 | 28 | 0.782485876 | 0.422316647 | 6.298397624 |
| 293 | 4 | 0.104519774 | -2.203689175 | 5.681195976 |
| 391 | 14 | 0.38700565 | -0.714576028 | 5.969730055 |
| 717 | 33 | 0.923728814 | 0.945251315 | 6.574657343 |
| 431 | 17 | 0.471751412 | -0.449121904 | 6.065643945 |

| | | |
|---|---|---|
| Enter the minimum number of cycles you desire the product to achieve: | 100 | |
| Enter the percentage of product you wish to survive the desired number of cycles: | 90 | % |
| Shape Parameter, Beta: Infant life failures (< 1), wearing out (> 1), or constant failure rate (= 1) | 3.38 | |
| Characteristic Life, Alpha: The number of cycles at which 63.2% of the product will fail | 521 | |
| Reliability at 100 cycles | 99.63 | % |

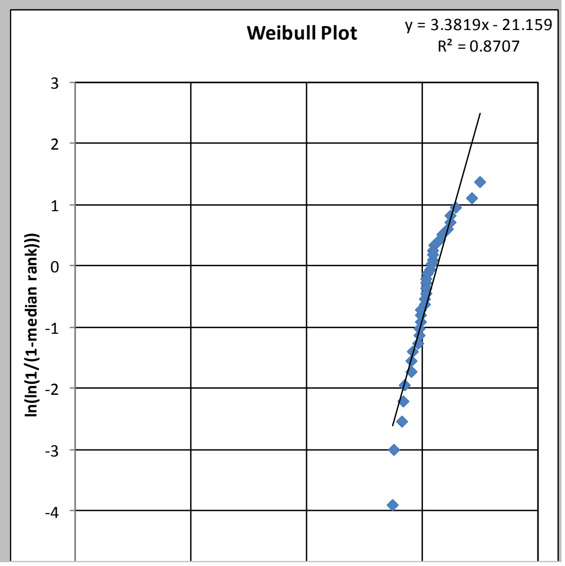



Table 5: Monthly Statistical analysis of rainfall data from 1980-2015

# 10. CHAPTER 9

### 10.1.1. Discussion

### 10.1.2. Rainfall distribution

The statistical analysis of Francistown catchment reveal that 67% of the time rainfall will vary by +/- 38.04% (coefficient of variation: 0.3804) from the long-term mean of 468.52mm. The standard deviation provides useful information in the analysis of rainfall. The results shows that 70% of the estimate amount of precipitation in any given year is 468.52+/-178.239 for Francistown. This mean annual rainfall is substantially high considering the fact that historic annual average rainfall in Botswana is between 250mm and 600mm (Document-of-the-World-Bank, 2010).

The least ever recorded rainfall in Francistown was 241.80mm in 1991/92 year. Research by Holloway, (2000) shows that the drought was triggered by an El Nino climate in the southern Africa region. The drought led to dramatic increase in food production and the country's GDP fell by 5%.

Rainfall distribution of the Francistown catchment for 35 years was analyzed for both monthly and annual distribution as shown in graph 1 and Graph 2 above. The trend shows a high interannual variability which is a clear indication that the catchment is influenced by the semi-arid climate (Batisani & Yarnal, 2010). The catchment experienced peak rainfall in the year 1984/87 and 1999/2000, which resulted in flooding across the country. This flood was experienced in all parts of Southern African countries and has led to high instance of pests and diseases (Bonifacio, 2017). The above catchment just like most African countries the suffered from single and multi-year droughts. Research shows that these droughts are very complex in nature and are caused by many physical mechanisms such as El Niño–Southern Oscillation (ENSO), sea surface temperature (SST) and land–atmosphere feedback (Bonifacio, 2017). The droughts are more prominent and pronounced in the years: 1982–1987, 1991–1992, 2001-2004, 2007-2008, and from 2011-2013. A report by Botswana Statistics revealed that, for the period 1999 to March 2015 a total of BWP6.01 Billion was used to import cereals (maize, rice, sorghum, millet and wheat) to compensate for the drought (STATISTICS-BOTSWANA, 2015).

The general observation however shows that the catchment receives rainfall on average annual rainfall of 468.52mm; this is a significant amount of rainfall. There few peak precipitations and below average rainfall years which describes a typical semi-arid climate. The graphs clearly depicts that rainy season ranges between September and June. It is a unimodal type of rainfall. Between July and September is dry season, however, some years' experience light showers during that period.

A close analysis of the results above in graph 2 shows that rainy seasons begins in September with light showers, less than 30mm per year. The onset intensifies in October, increasing its magnitude up to 120mm in some years. February is the month with the highest rainfall, that's the peak of rainy season for almost all time in record. June is however the cessation of the rainy season of Botswana. There are however some traces of rainfall recorded in July for example in 1996/97 25.6mm of rainfall was recorded in Francistown.

The Chi-square test of observed data is 2059.12 which is greater than the critical value of 49.98 therefore the null hypothesis should be rejected. In consequence it can be concluded that there is a significant difference between rainfall distribution in Francistown. The regression analysis of the two catchment is very small as shown in graph 3. This is due to the unpredictable, highly variable rainfall in Botswana. The rainfall is not constant over the years. The major objective of the study addresses the consequences of this unreliable rainfall by estimation catchment runoff then harvest it for irrigation purposes. By so doing the agricultural sector will improve production instead of depending on low unreliable rainfed agriculture.

The rainfall remains inconsistent in the pattern of distribution. High precipitation was recorded in 1988/89 and 1990/2000 while low records were measured in 1981/80 and from 2002-2005. The research concurs with the study done by Batisani & Yarnal, (2010) which agrees that there is climate change in southern Africa, however the Francistown catchment a steady increase in rainfall distribution over the years.

Rapid changes in climatic variability has the potential to severely disrupt production systems and livelihoods (Desanker et al., 2001). Rural households and the poor are susceptible to drought as they depends entirely on arable agriculture(Jacques, 1995). Since climate Botswana is dry, it is expected that rainfall variability will continue to increase.

## 11. Conclusion 10

From the catchment studied above demonstrates that Botswana has great spatio-temporal variation in its climate. Drought observed in this study is a recurrent phenomenon with a dreadful impact on a nation highly dependent on rainfed agriculture. Comprehensive research is required for sound planning and risk management. Therefore studies such as this will go a long way in drought crisis management considering the fact that Botswana is a water resources limited country. This study is a buildup of a series of research that shall be conducted country wide to analyze the spatio-temporal variability of rainfall in Botswana.

Even though rainfall is variable is the trend, there is a slight increase in the total annual rainfall distribution. Even though floods occurs once in a while their impact are detrimental to socio-economic livelihood of communities. Even though research reveals that such catastrophic events are on the rise, the risk of floods can be mitigated and flood water can be harnessed, stored in reservoirs, ponds and dam for future use when the country is in drought. Rainfall onset, is shifting over the years, dry season like June and August are receiving rainfall which an abnormal condition these are signs of climate change attention from policy makers in large stakeholders.

# 12. Chapter 11

### 12.1.1. RELEVANCE OF THE STUDY

"True development is an ecological process in which a society increases its capacity for dealing with the environment, including extreme environment conditions that produce disaster. This coping capacity depends on three basic factors: the extent to which society understands the laws of nature, that is, science; the extent to which society puts that understanding into practice in the form of technology; and the manner in which society is organized. On all three levels underdeveloped nations are at risk and more likely to be devastated by the effects of severe and/or prolonged drought conditions within their borders" (Jacques, 1995). It is in this pursuit that this research analysis the rainfall variability and hydrological process for the society, for it to understand and put it into practice through rainfall harvesting, and irrigated agriculture than relying on rainfed production. This can be achieved if policy makers take initiatives by adopting scientific understanding into practice.

# 13. Chapter 10

### 13.1.1. POLICY IMPLEMENTATION

Limited information on the potentiality of harvesting rainwater for irrigation is hampering policy makers, practitioners and researchers to make informed decisions that will help boost food production and increase food security that has negatively affected Botswana's socio economy. The limitation is brought mainly by inadequate scientific research on this valuable resource. This study has provided information and necessary data required for strategic decision-making. To achieve speedy sustainable development and implementation of Integrated Water Resources Management the country needs institutional transformation and a radical, supportive government structure.

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# 14. APPENDICES

| 033-FRAN FRANCISTOWN AIRPORT 21 Deg 09 Min S 27 Deg 29 Min E Elevation: 1000 Metres | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | jul | aug | sept | oct | nov | dec | jan | feb | march | april | may | jun |
| 1980/81 | 0 | 1.4 | 7.5 | 25.1 | 163.7 | 40.4 | 180.7 | 145.8 | 59.4 | 29.1 | 6.5 | 0 |
| 1981/82 | 0 | 0.6 | 0.4 | 58.4 | 117.7 | 46.7 | 14.2 | 2.5 | 7.8 | 34 | 15.5 | 0 |
| 1982/83 | 0 | 4.1 | 0 | 125.1 | 29.8 | 38.7 | 60.5 | 41.7 | 42.4 | 83.9 | 6.1 | 0 |
| 1983/84 | 0.1 | 2.4 | 0 | 8.9 | 122.5 | 55.3 | 4.8 | 20.4 | 145.5 | 17.2 | 0 | 6.6 |
| 1984/85 | 4.1 | 0 | 31.5 | 29 | 59.4 | 36.6 | 127 | 69.9 | 15.9 | 12.6 | 2.6 | 0.8 |
| 1985/86 | 0 | 0 | 1 | 46.8 | 24.1 | 21.6 | 6.9 | 24.3 | 65.8 | 93.5 | 0 | 0 |
| 1986/87 | 0 | 0 | 15.4 | 46.6 | 97.2 | 100.8 | 62.8 | 42.5 | 11.7 | 0 | 0 | 0 |
| 1987/88 | 0 | 0 | 8.5 | 12.6 | 89.7 | 292.8 | 57.7 | 348.4 | 125.4 | 8.2 | 2.9 | 0 |
| 1988/89 | 0 | 0 | 0 | 60.8 | 11.1 | 42.4 | 59.6 | 162.7 | 0.9 | 44.9 | 0 | 5.4 |
| 1989/90 | 0 | 0 | 0 | 31.2 | 76.3 | 46.9 | 76.3 | 49.7 | 35.6 | 14.3 | 12.4 | 0 |
| 1990/91 | 0 | 0 | 0 | 0.2 | 13.6 | 128.9 | 110.5 | 82.1 | 96.6 | 0 | 0 | 0.3 |
| 1991/92 | 0 | 0 | 0.9 | 12.3 | 55.9 | 50 | 51.1 | 24.6 | 13.3 | 27.5 | 0 | 6.2 |
| 1992/93 | 0 | 0 | 0 | 35.8 | 52.8 | 194.7 | 89.7 | 37.8 | 13.9 | 17.3 | 0 | 0 |
| 1993/94 | 8.2 | 0 | 1.3 | 2.3 | 112.6 | 39.2 | 50.5 | 114.7 | 3.9 | 0 | 0 | 0 |
| 1994/95 | 0 | 0 | 0 | 13.8 | 22.1 | 33.9 | 142 | 78.4 | 88.3 | 9.1 | 33.5 | 0 |
| 1995/96 | 0 | 0 | 0.9 | 1.4 | 185.4 | 105.6 | 117.1 | 92.2 | 116 | 0 | 13.7 | 0 |
| 1996/97 | 25.6 | 0 | 0 | 7.3 | 121.8 | 48.9 | 63.1 | 42.4 | 81.8 | 18.3 | 16.3 | 0 |
| 1997/98 | 0 | 0 | 15.8 | 9 | 131.1 | 86.6 | 153.1 | 77.2 | 22.2 | 0 | 0 | 0 |
| 1998/99 | 0 | 0 | 0 | 29.2 | 106.8 | 163.1 | 61.2 | 47.6 | 72.4 | 0 | 6.2 | 0 |
| 1999/00 | 0 | 0 | 0 | 29.9 | 162.4 | 98.3 | 300.9 | 288.1 | 135.3 | 11 | 6.4 | 54.1 |
| 2000/01 | 3.3 | 0 | 0 | 5.3 | 70 | 37.2 | 37.5 | 126.9 | 42.6 | 1 | 10.4 | 0 |
| 2001/02 | 0 | 0 | 0 | 7 | 234.1 | 83.6 | 24.7 | 13.4 | 3.3 | 47.7 | 14.6 | 2.9 |
| 2002/03 | 0 | 3.2 | 5.5 | 10.4 | 10.1 | 27.2 | 96.8 | 46.8 | 20.1 | 0 | 0 | 28.8 |
| 2003/04 | 0 | 0 | 3 | 4.2 | 59.4 | 49.4 | 137.7 | 128.7 | 181.7 | 83.8 | 0 | 0 |
| 2004/05 | 0 | 0 | 0.2 | 48.7 | 18.9 | 233.5 | 87.2 | 0.4 | 55.4 | 38.2 | 0 | 0 |
| 2005/06 | 0 | 0 | 0 | 0 | 67.4 | 86.2 | 114.2 | 98.5 | 89.9 | 9.8 | 0 | 1 |
| 2006/07 | 0 | 0 | 0 | 8.1 | 171.8 | 140.8 | 7.2 | 20 | 39.1 | 2.9 | 0 | 0 |
| 2007/08 | 0 | 0 | 8.3 | 38 | 50.9 | 176.5 | 119.3 | 5.4 | 73.7 | 6.4 | 2.2 | 0 |
| 2008/09 | 0 | 0 | 0 | 4.4 | 34.1 | 59.7 | 149 | 173.2 | 63.8 | 0 | 15.5 | 65.8 |
| 2009/10 | 1 | 0 | 18.6 | 16.6 | 60.5 | 85.2 | 66.5 | 72.4 | 37.4 | 98.9 | 20.4 | 0.9 |
| 2010/11 | 0 | 0 | 0 | 32.3 | 92.3 | 117.4 | 198.5 | 25.8 | 14.3 | 60 | 3.1 | 0 |
| 2011/12 | 0 | 0 | 0 | 5.2 | 115.9 | 125.3 | 0 | 15.8 | 31.1 | 0 | 0 | 0 |
| 2012/13 | 0 | 0 | 0 | 29.5 | 83.3 | 54.4 | 208 | 4.2 | 5.4 | 6.6 | 0 | 0 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2013/14 | 0 | 0 | 0 | 24.7 | 31.8 | 133.3 | 193.6 | 94.4 | 221.5 | 17.4 | 0 | 0 |
| 2014/15 | 0.6 | 0 | 0 | 1.5 | 105.3 | 176.1 | 3.4 | 65.3 | 38.3 | 37.6 | 0 | 2.7 |

Table 4: Francistown rainfall data