Characterisation of Drought Using Hydrological and Meteorological Indices: A Case Study of Bethlehem, South Africa

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MASTERS RESEARCH REPORT

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DECLARATION

I **Khanyisile A. Tshabalala** declare that this Research Report is my own, unaided work. It is being submitted for the Degree of **Master of Science by Coursework and Research Report Interdisciplinary Global Change Studies** at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Signature of Candidate:

Date: 27 February 2023

DEDICATION

This report is dedicated to my research supervisors under whose constant guidance I have completed this study. They not only enlightened me with academic knowledge but also gave valuable advice whenever I needed it the most.

ABSTRACT

The study aims to assess the severity and evolution of drought/s in Bethlehem using the hydrological: Streamflow Drought Index (SDI), Reconnaissance Drought Index (RDI), Effective Reconnaissance Drought Index (eRDI) and meteorological: Standardised Precipitation Index (SPI), Agricultural Standardised Precipitation Index (aSPI), and Precipitation Deciles (PD) indices. These indices were computed using the Drought Indices Calculator (DrinC). The RDI, eRDI, aSPI, and SPI identified three drought events between 1980 and 2017. The PD on the other hand, identified particular years between 1980 and 2017 that received below-normal to much below-normal precipitation. Further, the years identified to have received below normal to much below normal precipitation fell between the drought periods identified by the other indices, such as the 1980 – 1990 drought identified by the SPI, RDI, aSPI, and eRDI; the PD identified 1982, 198, 1985, and 1986 as specific years the received significantly low precipitation within the decade long drought. Of critical note is the absence of the SDI results, stream levels data was not available at the time the results presented in this report were computed. The unavailability of SDI values did not compromise or negatively affect the results presented in this study as the computed indices had a strong correlation, implying the reliability of the results presented in this report.

Keywords: Drought, Drought Index, Drivers of drought, climate change, climate variability, effective precipitation, and potential evapotranspiration.

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ABBREVIATIONS

aSPI	Agricultural Standardized Precipitation Index
DrinC	Drought Indices Calculator
ENSO	El Nino Southern Oscillation
eRDI	Effective Reconnaissance Drought Index
FAO	Food and Agricultural Organization
GUI	Graphical User Interface
MDM	Meteorological Drought Monitor
MS	Microsoft
PD	Precipitation Deciles
P_e	Effective Precipitation
PET	Potential Evapotranspiration
RDIT	Rain-Based Drought Indices Tool
RDI	Reconnaissance Drought Index
SAWS	South African Weather Service
SDI	Streamflow Drought Index
SOI	Southern Oscillation Index
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SSTs	Sea-Surface Temperatures
USDA-SCS	Soil Conservation Service of the United States Department of Agriculture
USBR	United States Bureau of Reclamation

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Chapter 1: Introduction

1.1 Background

‘Drought’ refers to a wide range of complicated phenomena; and describes a protracted period of a water system that is out of balance with the local climate (Mishra and Singh, 2010; Vicente-Serrano *et al*., 2010; Bae *et al*., 2019). Drought is complex in both nature and the spectrum of effects it has (Byun and Wilhite, 1999; Vicente-Serrano *et al*., 2012; Mo and Lettenmaier, 2014). Three factors primarily describe a drought: intensity, duration, and spatial extent of precipitation (Trenberth *et al*., 1988; Marsh *et al*., 1994; Mishra and Singh, 2010). When precipitation totals are significantly reduced over a given period relative to the average precipitation patterns of the specific location, meteorological drought results (Haied *et al*., 2017; Bae *et al*., 2019). Other elements of weather like temperature, humidity, or wind drive meteorological drought (Haslinger *et al*., 2019). And in agriculture drought is often characterised by a shortage of water for crop production for a prolonged period (Leng *et al*., 2015). Now, when the prolonged or protracted period of water shortage affects water bodies (storages) i.e., reduced stream flow and declining dam levels, hydrological drought results (Nalbantis and Tsakiris, 2009). When the negative consequences of drought spread across society affecting both daily living and socio-economic activities, socio-economic drought results (Verschuur *et al*., 2021).

While it is necessary to understand drought in a changing climate, why and how drought evolves and space is still contentious (Yang *et al*., 2020). Some studies have found an increase in the frequency of droughts, whereas others have found no significant changes (Kurnaz, 2014; Apurv *et al*., 2019). For instance, droughts are common in the Free State and Northwest provinces in South Africa, affecting the water supply and farm productivity of the whole country (Botai *et al*., 2016). In the 2015/16 hydrological year, the South African government declared the two provinces disaster areas, which had significant economic implications, since both, being the agricultural hub with major water reservoirs of the country, are prominent contributors to the national economy (Botai *et al*., 2016). Thus, understanding droughts in a changing South African climate is critical since it directly affects the status of food security. This study relies on the use of the Drought Indices Calculator to model previous drought events in Bethlehem, South Africa.

A drought index is a single number that is defined as a range of abnormally wet, average, and dry (Van Lanen *et al.*, 2008; Tigkas *et al.*, 2013). These are critical tools for identifying and tracking droughts because they simplify complex climatic conditions and measure anomalies in terms of severity, length, and frequency per drought event or episode (Beck *et al.*, 2014; Deo *et al.*, 2017). Drought indices may be computed manually or using the software Drought Indices Calculator (Drinc) (Tigkas, Vangelis and Tsakiris, 2013). DrinC is a simple offline program with low data requirements that calculates drought indices through a versatile interface (Tigkas *et al.*, 2013, 2015; Khan *et al.*, 2017). Drought indices are significant tools for characterising and monitoring drought events with minimum cost as they can quantify climatic anomalies through the analysis of daily or monthly weather conditions. In DrinC version 1.7 only six drought indices can be computed namely the Reconnaissance Drought Index (RDI), Streamflow Drought Index (SDI), Standardised Precipitation Index (SPI), Agricultural Standardised Precipitation Index (aSPI), Precipitation Deciles (PD), and the Effective Reconnaissance Drought Index (eRDI). The RDI, SPI, and PD allude to a meteorological drought and use precipitation as their primary factor (Tigkas *et al.*, 2013, 2015). The RDI also makes use of the potential evapotranspiration because it accurately describes water balance and is particularly useful when reference periods linked to crop growth phases are selected (Tigkas *et al.*, 2016, 2017; Abubakar *et al.*, 2020). Thus, the RDI can also be utilised for the analysis of agricultural drought (Tigkas *et al.*, 2017). The SDI pertains to hydrological drought and makes use of streamflow as a primary factor (Tallaksen and Lanen, 2004).

1.2 Aims and Objectives

1.1.1 Aim

This study aims to investigate specific drought indices such as the Reconnaissance Drought Index (RDI), Streamflow Drought Index (SDI), Standardised Precipitation Index (SPI), Agricultural Standardised Precipitation Index (aSPI), Precipitation Deciles (PD), and the Effective Reconnaissance Drought Index (eRDI) to assess the severity and evolution of the drought in Bethlehem between 1980 and 2017.

1.1.2 Objectives

To achieve the aim the following objectives will be employed:

- Calculate the Reconnaissance Drought Index (RDI), Streamflow Drought Index (SDI), Standardised Precipitation Index (SPI), Agricultural Standardised Precipitation Index (aSPI), Precipitation Deciles (PD), and Effective Reconnaissance Drought Index (eRDI) using climate data obtained from the South African Weather Services (SAWS) to determine the number of drought events in Bethlehem.
- Investigate the spatial and temporal transition of the drought event/s using the indices.

1.3 Rationale

A drought characterisation study in Bethlehem is important because droughts are a natural phenomenon that can have serious consequences for society and the environment (Wilhite, 1992; Vicente-Serrano *et al.*, 2013; Hannaford, 2018). Given the weather patterns, South Africa experiences two main farming seasons: Summer (maize farming season) which occurs from October (earliest rainfall onset) to April (rainfall cessation), and winter (dryland wheat farming season) which occurs from May to September (Beletse *et al.*, 2016; Serage, 2017; Abubakar *et al.*, 2020). Wheat is the second-most significant crop after maize, the two crops are essentially the staple diet of the South African population (Serage, 2017). The consequences of climate change, in the context of this study, drought, pose serious challenges to the production of dryland wheat in winter and rainfed maize in summer (Botai *et al.*, 2016; Serage, 2017; Verschuur *et al.*, 2021). Bethlehem is the **'pantry'** of South Africa. Thus, it has a direct impact on food security, society, and the economy (Verschuur *et al.*, 2021). Hence, the characterisation of drought in the South African context is significant in the planning and management of agricultural production alongside usable water resources. Drought characterisation and analysis studies have recently attracted increased interest from scientists with different backgrounds and fields of study including agriculture, hydrology, and meteorology (Khan *et al.*, 2017; Singh and Shukla, 2020; Yang *et al.*, 2020). Thus, it is critical to be able to determine the severity of drought event/s as well as predict the occurrence of droughts to put in place the necessary mechanisms for mitigating any potential effects. To do this drought indices such as the SPI, the Deciles Index (DI) and the SDI among many other indices are employed to determine the frequency, length, and severity of a given drought event as well as monitor the spatiotemporal evolution of the drought event effects (Khan *et al*., 2017).

1.4 Structure of the report

This report starts by reviewing some concepts related to droughts including defining drought, drivers of drought, and the evolution of drought Chapter 1: Introduction. This is followed by a detailed description of the study area, Bethlehem Chapter 3: Study Site. Next, the report provides detailed methods employed during the calculation of the indices in Chapter 4: Methodology as well as the data requirements followed by a presentation of the findings in Chapter 5: Results and a detailed analysis of the findings relating to the objectives of this study in Chapter 6: Discussion. Finally, the report ends with a detailed summary of the study and recommendations for future research in Chapter 7: Conclusion.

Chapters 2: Literature Review

This section of the report will review and discuss issues related to defining drought, followed by factors influencing droughts, and approaches to quantifying and characterising droughts. For this study, only the selected drought indices will be described as an approach to drought quantification and characterisation.

2.1 Types of Droughts

The lack of precipitation for an extended period (often a season or more), resulting in water scarcity is what is popularly understood as a drought (Dracup, Lee and Paulson, 1980; Van Lanen and Peters, 2000; Mishra and Singh, 2010). Some definitions are theoretical which is important for developing policy (Mishra and Singh, 2010). Others describe the operation of the drought in ways that can be described (Mishra and Singh, 2010). Thus, defining droughts using three key factors: duration, intensity, and spatial extent (Rouault, 2005; Kumar *et al.*, 2009). Now considering the different definitions of droughts, classifying them becomes an alternative leading to the several types of droughts that this sub-section discusses (Mo and Lettenmaier, 2014).

There are several types of droughts, and these can evolve into each other; precipitation deficits can be used to determine and define meteorological droughts, if the precipitation deficits last for an extended period farmers may start to experience declines in crop yields and this is commonly referred to as an agricultural drought (Botai *et al.*, 2016; Bae *et al.*, 2019). When precipitation deficits result in reduced dam levels and streamflow, this is then referred to as a hydrological drought (Tallaksen and Lanen, 2004; Nalbantis and Tsakiris, 2009; Leng *et al*., 2015). Different forms of droughts can inflict economic, social, and environmental problems, which are referred to as socioeconomic droughts (Adger, 1999; Bangalore *et al*., 2019; Verschuur *et al.*, 2021).

Groundwater drought, like other types of droughts defined above, is caused by low precipitation combined with high evapotranspiration rates (Van Lanen and Peters, 2000; Calow *et al.*, 2010). Thus, the responsiveness of groundwater storage to droughts is critical (Calow *et al.*, 2010). A groundwater drought can also be caused by abstraction and over-exploitation of groundwater for various anthropogenic activities including mining (Chang and Teoh, 1995; Calow *et al.*, 2010; Kolusu *et al.*, 2019). Abstraction and over-exploitation for anthropogenic activities can also enhance the effects of groundwater drought when caused by precipitation deficits(Pitner and Sakamoto, 2005; Halwatura *et al*., 2015).

2.2 Drivers of Drought

There are natural and anthropogenic drivers of drought which include climate variability (natural); climate change, and heat waves (a consequence of climate change) (anthropogenic).

2.2.1 Climate Variability

The El Nino and La Nina phases define the extremes of climatic variability in the southern hemisphere (Apurv *et al.*, 2019; Kolusu *et al.*, 2019; Chikoore and Jury, 2021). El Nino-Southern Oscillation (ENSO) is connected to rainfall, with the positive phase being associated with above-average rainfall and the negative phase being associated with drought conditions (Driver and Reason, 2017; Singh and Shukla, 2020; Chikoore and Jury, 2021). As a result, the rainfall season is less favourable for crop production during El Nino years, and there is a significant water shortage for rain-fed agricultural production (Beniston and Stephenson, 2004; Moeletsi *et al*., 2011; Hu and Feng, 2012; Dieppois *et al*., 2015). In contrast, La Nina years are characterised by increased rainfall events, which are generally linked to better crop yields in the greater part of semi-arid regions of southern Africa (Moeletsi *et al*., 2011; Dieppois *et al*., 2015; Kolusu *et al*., 2019).

2.2.2 Terrestrial-Atmosphere Interactions: Droughts and Heatwaves

A growing problem among the potential health dangers brought on by urbanisation and global change is the occurrence of heat waves (Maggiotto *et al.*, 2021). Heatwaves, which are meteorological severe occurrences characterised by lengthy periods of exceptionally high temperature in a specific region are growing increasingly common, persistent, and intense (Miralles *et al.*, 2014; Mazdiyasni and AghaKouchak, 2015; Raja *et al.*, 2021). Thus, posing a serious threat to current and future food security (Raja *et al.*, 2021). Moreover, it has been proposed that feedback between the land and the atmosphere causes droughts and heat waves to intensify and proliferate (Roundy *et al*., 2014). Present knowledge of the mechanics driving meteorological droughts and heatwaves indicates that comparable persistent large-scale circulation irregularities are crucial for the beginning of both phenomena, which helps to explain why both events frequently co-occur (Leng *et al*., 2015; Mazdiyasni and AghaKouchak, 2015; Haslinger *et al.*, 2019).

Miralles *et al.*, (2019) propose that similar land-atmosphere feedback has played a key role in the onset and evolution of droughts and heatwaves despite the variations in the temporal acres of these two extremes. It makes sense that this feedback would occur as soil and vegetation dry out, and evapotranspiration from the land decreases, making the air even drier (Maggiotto *et al.*, 2021). This may further lower the probability of precipitation and promote the development of meteorological droughts (Haslinger *et al.*, 2019; Miralles *et al.*, 2019). In addition, when evaporation gradually decreases, a greater percentage of the insolation warms the environment, which causes an accumulation of sensible heat in the atmosphere that could turn into a heatwave or enhance its extent (Miralles *et al.*, 2019).

2.2.3 Climate Change

Greenhouse gases like carbon dioxide (CO_2), and methane (CH_4) are released during agricultural production and play a role in climate change (Serage, 2017). The pre-processing system, which includes the management of production inputs such as fertilisers, emits CO_2 throughout the production process (Haverkort and Hillier, 2011; Leng *et al.*, 2015). Ruminant animals are primarily responsible for the production of methane in the agricultural sector (Serage, 2017). When enteric fermentation occurs, methane is produced in the stomachs of ruminant animals (Haverkort and Hillier, 2011; Serage, 2017). Essentially, CO_2 and CH_4 are the two main greenhouse gases responsible for driving and/or enhancing global warming, which in the context of this study will be regarded as climate change (Soutter and Mõttus, 2020).

Human interactions and natural phenomena can alter the water cycle directly and indirectly (Otto *et al.*, 2018; Kakaei *et al.*, 2019). Drought has emerged as a key concern for sustainable water resource management internationally in the context of global warming due to the numerous negative consequences, including those on the environment, access to safe drinking water, public health, etc (Körner *et al.*, 2011; Mbiriri *et al.*, 2018). Drought has traditionally been described as a natural occurrence caused by climate change (Leng *et al.*, 2015). However, the impact of interactions between anthropogenic activities and natural processes on drought phenomena, propagation, and characteristics was not considered in those descriptions (Verschuur *et al.*, 2021).

Human influences on water supplies can alter the climate, hydrological processes, and the condition of water in various parts of the land surface hydrological cycle, directly and/or indirectly

(Bates *et al.*, 2008). Human interventions and hydro-climate change are considered to be the key reasons for the frequency of hydrological drought in our human-influenced period (Yuan *et al.*, 2019). Drought management in the Anthropocene is undeniably influenced by the multidirectional relationship between human forces as social processes and natural processes (Mishra and Singh, 2010). Drought must be viewed as a dynamic interdisciplinary phenomenon rather than a strictly natural phenomenon by hydrologists to gain a deeper understanding of the interplay between humans, the environment, and hydrology (Otto *et al.*, 2018; Kakaei *et al.*, 2019).

2.3 Drought Evolution: Indices Applicability and Limitations

A drought index is a common metric for evaluating the impact of a drought and specifying several drought factors, such as intensity, length, severity, and spatial and temporal extent (Surendran *et al.*, 2017). It should be highlighted that a drought variable should be able to quantify the drought over a variety of periods, which necessitates the use of a large time series thus indices are more useful in retrospect (Karamouz *et al*., 2009; Surendran *et al.*, 2017). A year is the most typical time scale for drought study, followed by a month (Tigkas *et al*., 2013).

2.3.1 Effective Precipitation

The combination of meteorological factors that affect crop evapotranspiration affects how much water is used for irrigation in agricultural production (Ali and Mubarak, 2017). Irrigation is not necessary if the amount of precipitation is sufficient to meet the plant's water needs (Tigkas *et al*., 2016). If there is some precipitation, but not enough to meet the plant's water needs, irrigation water must be used to make up the difference so that irrigation water and rainwater combined can meet the needs of the crops (Moeletsi and Walker, 2012; Moeletsi *et al.*, 2013). The amount of precipitation that can be used for plant growth and photosynthesis without taking irrigation water into account is known as effective precipitation (Ali and Mubarak, 2017). Effective precipitation is influenced by several parameters, including precipitation, evapotranspiration, terrain, land cover, and soil properties (Tigkas *et al*., 2016; Ali and Mubarak, 2017; Abubakar *et al*., 2020).

A technique for calculating effective precipitation should consider crop characteristics, evapotranspiration, changes in water storage in the roots of the plants, and surface storage capacity (Ali and Mubarak, 2017). The Food and Agricultural Organization (FAO) has suggested a straightforward empirical method that can be used in regions with a maximum slope of 4-5%

(Tigkas *et al*., 2016, 2017). The USDA-SCS CROPWAT method, which was developed with water balance calculations based on 50 years of weather data from 22 stations within the United States and uses daily soil moisture balance incorporating crop evapotranspiration, rainfall, and irrigation, and the United States Bureau of Reclamation method, which uses mean seasonal precipitation of the 5 most dry years consecutively, have identical responses for total monthly precipitation up to 110 mm, which is usual for arid regions (Bos *et al.*, 2009; Ali and Mubarak, 2017). With lower effective precipitation estimates for the same amount of total monthly precipitation, the FAO technique exhibits a distinct pattern (Tigkas *et al*., 2017, 2022). The USDA-SCS CROPWAT and U.S. Bureau of Reclamation methodologies are mainly regarded as being appropriate for dry and semi-arid climates, with their use in humid situations possibly having questionable validity (Bos *et al.*, 2009; Ali and Mubarak, 2017).

2.3.2 Reconnaissance Drought Index (RDI) and Effective Reconnaissance Index (eRDI)

Tsakiris *et al.*, (2007) created the RDI to express the water deficit more accurately, for drought characterisation and monitoring. The RDI is calculated using both precipitation (P) and PET. When compared to the average conditions of the area, positive RDI values indicate wet periods and negative values suggest dry periods(Kousari *et al.*, 2014; Abubakar *et al*., 2020). Drought severity is divided into four categories: mild, moderate, severe, and extreme, with RDI border values of (−0.5 to −1.0), (−1.0 to −1.5), (−1.5 to 2.0), and (greater than −2.0) (Tsakiris *et al.*, 2007). The RDI is a good index to use in drought characterisation studies since it determines the total deficits between precipitation and the atmosphere's evaporative demand is calculable over any time frame and can be used to make inferences on past, current, and future climate change (Tigkas *et al*., 2015; Surendran *et al.*, 2017). Based on the aforementioned qualities, it can be stated that the RDI is a suitable index for reconnaissance drought severity evaluation for general usage, providing comparable results across a vast geographic area (Tsakiris *et al.*, 2007).

The eRDI’s significant change is the replacement of total precipitation with effective precipitation (Tigkas *et al*., 2016, 2017, 2022). The eRDI is anticipated to represent the amount of water that is advantageously used by the crops more accurately than the RDI, leading to the conceptual improvement of the index for the characterisation of drought (Tigkas *et al*., 2017). Furthermore, depending on the climate of the location and other environmental factors, each crop may be more vulnerable to drought events at different phases of development (Moeletsi *et al.*, 2013). As a result, the foregoing issues should be considered when choosing acceptable reference periods for calculating eRDI (Tigkas *et al.*, 2015).

2.3.3 The Streamflow Drought Index (SDI)

Streamflow Drought Index was created by Nalbantis and Tsakiris (2009) to characterise hydrological droughts by taking monthly streamflow into account (Pathak *et al.*, 2016). Hydrological droughts are classified into five intensity ranges based on SDI values. **Table 1** presents the SDI classification. When computing this index, distinguishing between intermittent and ephemeral flows is important (Tallaksen and Lanen, 2004). Also, this index can only be used to characterise a hydrological drought. The calculation of the SDI depends on the size of the basin (Tallaksen and Lanen, 2004; Leng *et al.*, 2015; Pathak *et al.*, 2016). “Generally, for small basins, streamflow may follow a skewed probability distribution which can well be approximated by the family of the gamma distribution functions. The distribution is then transformed into normal. Using the two-parameter log-normal distribution (for which the normalisation is simply reclaiming the natural logarithms of streamflow), the SDI index is defined as:

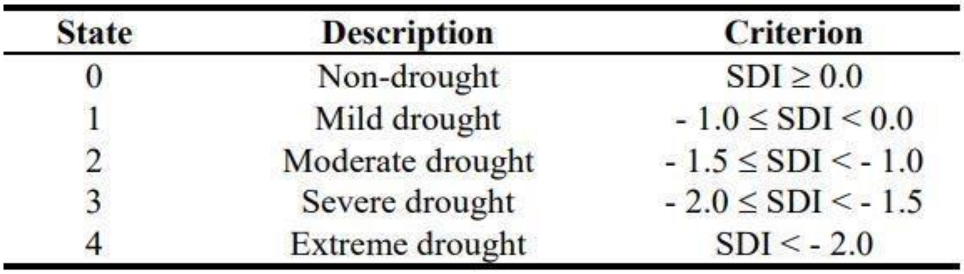
$$\mathrm{SDI}_{i,k} = \frac{y_{i,k} - \bar{y}_k}{s_{y,k}} \quad \mathrm{i} = 1, 2, \ldots, \quad \mathrm{k} = 1, 2, 3, 4$$

in which

$$\mathrm{Y}_{i,k} = \ln\left(V_{i,k}\right), i = 1,2, \ldots; k = 1,2,3,4$$

are the natural logarithms of cumulative streamflow with mean Y_k and standard deviation $S_{y,k}$ as these statistics are estimated over a long period" (Tigkas *et al.*, 2013, p. 1336).

Table 1: States of Hydrological Drought *(adapted from* (Tigkas *et al.*, (2013), p. 1336 edited by Khanyisile Tshabalala, 2023

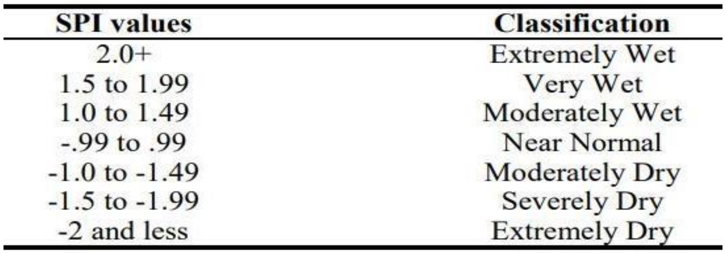


State	Description	Criterion
0	Non-drought	SDI ≥ 0.0
1	Mild drought	- 1.0 ≤ SDI < 0.0
2	Moderate drought	- 1.5 ≤ SDI < - 1.0
3	Severe drought	- 2.0 ≤ SDI < - 1.5
4	Extreme drought	SDI < - 2.0

2.3.4 Standardised Precipitation Index (SPI) and Agricultural Standardised Precipitation Index (aSPI)

The SPI is a method for identifying and tracking drought (Kumar *et al.*, 2009; Vicente-Serrano *et al.*, 2010). The data is normally distributed to ensure that zero is the average precipitation (Wu *et al.*, 2005; Yaseen *et al.*, 2021). The SPI in simpler terms is a measure of the deviation from the normal precipitation. Table 2 below presents the interpretations of SPI values. To put it simply, the SPI is a measure of deviations from the normal.

Table 2: Classifying Drought Conditions Based on SPI, (adapted from Tigkas, *et al.*, (2013), p. 1337 edited by Khanyisile Tshabalala



SPI values	Classification
2.0+	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-.99 to .99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

Since the SPI is based on the long-term record and is adjustable for different reference periods. Thus, allowing it to monitor short-term to long-term drought episodes (Wu *et al.*, 2005; Vicente-Serrano *et al.*, 2010; Tigkas *et al.*, 2013, 2022). On a short time scale, soil moisture responds to abnormal shifts in precipitation (Mishra and Singh, 2010). On a long-time scale, the abnormal shifts in precipitations are reflected in the groundwater, streamflow as well and water storage systems (Mishra and Singh, 2010). However, the SPI is influenced by the length of the precipitation record and probability distribution functions (Yaseen *et al.*, 2021). The SPI is affected by the distribution curve used (Kumar *et al.*, 2009). The SPI's applicability in vegetation-related applications is limited due to the lack of a soil water balance component (Tigkas *et al.*, 2022). However, such a component is conceptually included in the effective precipitation parameter. As a result, replacing total precipitation with effective precipitation improves SPI's applicability for assessing drought impacts on plants and makes it a sounder formulation for agricultural drought characterisation (Tigkas *et al*., 2019, 2022). Furthermore, estimating effective precipitation using the aforementioned approaches, which are entirely based on precipitation data, retains the main advantage of the original index, allowing it to be used even in places where data is scarce (Tigkas *et al*., 2016; Ali and Mubarak, 2017). The aSPI uses a standardisation strategy similar to the SPI, which involves fitting the effective precipitation time series to a correct statistical distribution and then transforming it into a normal distribution (Tigkas *et al*., 2019, 2022).

2.3.5 The Precipitation Deciles (PD)

The precipitation deciles are a simple statistic in which the precipitation totals for the previous three months are rated against the climate record (Tigkas *et al*., 2013, 2015; Abbasian *et al*., 2021). The region is said to be experiencing a drought when the precipitation sum amount falls within the lowest decile of the historical distribution of three months' totals (Tsakiris *et al.*, 2007). When the precipitation total for the previous month is in or above the 8th decile, the drought is over (Tsakiris *et al.*, 2007). To create a cumulative frequency distribution for deciles, the long-term monthly rainfall records are first arranged from highest to lowest. Based on equal probability, this distribution is then divided into deciles (Tsakiris *et al.*, 2007; Abbasian *et al*., 2021). The monthly rainfall distribution is separated into tenths of the distribution over a long period (Tigkas *et al*., 2013). The deciles are divided into **FIVE** categories, the classes are presented in **Table 3**.

Table 3: Decile-based Classification of Drought Conditions (adapted from Tsakiris *et al.*, (2007), p. 90 edited by Khanyisile Tshabalala

Decile Classifications	
deciles 1-2: lowest 20%	much below normal
deciles 3-4: next lowest 20%	below normal
deciles 5-6: middle 20%	near normal
deciles 7-8: next highest 20%	above normal
deciles 9-10: highest 20%	much above normal

The decile technique has the advantage of being computationally simple, however, this simplicity may lead to conceptual issues (Kininmonth *et al.*, 2000; Tsakiris *et al.*, 2007). For instance, it is realistic to expect drought to end when the precipitation levels are close to or above normal for any given period for which the deciles are computed (Tsakiris *et al.*, 2007). However, even if the amount of precipitation is low and does not terminate the water deficit, minor amounts can still activate the first halting stage (Abbasian *et al*., 2021). It is possible to employ a supplemental third rule that considers the total precipitation since the commencement of the drought event (Kininmonth *et al.*, 2000; Tsakiris *et al.*, 2007). The meteorological drought may be considered if the total precipitation surpasses the first decile for all the drought months (Tigkas *et al*., 2013).

2.4 Conclusion

Drought is best described as a complex natural hazard by numerous climatological and hydrological characteristics (Bae *et al*., 2019). To overcome the effects of drought, an understanding of the relationship between droughts and the environment, economy and people is significant in retrospect as well as planning for the future given various climate change scenarios. Hence, the use of drought indices to describe the different types of drought/s (Wilhite, 1992; Haslinger *et al.*, 2019).

Chapter 3: Study Site

In this study, the RDI, SDI, SPI, aSPI, PD, and eRDI were employed to assess the severity and evolution of drought in Bethlehem between 1980 and 2018. The Free State was chosen because it is one of South Africa's rain-fed agricultural centres with considerable unpredictability in the rainfall season. This section of the report describes the geographical location as well as the attributes of the study site, Bethlehem.

3.1 The Geographical Location of Bethlehem

Bethlehem is a town in the eastern Free State, it is located on the Lienbergs River in a fertile valley, north of the Rooiberg Mountain along the N5 pass, on the coordinates, 28.2423^{0}S, 28.3111^{0}E (Latitude. to, 2011). Legislatively, Bethlehem is a town within the broader Thabo Mofutsayane District under the Dihlabeng local municipality **Figure 1.1**.

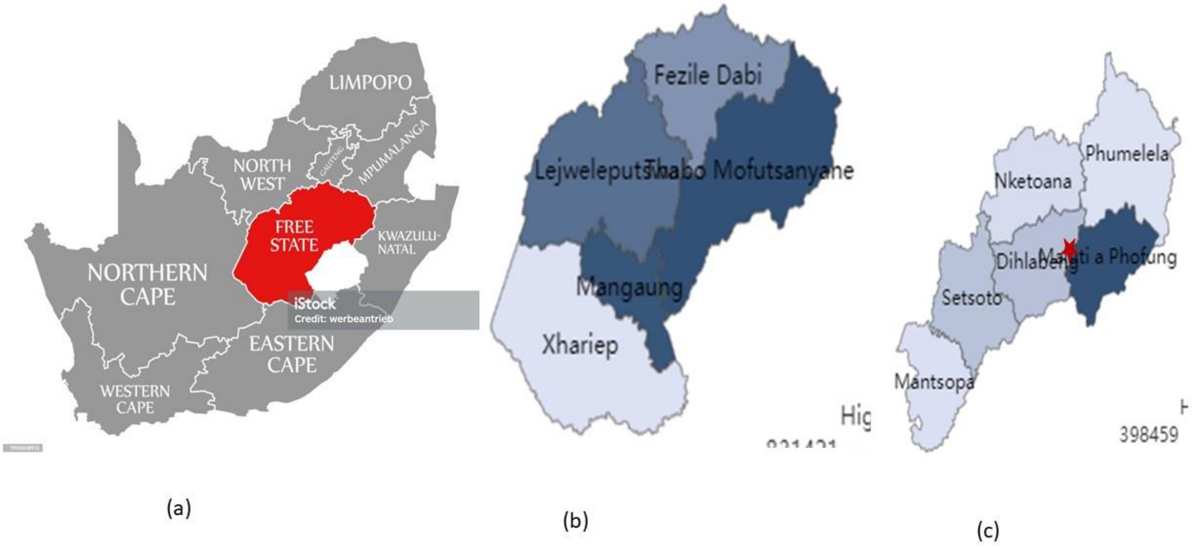


Figure 1.1: (a) The geographical location of the Free State Province of South Africa (highlighted in red), (b) The Location of Thabo Mofutsayane District in the Free State (Darker navy blue), and (c) The location of Dihlabeng local municipality and Bethlehem (red star), adapted from (Werbeantrien, 2019; Census, 2022)

3.2 The Attributes of Bethlehem

The town of Bethlehem, which is where Jesus was born in the Bible, inspired the name Bethlehem. "House of bread" is what the name implies (Census, 2022). In the South African context, Bethlehem exemplifies one of the large-scale systems for growing dryland maize and wheat (Beletse *et al.*, 2016; Serage, 2017; Census, 2022). Thus, it was chosen for this study as it is the 'house of bread' for the South African economy and population. Bethlehem receives 600 mm of rain per year on average (Moeletsi *et al*., 2011; Moeletsi and Walker, 2012). With vast areas of fertile, arable land, the Free State has the largest number of farming units in South Africa and supports a substantial portion of the agricultural sector (Moeletsi *et al*., 2011, 2013). The Free State falls within the summer rainfall zone, except for the eastern regions of the province, which are listed as subtropical, the rest of the province is described as semi-arid (Moeletsi and Walker, 2012). According to a study conducted by Moeletsi and Walker, (2012), the earliest rains in the Free State occur between October and March. Despite the unpredictability of the rainfall onset, some areas are more likely to receive rainfall earlier or later than others, meaning that within the Free State rainfall season onset is significantly variable (Moeletsi and Walker, 2012). Bethlehem (red box) is particularly interesting because it is located on the boundary between areas slightly likely to have late onset rainfall season and areas more likely not to experience onset failure **Figure 1.2**.

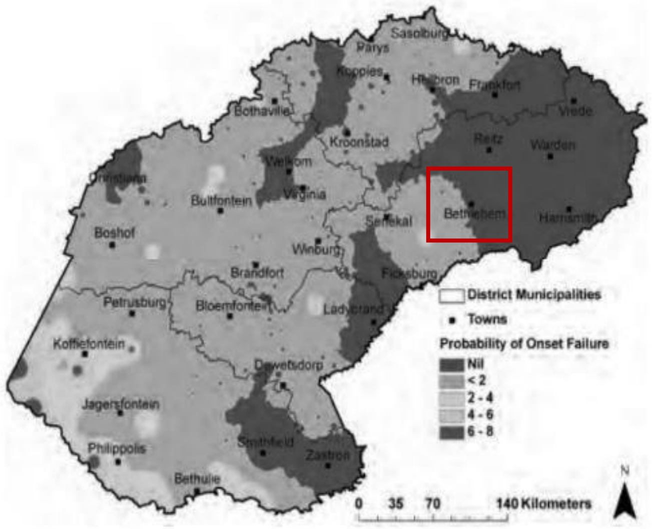


Figure 1.2: Free State Province probability of delayed rainfall season onset adapted from (Moeletsi and Walker, 2012) edited by Khanyisile Tshabalala, 2022

Chapter 4: Methodology

The study employs five drought indices (SPI, aSPI, RDI, eRDI, and PD) that combine precipitation and temperature. The aSPI is very easy to compute as it is based on the original SPI calculation. The SPI computation requires monthly or weekly precipitation data whereas aSPI requires monthly or weekly Pe and PET. Similarly, the eRDI calculation is based on the RDI standardisation. The RDI computation requires monthly or weekly precipitation and PET whereas the eRDI requires monthly or weekly effective precipitation and PET. The PET is computed based on the minimum and maximum daily, weekly, or monthly temperature. The PD is the easiest index to compute as it only requires monthly precipitation data.

4.1 Data Set and Collection

The data used in this study were acquired in Microsoft Excel format from the South African Weather Services (SAWS); and contain weather (minimum and maximum daily temperature, wind speed, humidity, rainfall etc) data from January 1980 to December 2017.

4.2 Data Analysis

The analysis of all data used in this study was completed through the use of DrinC and output results were further analysed using Microsoft Excel.

4.2.1 Data Input and Management

Each index in this study was computed with different input data, **Table 4**. Monthly data were considered for this study.

Table 4: Input Data Requirements for Each Index

INDEX	DATA INPUT
RDI	Precipitation, potential evapotranspiration (PET)
SDI	Streamflow
SPI	Precipitation
aSPI	Effective precipitation
PD	Precipitation
eRDI	Cumulative precipitation, potential evapotranspiration (PET)

4.3 The Drought Index Calculation

The indices were calculated through DrinC, this section explains how each index was computed in this study.

4.3.1 Potential Evapotranspiration (PET) Calculation

Thornthwaite (1948); Doorenbos and Land and Water Division (1977); and Hargreaves and Samani (1982,1985) provide temperature-based methods for calculating potential evapotranspiration in DrinC. The Hargreaves method requires minimum and maximum temperature, whereas the other two require average temperature. The mean monthly minimum and maximum temperatures were extracted from the main SAWS data file for the period 01 November 1980 to 31 December 2017. On the data management window, the 'calculate PET' option was selected, and the calculate PET window appeared. The mean monthly minimum and maximum temperature data files were uploaded respectively. The first year was set to 1980, and the number of years was set to 38. The default hydrological year, October to September was selected. The latitude for Bethlehem was entered in degrees-minutes. And the Hargreaves method was selected, and the calculated mean temperature was checked as well as the open after-calculation option. Before the 'calculate PET' option was entered, the output file was saved on the desktop in Microsoft Excel format.

4.3.2 Reconnaissance Drought Index (RDI) Calculation

The RDI is calculated using both cumulative precipitation and PET (Tigkas *et al*., 2013). The PET calculating approach, on the other hand, does not affect the RDI results. Cumulative precipitation is measured, and PET is calculated. On DrinC, the data management window was opened, and the input files, precipitation and PET were loaded respectively. The 'calculate indices' window was opened next, and the RDI was checked. The distribution settings were left as default. For the calculation settings, the reference period was set to twelve months, and the time step was left as annual.

For manual calculations:

“The initial value (αk) of RDI is calculated for the i-th year in a time basis of k (months) as follows:

$$\alpha_k^{(i)} = \frac{\sum_{j=1}^{k} P_{ij}}{\sum_{j=1}^{k} PET_{ij}}, i = 1(1)N \; and \; j = 1(1)k \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which Pij and PETij are the precipitation and potential evapotranspiration of the j-th month of the i-th year and N is the total number of years of the available data. The values of αk follow satisfactorily both the lognormal and the gamma distributions in a wide range of locations and different time scales, in which they were tested (Tigkas, 2008; Tsakiris et al., 2008). By assuming that the lognormal distribution is applied, the following equation can be used for the calculation of RDIst:

$$RDI_{st}^{(i)} = \frac{y^{(i)} - \bar{y}}{\hat{\sigma}_y}$$

in which y is the $\ln\left(\alpha_k^i\right)$, $\bar{y}$ is its arithmetic mean and $\hat{\sigma}_y$ is its standard deviation”, (Tigkas *et al.*, 2013, p. 1335).

4.3.3 Standardised Precipitation Index (SPI) Calculation

The SPI is calculated for Bethlehem based on a given period using long-term precipitation data (Tigkas *et al.*, 2013). The precipitation data is fitted to a distribution curve and then transformed into a normal distribution, such that zero defines normal conditions (Tigkas *et al.*, 2013). On DrinC the distribution settings were left as default. For the calculation settings, the reference period was set to twelve months, and the time step was left as annual.

For manual calculation:

“Thom (1958) found the gamma distribution to fit well climatological precipitation time series well. The gamma distribution is defined by its probability density function:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}}, for \; x > 0 \ldots\ldots\ldots\ldots\ldots\ldots. (1)$$

where: α, and β are the shape and scale parameters respectively, x is the precipitation amount and Γ(α) is the gamma function. Computation of the SPI involves fitting a gamma probability distribution to a given frequency distribution of precipitation totals for a station. The alpha and beta parameters of the gamma probability density function are estimated for each station, for each time scale of interest (1, 3, 6, 9, 12 months, etc.), and each month of the year. Maximum likelihood solutions are used to optimally estimate α and β:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2)$$

$$\beta = \frac{\bar{x}}{\alpha}$$

where $A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}, and\ n = number\ of\ observations$

The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given month and time scale for the station in question. Since the gamma function is undefined for x = 0 and a precipitation distribution may contain zeros, the cumulative probability H(x) is calculated by the equation:

$$H(x) = q + (1 - q)G(x),$$

where q is the probability of a zero and G(x) is the cumulative probability of the incomplete gamma function. If m is the number of zeros in a precipitation time series, then q can be estimated by m/n. The cumulative probability is then transformed to the standard normal random variable z with mean zero and variance one, which is the value of the SPI", (Tsakiris *et al.*, 2007, p. 91).

4.3.4 Agricultural Standardised Precipitation Index (aSPI) Calculation

The aSPI uses a standardisation like SPI, which involves fitting the effective precipitation to a distribution curve and then transforming it to a normal distribution. The distribution was set to ‘gamma’, and the ‘open after calculation’ boxes were all checked. The effective precipitation (Pe) estimation method was set to USBR. Tigkas *et al.*, (2019) illustrate the relationship between the FAO, USBR, and USDA-SCS (simplified) methods for estimating Pe. The USBR and USDASCS (simplified) methods had a similar trend. Thus, this study adopted the USBR method. Moreover, the FAO according to Tigkas *et al.*, (2019) is more suitable for localities with a small difference in slope. The data used in this study is generalised and does not indicate slope differences. For the calculation settings, the reference period was set to 3 months, and the time step left was annual.

4.3.5 Precipitation Deciles (PD) Calculation

For the calculation settings, the reference period was set to 12 months, and the time step was left as annual. Manually, PD is computed using the following equation:

$$P_i = \frac{1}{N+1} \times 100$$

Where P_i is the likelihood of rainfall in number i and N is the number of rainfall data (Khan *et al.*, 2017).

4.3.6 Effective Reconnaissance Drought Index (eRDI) Calculation

The eRDI's significant modification is the replacement of total precipitation with effective precipitation (Tigkas *et al.*, 2017). The distribution was set to 'gamma', and the 'normalised', 'standardised', and 'open after calculation' boxes were all checked. The effective precipitation estimation method was set to USBR, for uniformity purposes. For the calculation settings, the reference period was set to 3 months, and the time step left was annual.

The manual calculation for the eRDI is similar to the manual computation method for the RDI:

The initial value (αk) of RDI is calculated for the i-th year in a time basis of k (months) as follows:

$$\alpha_k^{(i)} = \frac{\sum_{j=1}^{k} P_{eij}}{\sum_{j=1}^{k} PET_{ij}}, i = 1(1)N \; and \; j = 1(1)k \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

in which Peij and PETij are the effective precipitation and potential evapotranspiration of the j-th month of the i-th year and N is the total number of years of the available data. “Assuming that the lognormal distribution is applied, the following equation can be used for the calculation of eRDIst:

$$eRDI_{st}^{(i)} = \frac{y^{(i)} - \bar{y}}{\hat{\sigma}_y}$$

in which y is the $\ln\left(\alpha_k^i\right)$, $\bar{y}$ is its arithmetic mean and $\hat{\sigma}_y$ is the standard deviation”, (Tigkas *et al.*, 2013, p. 1335).

4.3.7 The correlation of the drought Indices

The PD, RDI, eRDI, and aSPI were all correlated to the SPI using the correlation function in Excel. The data used to compute the correlation was extracted from the saved spreadsheets of the indices calculated respectively on DrinC as described above.

Chapter 5: Results

Various drought indices were used to examine the characteristics (prevalence, length, and intensity) of drought in Bethlehem in the Free State, South Africa. An index is a numerical value that indicates the severity of a drought event. These indices quantify the precipitation deviation from the normal (for the SPI, aSPI, RDI, and eRDI the normal is defined by zero, and for the PD the normal is defined by the median value which is five). This section of the report presents the findings from the computation of these indices starting with the RDI and ending with the correlation of the 5 indices calculated in this study.

5.1 Reconnaissance Drought Index

The RDI is calculated in two stages: the normalised RDI, and the standardised RDI for this study. For each month, the seasons, and the hydrological year, can be calculated. The first 10 years (1980 – 1990) are indicative of a near-normal to severe drought (**Figure 2.1**). This is followed by nine years (1991 – 1999) near normal to very wet conditions. The next four years (2000 – 2003) indicate a relatively short near normal to severe drought. The following seven years (2004 – 2010) are indicative of near-normal to very wet conditions. The last seven years (2011 – 2017) indicate a return of the near normal to severe drought.

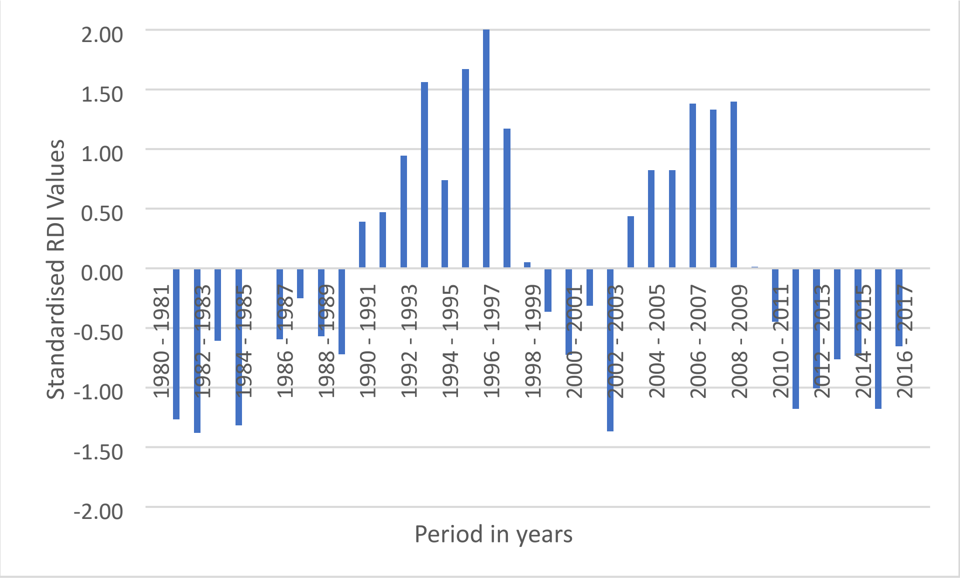


Figure 2.1: Standardised RDI graph of Bethlehem for the period 1980 - 2017

5.2 Standardised Precipitation Index

Using the software DrinC, an SPI analysis of the drought over Bethlehem in Free State was calculated and tabulated (**Table 2, Figure 2.2**). The first 10 years (1980 – 1991) indicated a near-normal to severe drought with SPI values ranging between -1.46 and -0.21. The next nine years (1990 – 1999) represented near-normal to very wet conditions with values ranging between 0.10 and 1.79. This period is followed by a relatively short near normal to severe drought of four years (1999 – 2003) with SPI values ranging between -1.40 and -0.32. The next 8 years (2004 – 2011) also indicate a relatively short period of near-normal to very wet conditions with SPI values ranging between 0.04 and 1.47. The last 7 years (2012 – 2018) indicate the return of the near normal to severe drought with SPI values ranging between -1.11 and -0.41. Of critical note is that none of the drought events were extremely severe i.e., there are no SPI values equal to, or below -2. There were also variations within the wet/ dry years i.e., 2004 – 2009 shows a steady increase in RDI values whereas the other years fluctuated.

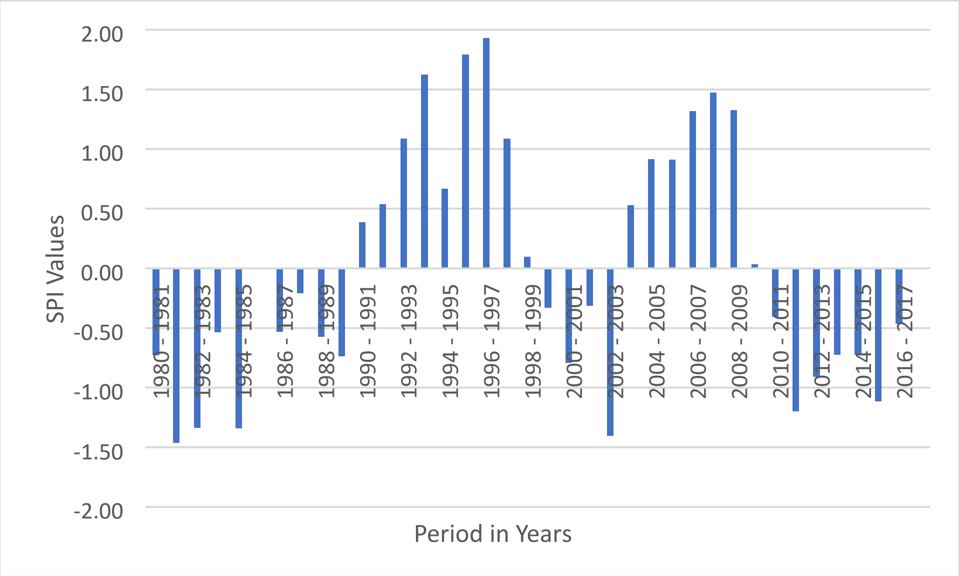


Figure 2.2: SPI graph of Bethlehem for the period 1980 - 2017

5.3 Agricultural Standardized Precipitation Index

The aSPI followed a similar trend to the SPI with five distinct periods of dry and wet conditions **Figure 2.3**. The aSPI uses effective precipitation instead of the normal precipitation as in the calculation of the SPI but the standardization is the same. Again, any values greater than or equal to zero mark the end of a drought episode. The first 10 years (1980 – 1990) indicate severely dry to near-normal conditions. The next nine years (1990-1991 – 1999) were indicative of near-normal to very wet conditions. The following four years (1999 - 2003) represent a relatively short near normal to severe drought. The next seven years (2003 - 2010) were indicative of near-normal to very wet conditions. The last eight years (2010 - 2018) indicate a return of severely dry to near-normal conditions.

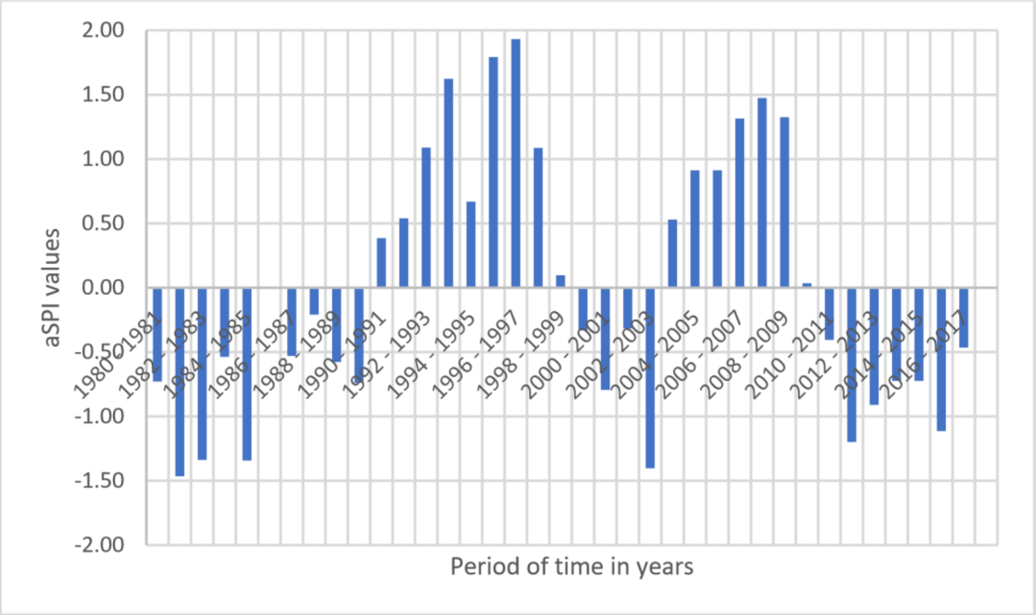


Figure 2.3: aSPI graph of Bethlehem for the period 1980 - 2017

5.4 Precipitation Deciles

Over the 38 years, **Table 3, Figure 2.4** following the Deciles technique, classify each year's drought from years with significantly below-normal precipitation to years with significantly above-normal precipitation. Using this method, we can see the first 20 years (1980 – 2000) received below-normal to much above-normal precipitation with values ranging between 4 and 10. The last 18 years (2001 – 2018) also had a similar trend to the first period with below-normal to much above-normal precipitation. Of critical note, the first 20 years (1980 – 2000) received predominantly near–normal to much above-normal precipitation. And the last 18 years received predominantly below-normal to near-normal precipitation, particularly the latter part of the period (2010 – 2018). Of critical note is that the decile technique identified four dry spells; 1980 – 1983; 1984 – 1985; 1988 – 1989; and the longest dry spell between 2012 – 2018. Other than that, the deciles technique only identified years' which received below-normal to much below-normal precipitation [2000, 2003, and 2018].

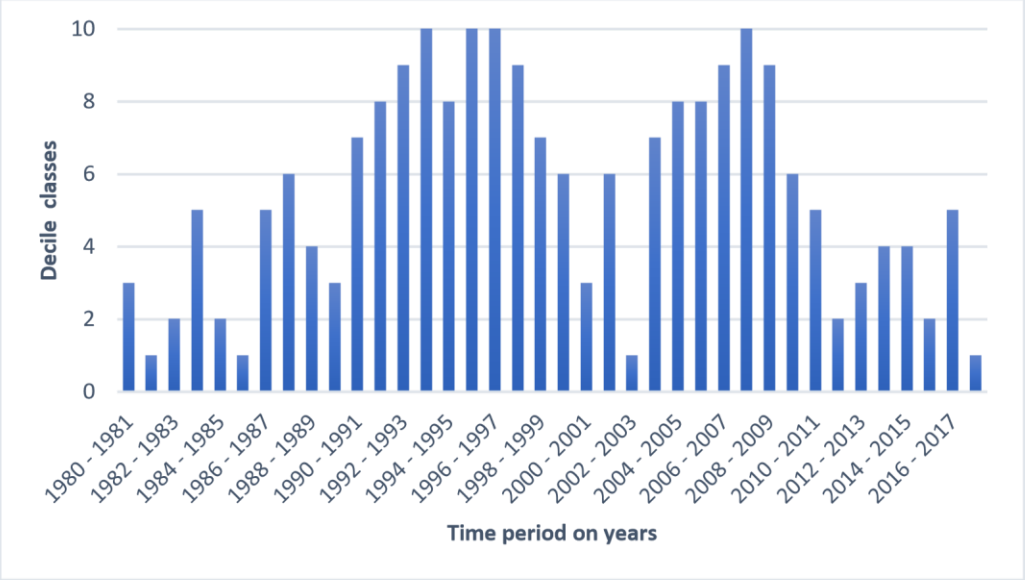


Figure 2.4: Drought Conditions in Bethlehem classified according to deciles between 1980 and 2017

5.5 Effective Reconnaissance Drought Index

The eRDI is computed in two primary methods, standardised, and normalised like the RDI. The first 10 years (1980 – 1990) were indicative of a moderate to severe drought **Figure 2.5**. This is followed by nine years (1991 – 1999) of moderate to very wet conditions. The next four years (2000 – 2003) indicated a relatively short moderate to severe drought. The following seven years (2004 – 2010) are indicative of a moderate to very wet spell. The last seven years (2011 – 2017) indicate a return of moderate to severe drought.

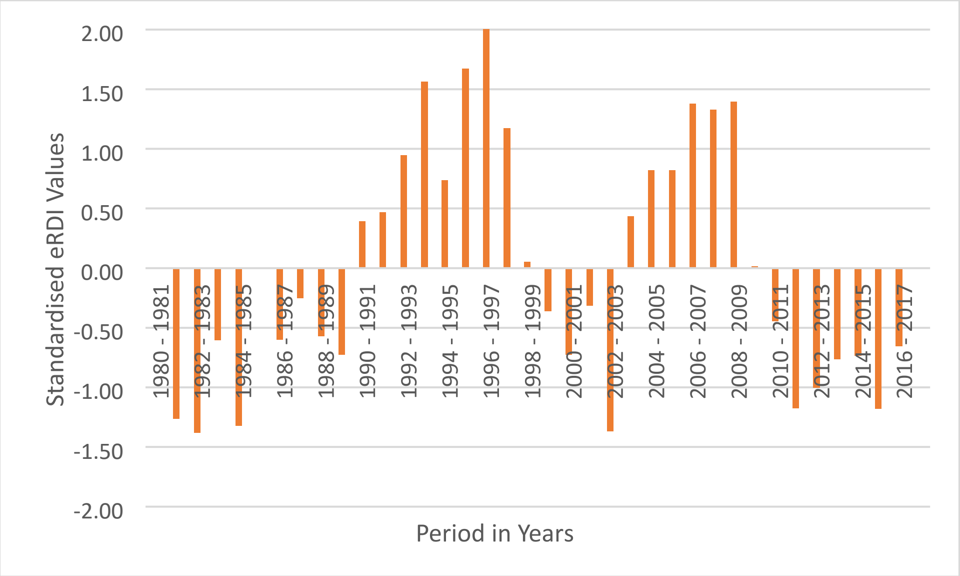


Figure 2.5: Standardised eRDI graph of Bethlehem for the period 1980 - 2017

5.6 SPI/PD correlation

Table 5 presents the correlation results for the correlation of the SPI results and the PD results. The outcome illustrates a strong positive correlation. The other results were not correlated because they yield very comparable results, i.e., the eRDI, RDI, aSPI, and SPI all yield similar results in that they identified the same drought periods, with similar duration and severity Figure 2.1, Figure 2.2, Figure 2.3, Figure 2.5. The PD on the other hand identified specific years when the precipitation over Bethlehem was above or below average Figure 2.4 and these years coincide with the identified drought periods and out-of-drought periods as identified by the SPI and other indices Table 5: The correlation of the SPI and PD.

Table 5: The correlation of the SPI and PD

Correlated Indices	**Correlation coefficient**
SPI/ PD	0.65

Chapter 6: Discussion

Society, the environment, and the economy may be significantly impacted by drought. For decision-makers to effectively plan and coordinate adaptation and mitigation strategies in the context of future climate change, they must have a thorough understanding of how climate change impacts all types of droughts at a local scale (Kolusu *et al.*, 2019). In the South African agricultural context, understanding and characterizing drought is significantly important since agricultural production is a primary contributor to the country's GDP (Abubakar *et al*., 2020). South African agriculture is mostly rainfed (Moeletsi *et al.*, 2013).

The primary objective of characterising drought is to quantify its severity, which is typically performed by using drought indices (Singh and Shukla, 2020). Several drought indices have been established for general or specific usage, supporting various research goals (Van Lanen *et al.*, 2008; Surendran *et al.*, 2017). The decile technique has the benefit of being computationally simple, yet conceptual complexity can result from simplicity (Tigkas *et al*., 2013). For instance, it makes sense for a drought to end when the recorded rainfall is at or above normal, but this is only referring to a change in day-to-day atmospheric conditions i.e., weather (Kininmonth *et al.*, 2000; Tigkas *et al*., 2015). The RDI can be used in two different ways: 1. as a drought index to define the onset and completion of one or more drought events; 2. can be used as a climatic index to spot potential trends on an annual or seasonal basis (Tsakiris *et al.*, 2007; Abubakar *et al*., 2020). This makes the RDI a useful index when studying drought under different climate contexts as in South Africa where some places are semi-arid, some subtropical, and some Mediterranean (Abubakar *et al*., 2020). Moreover, indices like eRDI, aSPI, and RDI are all derived using two base parameters to reflect the water balance: cumulative precipitation (RDI), effective precipitation (eRDI, and aSPI), and potential evapotranspiration for the chosen reference period (Tigkas *et al.*, 2022). Thus, when the aforementioned indices are integrated with the SPI and PD are more effective in characterising drought events.

The Free State produces a significant proportion of South Africa's agricultural output and has the most farming units per capita with significant tracts of fertile and arable land (Moeletsi and Walker, 2012). Except for the province's northeastern and eastern regions, which are categorized as subtropical, the climate is primarily semi-arid (Moeletsi and Walker, 2012). Since the entire province is classified as a summer rainfall area, October to April experiences a seasonal increase in rainfall (Moeletsi and Walker, 2012; Botai *et al.*, 2016). According to recent research conducted in the region, Bethlehem experiences its first rains on average in the final 10 days of October, and its last rains on average in the final days of March rainfall (Moeletsi and Walker, 2012).

6.1 The Evaluation of Drought Events in Bethlehem

The first drought event is between 1980 – 1990; the second one is between 2000 – 2003; and the last one is between 2010 – 2018. year. Botai *et al.*, (2016) conducted a study to investigate the drought conditions in the Free State and Northwest provinces in South Africa between the years 1985 – 2015 using the SPI and Standardized Precipitation Evapotranspiration Index (SPEI). This study identifies two main drought events: 1985 – 1994; 2005 – 2015. The SPI calculated using the 6 months reference period in the study conducted by Botai *et al.*, (2016) identified 2 drought events that occurred around the same time as identified by this study. This study identified a drought between 1980 – 1990, as well as 2010 – 2018. The PD does not identify any drought event but identifies years which received below-normal precipitation (Abbasian *et al*., 2021). Similarly, in this study the PD identified the years 1980 – 1983; 1985; 1986; 1989; 1990; 2001; 2003; 2012 – 2016; as well as 2017 as having received below-normal precipitation. The years identified by the PD as having received below-normal precipitation fall in between the drought events identified by the other 4 indices as well as the study conducted by (Botai *et al.*, 2016).

Botai *et al.*, (2016) found that the Free State experienced more droughts than the Northwest province. However, the drought events in the Free State province were moderately severe as compared to the severely dry to extremely dry droughts experienced in the Northwest (Botai *et al.*, 2016). Similarly, in this study, the droughts identified the SPI, aSPI, RDI, and eRDI, as well as the PD, were moderately severe, with some years experiencing near normal conditions (or simply put very mild drought).

6.2 The Precipitation Deciles as an Effective Tool for Drought Characterisation

The precipitation decile technique is based on the simplified understanding that a drought event will end when the precipitation sum amount falls in or above the 8th decile **Table 3**. A specific area is said to be in a drought if the precipitation sum amount falls within the lowest decile. This means that the precipitation decile is effective in identifying anomalies. For instance, the other indices identify a drought event from 2000 to 2005 with the year 2004 experiencing relative a very severe drought **Figure 2.1, Figure 2.2, Figure 2.3, Figure 2.4, Figure 2.5**. Yet, the precipitation decile is so sensitive, that it identifies precipitation anomalies within the 2000 – 2005 drought event: 2002, 2004, and 2005 are identified as years that received above-normal precipitation **Figure 2.4**. Now, given the definition of drought in the context of this index, the particular years would mark the end of drought.

6.3 The cyclicity of the drought events in Bethlehem

Botai *et al.*, (2016) refer to droughts as a common occurrence in the Free State province and go on to indicate the prevalence of more severe drought events in the Free State relative to the Northwest province. This study identifies that the occurrence of drought events in Bethlehem is at regular intervals; droughts occur almost every 10 years and last between 4 and 10 years. Given that Bethlehem is South Africa's 'house of bread', an inference can be drawn that during drought years, food security is highly variable, meaning the country is at risk of food scarcity.

Chapter 7: Conclusion

It is essential to carefully examine past drought occurrences to assess the likelihood of droughts in the future. Furthermore, a study of this nature is important because droughts have environmental and socio-economic implications. The severity, length, and spatial extent of rainfall shortfall determine the impact of the drought. In other words, severity, length, and extent define and characterise any drought event. In this study, we examined the characteristics of the drought in Bethlehem between 1980 and 2017 using different meteorological and hydrological indices. The goals of the present study were to apply hydrological and meteorological drought indices to determine the number of drought events and investigate the evolution of the drought event/s in Bethlehem between 1980 and 2017. To achieve the aforementioned aim, the study employed the Drought Indices Calculator as well as Microsoft Excel for simplified computation and analysis of the chosen drought (PD, SPI, RDI, eRDI, aSPI).

We found that the droughts became shorter but more severe after 1999. Of critical note are the years 1983, 2015, and 2016 experienced significantly severe droughts. To improve reliability as well as test for similarities, the PD results were correlated against the SPI revealing a moderately strong positive correlation and can easily be identified in terms of the number of drought events identified by the two indices; the SPI identifies three drought events in particular 1983, 1992, 2015, and 2016 whilst, PD identifies 1982, 1986, 2003, and 2018 as specific years where the precipitation received was in the1st– 2nd percentile. These years lie within the identified drought events.

7.1 Recommendations

- Since the drought indices used in this study are useful in retrospect, a more integrated methodology should be considered for future studies of this nature. The methodology should consider past drought events as well as projection climate models. The climate models are useful in depicting the behaviour of the climate based on current trends.
- This study also did not provide a drought map so in addition to the hydrological and meteorological drought indices, remote sensing technology should be employed.
- The knowledge of climate change within the South African context and the research into advanced farming technology and sustainable development are critical to the characterisation and management of droughts.

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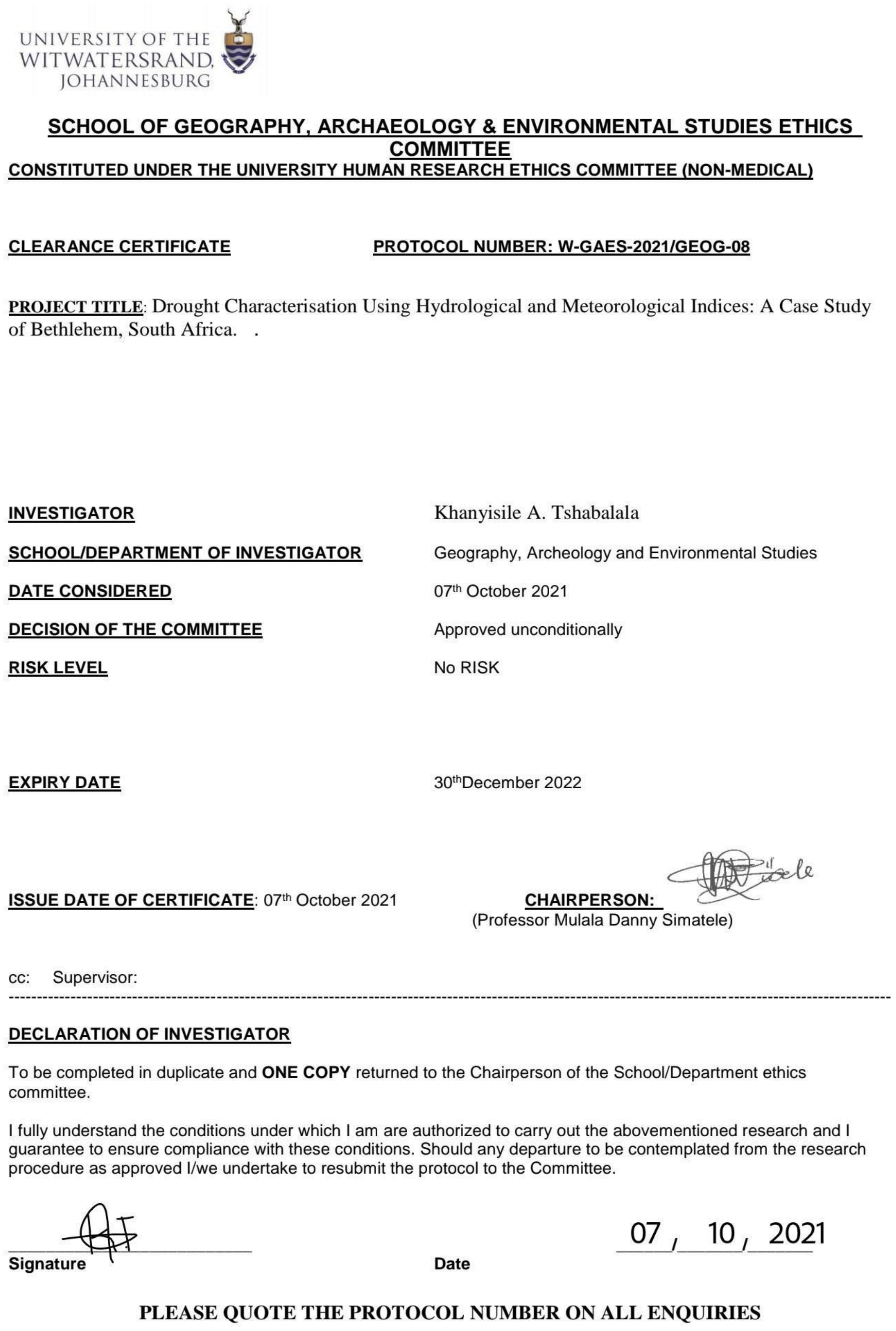
Appendices

Appendix A – Ethics Clearance Certificate



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

SCHOOL OF GEOGRAPHY, ARCHAEOLOGY & ENVIRONMENTAL STUDIES ETHICS COMMITTEE

CONSTITUTED UNDER THE UNIVERSITY HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)

CLEARANCE CERTIFICATE **PROTOCOL NUMBER: W-GAES-2021/GEOG-08**

PROJECT TITLE: Drought Characterisation Using Hydrological and Meteorological Indices: A Case Study of Bethlehem, South Africa. .

INVESTIGATOR	Khanyisile A. Tshabalala
SCHOOL/DEPARTMENT OF INVESTIGATOR	Geography, Archeology and Environmental Studies
DATE CONSIDERED	07th October 2021
DECISION OF THE COMMITTEE	Approved unconditionally
RISK LEVEL	No RISK
EXPIRY DATE	30thDecember 2022

ISSUE DATE OF CERTIFICATE: 07th October 2021

CHAIRPERSON:
(Professor Mulala Danny Simatele)

cc: Supervisor:

DECLARATION OF INVESTIGATOR

To be completed in duplicate and **ONE COPY** returned to the Chairperson of the School/Department ethics committee.

I fully understand the conditions under which I am are authorized to carry out the abovementioned research and I guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee.

Signature

Date 07 / 10 / 2021

PLEASE QUOTE THE PROTOCOL NUMBER ON ALL ENQUIRIES