Late mid-summer dry-spells and planting dates of maize in the western maize-growing region of South Africa

By

Siphamandla Daniel

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School of Agricultural, Earth and Environmental Sciences
College of Agriculture, Engineering and Sciences
University of KwaZulu-Natal
Pietermaritzburg
South Africa

SUPERVISOR: PROF. ALISTAIR CLULOW
CO-SUPERVISOR: DR. MICHAEL MENGISTU

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PREFACE

The research contained in this thesis was completed by the candidate while based at South African Weather Service. The research presented forms part of a Water Research Commission project, number K5/2830- "An investigation of the historical and projected occurrence of the South African mid-summer drought and its implications for the agro-water budget". The research was funded from the Water Research Commission (WRC) grant number K5/2830/1and2.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

[redacted]

Signed by: Professor Alistair Clulow (Supervisor)

05 December 2024

[redacted]

Signed by: Doctor Michael Mengistu (Co-Supervisor)

05 December 2024

DECLARATION 1: PLAGIARISM

I, Siphamandla Daniel, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written, but the general information attributed

to them has been referenced;

b) where their exact words have been used, their writing has been placed

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(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

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DECLARATION 2: PUBLICATION

Chapter 4 is a scientific paper that was published on MDPI- Water journal in 2023. **Author Contributions:** Conceptualization, S.D.; Methodology, S.D. and M.G.M.; Software, C.O. Formal analysis, S.D. and M.G.M.; Investigation, S.D.; Data curation, S.D. and C.O. Writing-original draft, S.D.; Writing-review and editing, M.G.M. and A.D.C.; Supervision, M.G.M. and A.D.C.

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ABSTRACT

South Africa experiences a climate characterised by arid conditions and significant variability in annual rainfall. This exerts a severe impact on water resources, agriculture, and the socio-economic sector of the region. Drought is a natural occurrence known for sustained below-average precipitation over a specified period, and it is a well-documented aspect of a region's climate variability. Existing research has predominantly focused on drought occurrence, impact, intensity, and duration, primarily on seasonal and annual scales. This study deviates by emphasising the importance of recognising mid-summer droughts in the agricultural sector, where the timing and severity of dry-spell periods hold greater significance than overall seasonal rainfall deficits.

Mid-summer droughts, occurring typically from December to January in the summer rainfall regions, coincide with a shift in atmospheric circulation from baroclinic to barotropic. This shift is dominated by tropical systems and is particularly critical as the timing aligns with the water stress-sensitive flowering stage of summer crops like maize and sorghum. Given the potential detrimental effect on crop yield, especially maize, there is a need to investigate and understand the patterns associated with these events. By delving into the specifics of mid-summer droughts, this research aimed to contribute valuable insights to aid and mitigate the adverse impacts on agricultural productivity in South Africa. However, in this study, the late-midsummer period, which spans from mid-January to the end of February is of particular importance. This is because maize is planted later in the western region of maize production than it is in the temperate and cooler eastern maize production regions. Therefore, dry-spells, which occur around the mid-January to the end of February period, normally correspond with maize's flowering cycle in the western maize growing regions of South Africa. However, it is worth noting that due to shifting planting dates, the flowering stage may occur later and remain unaffected by the phenomenon. During this sensitive stage of the growth cycle, even a few days without rain could result in lower crop production.

The Markov chain model analysed the probability of initial and conditional dry-spell pentads. In addition, the Mann-Kendall monotonic trend test and Sen's slope estimator were performed to check the direction and magnitude of dry-spell trends. It consistently revealed the impact of dry-spells throughout the mid-January to late February period, the most critical phase in the flowering of maize for the western maize-producing region. Although most districts showed a downward trend in the occurrences of dry-spells, this was not statistically significant. Sen's slope estimator further supported a reduction in the magnitude of dry spells over the study period. This research thus provides important information to farmers by enhancing their understanding of shifting risk profiles associated with dry-spells. Furthermore, utilising AquaCrop simulation simulations, the study explored the influence of planting dates on maize yield in the western maize growing region. The latest simulated planting date of 20 December was found to result in the best maize yields across most Rainfall Districts. However, certain districts with low dry-spell frequencies experienced lower average yields compared to medium-frequency seasons, potentially linked to heavy rainfall distribution during the flowering stage of maize. The analysis of the rainfall data showed that during some low frequency dry-spell seasons, extreme rainfall events occurred. These extreme rainfall events may have led to waterlogging issues, resulting in a reduction in crop yield below the typical maize production levels. In conclusion, the AquaCrop model provided reliable and realistic outputs, with crop yields aligning well with observed rainfall patterns. A two-way ANOVA test indicated that there is a statistical significance between maize yield and planting dates in most of the Rainfall Districts, with the planting date of 20 December simulating the best maize yields compared to the other planting dates in most of the Rainfall Districts. Thus, the period after the 20th of December has higher crop yield. This is because crops planted around this date will flower outside the late midsummer period, and as a result, they will not be affected by the dry spells. It is recommended that future research should focus on examining the impacts of dry spells on different maize varieties and assessing the effects of climate change on dry spell occurrence.

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CHAPTER 1: INTRODUCTION

1.1 General Introduction

The climate in South Africa is characterized by dry conditions and notable fluctuations in annual rainfall (Cook et al., 2004). This has an impact on water resources as well as the agricultural and socio-economic sectors of the region. Drought is a natural phenomenon resulting from a prolonged period of below-average rainfall, leading to a temporary imbalance in water availability (Pereira et al., 2009). Drought is part of the natural climate variability and can be observed through all climate regimes. Drought has been well-researched and documented, with the focus areas of research being the occurrence, impact, intensity, and duration of drought , however, this has often been conducted at seasonal and annual scales (Mengistu et al., 2021).

In the agricultural sector, monitoring mid-summer droughts is equally critical as assessing seasonal rainfall deficiencies since the duration and severity of the dry-spell period are significant to crop yield (Usman and Reason, 2004). Mid-summer droughts usually occur during the months of December to January in the summer rainfall regions of South Africa, due to a change in the atmospheric circulation from baroclinic (circulation dominated by southern systems) to barotropic (circulation dominated by tropical systems) (Bhalotra, 1984). Summer crops, such as sorghum and maize, blossom at this time of the year, and the mid-summer droughts usually devastate crop development since they are most vulnerable to water stress at this stage. Thus, the maize flowering stage usually coincides with the onset of mid-summer drought, making it essential to investigate their patterns to mitigate the effects (Du Plessis, 2003).

The primary staple food for South Africa's rural population is maize (*Zea mays* L.), which is grown in a variety of climates (Walker and Schulze, 2006). With abundant water supply and optimum temperatures, maize is a fast-growing crop within areas of South Africa (Aldrich et al*.,* 1986). Amongst the cereal crops, maize has a broad tolerance to agro-climatic zones within which it grows. Maize typically requires 400 to 600 mm of rainfall per growing season, though it can also be successfully cultivated in regions receiving as little as 300 mm (Du Plessis, 2003; Moeletsi, 2004; Moeletsi and Walker, 2012). Due to the aforementioned, maize is grown in South Africa across a range of climatic conditions, making it essential that maize cultivars are suited to specific growing conditions (Du Plessis, 2003). Several natural factors, such as soil characteristics and climatic variables that vary over time, influence an area's ability to produce agricultural products (Moeletsi, 2004). Crop production is negatively impacted by a number of climatic conditions, including variable rainfall patterns, high temperatures, high evapotranspiration, mid-summer droughts, and low humidity levels during the growing season. Therefore, there needs to be consistent investment in agro-meteorological studies within the different regions, to aid farming communities make informed decisions for crop selection (Moeletsi, 2004).

Climate change is predicted to have an influence on a number of crops, including maize, and these consequences will have a major effect on Sub-Saharan Africa's food security (Du Plessis, 2003). It has been found that maize is especially vulnerable to water stress during its flowering stage, which can decrease crop development, yield, and biomass production. Root growth is also affected during periods of water deficit, as fresh and dry shoots are significantly reduced (Shao et al., 2008). Planting dates should, therefore, be selected so that this growing stage falls outside the period when mid-summer droughts occur and coincides with more favourable growing conditions (Du Plessis, 2003).

A number of crop models are utilised for planning and management applications in the agricultural sector. These models are useful as they minimise the need to conduct field experiments, which are expensive, time-consuming and with site-specific results (Babel et al., 2019). These models also serve as analytical tools in yield gaps between the actual and potential productivity of various crops (Babel et al., 2019). Due to their accuracy and low data requirements, the AquaCrop and the Decision Support System for Agrotechnology Transfer (DSSAT) models are widely utilised crop models in the southern African region. High levels of uncertainty in model structure and input parameters are common drawbacks of crop models (Babel et al., 2019). Proper model standardisation and evaluation are crucial when working with models, but these steps are often overlooked by users.

The DSSAT software application includes crop simulation models for over 42 different crops (Hoogenboom et al., 2019). Amongst the tools that are required in a DSSAT model are utilities, application programmes, and database management systems for meteorological, soil, agricultural management, and experimental data. (Hoogenboom et al., 2019). The crop simulation models replicate how soil, plant, and atmospheric dynamics affect growth, development, and yield. (Hoogenboom et al., 2019). Numerous applications at various temporal and spatial scales have made use of DSSAT and its crop simulation models.

The AquaCrop model was created by the Food and Agricultural Organisation (FAO), by utilising the link between biomass increase and water loss through transpiration, the model forecasts agricultural output and determines the required quantity of water (Steduto et al., 2009; Hsiao et al., 2009). A model calibrated for a specific crop can be applied to a wide range of other crops, provided the data used is relevant to those crops (Doorenbos and Kassam, 1986). The type of crop, such as whether the plant is a C3 or C4 type or whether any part of the crop, such as grain, root, tuber, or vegetative material, is economically relevant, determines the data needed to compute the harvest index. Predicting transpiration and biomass accumulation depends on the rate at which the leaf canopy develops (Raes et al., 2009). Several studies have shown that both models produce very good results (Adeboye et al., 2019). However, AquaCrop was chosen as the preferred crop model for this study due to the lower data requirements. Such low data requirements are ideal for studies on the African continent, where there is often limited data available for running the models. The AquaCrop model, extensively tested on maize, was utilised to simulate maize yield in the western maize production region of South Africa during the summer rainy season to assess the impact of late mid-summer droughts on maize yield.

1.2 Aim

The aim of this study was to investigate the impacts of late mid-summer droughts on maize yield and optimal planting dates in the western maize-growing region of South Africa, using the AquaCrop model.

1.3 Specific Objectives

- To investigate the initial and conditional probabilities of dry and wet spell pentads using the Markov chain model and determine the direction and magnitude of trends in dry-spells in the western maize-growing region of South Africa.

- To explore the effects of dry-spells in January and February and assess different planting dates on maize yield in the western maize-growing region of South Africa.

1.4 Research Question

What is the impact of late mid-summer droughts, and which planting dates can minimize the risks associated with these droughts in the western maize-growing region of South Africa?

CHAPTER 2: LITERATURE REVIEW

2.1 Climate Variability of South Africa

2.1.1 Onset and Cessation of the Rainy Season

The onset and end of seasonal rainfall are critical since it is essential to agriculture's productivity (Phakula, 2016). In South Africa, the summer rainy season typically begins near the end of October, while specific locations within the region may experience varying timings. Whereas the late commencement and early cessation of summer rains can result in drought conditions that adversely affect the agricultural sector and the livelihoods of communities, flooding, destruction to infrastructure, and fatalities may result from the early commencement and late cessation (Otun and Adewoni, 2009; Phakula, 2016). In agroclimatology, the start and end period of the rainy season are determined by a rainfall threshold over a pentad, which is an interval of five consecutive days and in this context, it is the accumulation of rainfall over a five-day period (Cheruiyot and Osunmakinde, 2010; Phakula, 2016). In South Africa, the onset of rainfall is considered as the first day where two pentads receive at least 25 mm of rainfall, provided that the succeeding five pentads have at least 20 mm of rainfall (Reason et al., 2005). Six pentads with less than 20 mm of rainfall in each pentad constitute the end of the rainy season (Reason et al., 2006).

2.1.2 El Niño Southern Oscillation (ENSO)

ENSO is an important driver behind South Africa's inter-annual rainfall variability (Richard et al., 2000; Crétat et al., 2012). ENSO is a naturally occurring phenomenon that involves the large-scale interaction between the atmosphere and the upper ocean layers in the Indo-Pacific Ocean (Richard et al., 2000; Crétat, 2012; Mpheshea, 2014). The El Niño and La Nina events are represented by the warm and cooling phases of the Southern Oscillation, respectively, which demonstrates variations in the tropical Pacific Ocean's surface temperature (Cane et al., 1985; Philander, 1985; Phakula, 2016). The two events have an influence in the high-pressure systems, with La Nina favouring the occurrence of a low pressure over the western pacific and El Niño favouring the development of a high pressure over the western Pacific Ocean. During an El Niño event, South Africa experiences drought conditions and below-normal rainfall. These climatic anomalies that impact the summer rainfall in the region can be easily identified and forecast (Dieppois et al., 2015).

El Niño has adverse effects on the southern African region, with South Africa as no exception (Mason, 2001). According to Mason (2001), this phenomenon is in full effect during the summer season, where it results in warm and dry conditions dominating the region (Figure 1). This phase is characterised by below-normal rainfall and, on occasion, severe droughts. This has detrimental effects on both the agriculture industry and the overall socioeconomic sector. This phase is often associated with low output yields in the staple grains such as maize and sorghum, as these grains are cultivated when the system is in the mature phase in the summer months (Du Plessis, 2003).

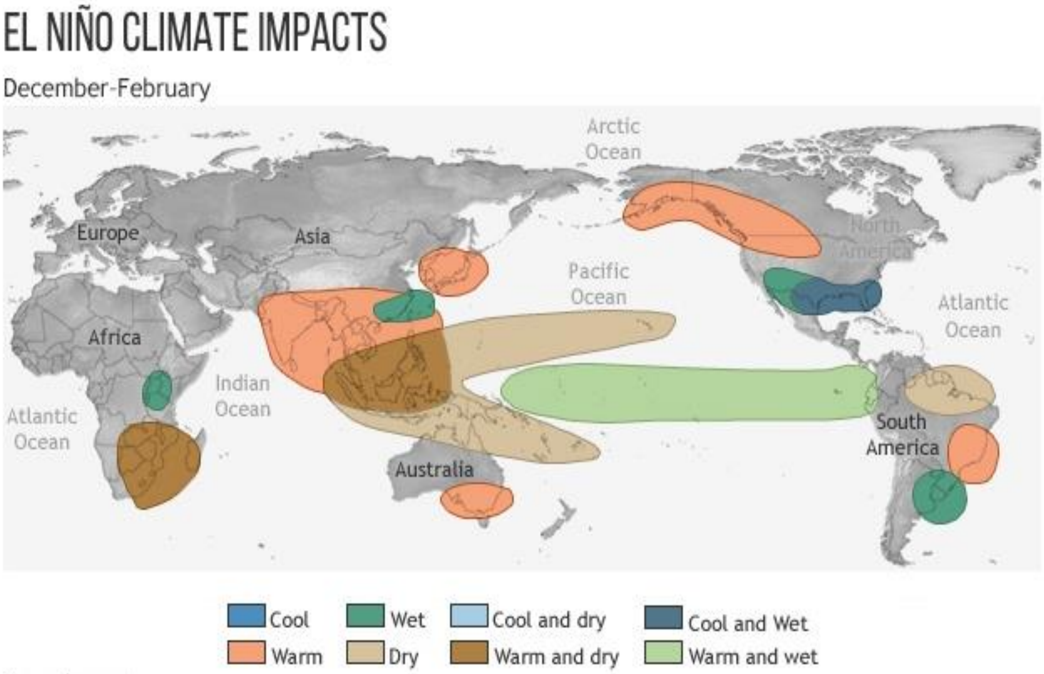

Figure 1: Global climatic conditions during El Niño events (www.pmel.noaa.gov).

La Nina has advantageous weather conditions for the region as cool and wet conditions (Figure 2) dominate during this phase (Tyson 1986: Reason, 2017). During this phase, above-normal rainfall is dominant, and, on some occasions, severe flooding is a norm (Tyson, 1986; Reason 2017; Webster, 2019). La Nina period is favourable for hydrological replenishment within regions. Although above-normal rainfall is incredibly significant for agricultural production, on some occasions, this period is associated with destructive events within the sector (Sazib et al., 2020). The events of heavy rainfall may wash seeds away and even affect the crops during the harvesting period. This is usually because crop disease development is often favourable due to moist conditions dominating (Diko and Jun, 2020).

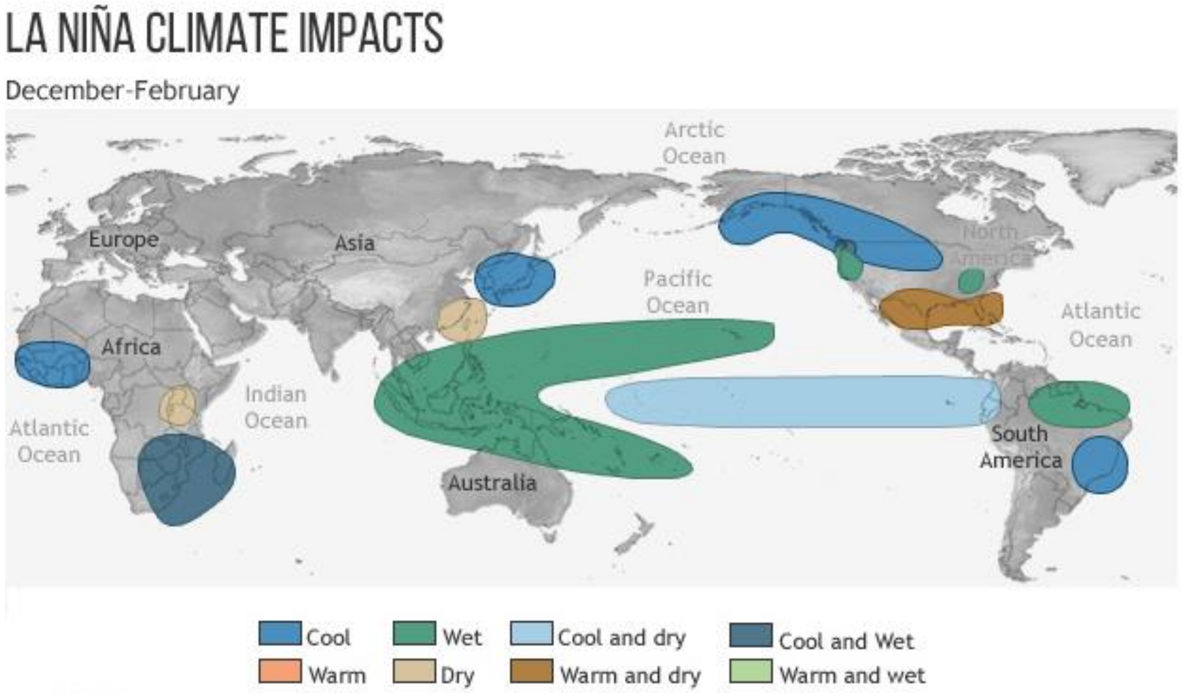

Figure 2: Global climatic conditions during La Nina events (www.pmel.noaa.gov).

2.1.3 Heatwaves

There are many definitions that are used to define heatwaves. The South African Weather Service (SAWS) states that a heatwave is when temperatures are five degrees Celsius above the average maximum temperature in a certain area for three days in a row (Mbokodo, 2017). Heatwaves usually occur from large-scale high-pressure systems that remain over a region over an extended period (Patulikof et al., 1996; Mbokodo, 2017). This process influences the surface temperatures, as the descending air from high-pressure system is warm and dry. Heatwaves are associated with dry atmospheric conditions, and cyclonic conditions are unfavourable (Patulikof et al., 1996; Unkaševica and Tošic, 2009; Mbokodo, 2017). Thus, the formation of clouds and precipitation rarely occurs when these conditions persist.

2.1.4 Sea-Surface Temperatures (SST)

ENSO, which is recognized as the main source of inter-annual variability in the tropics, is primarily caused by SST variations over the Pacific Ocean (McKellar et al, 2014). There is an indication that the south-west Indian Ocean's SST anomalies and summer rainfalls over southern Africa are closely related (Reason and Mulenga, 1999). Walker (1990) suggested that warm ocean SSTs are often associated with increased trade winds, resulting in moisture convergence over the subtropical region of the continent. Warmer SST in the southwestern Indian Ocean positioned below the continent is linked with increased surface fluxes and mid-latitude baroclinicity (Reason and Mulenga, 1999).

Changing SST will have a considerable impact on the climatic variation around the region of southern Africa (Tyson, 1986). Furthermore, when the diabatic heating of the atmosphere over Africa is strongest and the pressures over the continent are lowered, the South Atlantic High-Pressure system is moderately stronger (Tyson, 1986). Walker (1990) suggested that increasing trade winds are correlated with warmer SST and that this is advantageous for the development of moisture convergence over the continent's tropical and subtropical regions. Mid-latitude baroclinicity and heightened surface flux are linked to warmer SST over the far southwestern Indian Ocean near the Agulhas retroflexion, which is south of Africa (Reason and Mulenga, 1999).

2.1.5 Droughts

Due to the region's considerable rainfall variability, South Africa is vulnerable to droughts (Richard et al., 2001; Thomas et al., 2007; Monyela, 2017). There are numerous drought definitions. According to the Intergovernmental Panel on Climate Change (IPCC), a drought is an extended period of below-normal rainfall in a region that results in a lack of sufficient water for certain activities (IPCC, 2007). The natural phenomena known as drought is caused by a prolonged duration without rain, which leaves water scarcity. The effects of drought build up gradually over time and are influenced by temperature, humidity, and rainfall (Hassan, 2018). Drought occurs in all the climatic regimes of the world (Mniki, 2009). In contrast to other natural disasters, droughts have a delayed onset and may persist for an extended period of time (Maybank et al., 1995; Dube, 2008; Wilhite, 2016). Each occurrence of a drought can be identified by its intensity, duration, and geographic coverage due to its distinct meteorological features (Wilhite and Svoboda, 2000). Drought is one of the main natural disasters that causes malnutrition and food insecurity on the African continent (Shiferaw et al., 2014). Previous studies focused on the frequency, severity, impacts, and forecasting of drought on a seasonal and annual basis; however, short-term droughts are equally significant to the agriculture sector because the timing and intensity of the dry periods are more important than seasonal rainfall deficits (Usman and Reason, 2004; Mengistu et al., 2021). Drought is categorised into four pillars, namely, meteorological, agricultural, hydrological, and socio-economic drought.

2.1.5.1 Meteorological Drought

The amount of dryness and duration of a dry period in relation to the average rainfall is referred to as a meteorological drought (Oladipe, 1985; Labedzi and Bak, 2014; Phakula, 2016). This type of drought focuses on the physical aspects of droughts, including when precipitation deviates from average, and not the impacts associated with droughts. Since local atmospheric conditions differ, definitions of meteorological drought must be specific to a given region (Sivakumar et al., 2011; Phakula, 2016).

2.1.5.2 Agricultural Drought

Agricultural drought associates hydrological drought with its impacts on the farming sector (Wilhite and Glantz. 1985). The primary impact of drought on agriculture is the soil moisture deficit, which is the difference between the actual and anticipated levels of precipitation and evapotranspiration (Wilhite and Glantz. 1985; Botai et al., 2017). It is critical to recognise that agricultural water requirements are influenced by the environment, crop species, and crop growth stage. Thus, the duration and timing of an agricultural drought are just as crucial as a lack of precipitation (Fraisee et al., 2011).

2.1.5.3 Hydrological Drought

A hydrological drought is characterised by a continuous decrease in the volume and discharge of surface water bodies, including lakes, rivers, streams, and dams (Fraisee et al., 2011). Hydrological drought is a natural phenomenon and is aggravated by the prolonged occurrence of meteorological and agricultural droughts. This type of drought can also be worsened by social activities such as extraction of underground and/or stream water for irrigation and domestic use.

2.1.5.4 Socio-economic Drought

Socio-economic drought occurs when lack of rainfall starts to affect the livelihoods of citizens and their quality of life (Sun, 2009). It differs from the other types of droughts as the agricultural production (crops, grazing pastures) largely depends on the amount of precipitation received per season. Socio-economic drought connects human vulnerability to the relationships between climatic, agricultural, and hydrological droughts (Wilhite and Buchanan-Smith, 2005). Due to climate variability, water is abundant in some years and in some there is a shortage of water (Wada et al., 2011; Phakula, 2016).

2.2 Dry-spells

South Africa is a region of high spatial and temporal rainfall unpredictability and has been subjected to severe droughts and floods (Tyson, 1986). Water availability limitations during these events has an unfavourable effect on dryland agriculture of an area (Schulze, 1997). Dry-spells are characterized as prolonged durations without precipitation occurring during a rainy season (Ngetich et al., 2014). Water stress is one of the primary limitations of rainfed agriculture, which can lead to reduced crop output, delayed maturity, and stunted development. A number of crops, including maize, are susceptible to droughts at particular phonological phases (Aslam et al., 2015). It has been observed that maize is most susceptible to water stress during the blooming stage. For example, crop yield, biomass output, and crop growth are all affected during water stress (Ge, 2012; Cakir, 2004). Thus, planting dates must be selected so that the maize crop's flowering stage corresponds with favourable growing conditions and avoids midsummer drought periods (Du Plessis, 2003).

Mid-summer drought occurs between late December and early January in the southern hemisphere (Grobler, 1993; Mengistu et al., 2021). However, in this study, the late-midsummer period, which spans from mid-January to the end of February is of particular importance. This is caused by the reality that maize is planted later in the western region of maize production than it is in the temperate and cold eastern maize production regions. Therefore, dry-spells which occur around this time normally correspond with maize's flowering cycle. During this time, even a few days without rain could result in lower crop production.

Agricultural planning has to consider both dry and wet periods because of the relative dryness of South Africa's western region that produces maize. In the agricultural sector, it is understood that above normal rainfall may not necessarily be more beneficial than a below normal rainfall if it is not distributed well in time and space (Usman and Reason, 2004). When it comes to crop productivity, the timing of rain matters more than the amount received. When precipitation is distributed evenly throughout the growing season, crops often fare better than when torrential downpours are interspersed with dry-spells (Usman and Reason, 2014). For optimal crop production in relation to the growing season, the incidence or timing of dry periods is more important than the total amount of seasonal rainfall received (Usman and Reason, 2004).

Rubin (1956) illustrated that near-surface pressure systems undergo specific adjustment during wet and dry-spell periods. During dry summers, the isobars are above normal over the interior (Tyson, 1986). Using a 20-day dry period made up of four dry-spells in January 1961, Triegaard and Kits (1963) discovered that during dry-spells, positive anomalies are formed over the Marion Island and the country's interior, whereas negative anomalies emerged in the Gough Island region. Dry-spells are linked with weakened tropical easterlies. An increase in low-level southerly meridional wind anomaly is observed during the extended dry-spell periods, as well as higher SST occurring in the southern Benguela system, but not to the region in the north where the anticyclone is settled (Tyson, 1986). Cook et al (2004) studied the theoretical model of SST anomalies and circulation patterns throughout extended durations of both wet and dry-spells across eastern South Africa. According to the study, during dry-spells, there is an uneven moisture flux from the southwest (Cook et al., 2004). The report went on to say that warm SSTs in South Africa's south Atlantic Ocean and south Indian Ocean are typical during dry-spells (Cook et al., 2004). Additionally, the study indicated that warm SSTs in South Africa's Atlantic Ocean and south Indian Ocean are regular during dry-spells (Sifer, et al., 2016).

Precipitation modelling attempts to represent the hydrological processes in a physical way. In short, these models offer a mathematical explanation of the characteristics of precipitation over a certain spatial region (Sifer, et al*.,* 2016). It is essential to understand the occurrence of dry and wet spells during the growing season in dry land agriculture to attain optimal production (Sifer, et al*.,* 2016; Usman and Reason, 2014). Dry-spells have an influence not only on the agricultural industry but also other industries including fishing, health, and electricity. The findings on studies of the frequency of dry-spells can be utilised for breeding new crop varieties and choosing a specific crop variety for a certain area (Sifer, et al*.,* 2016). The information can also be utilised to advise decision makers on field operations to perform in agriculture and supplemental irrigation.

2.3 Wet Spells

Wet spells are periods of persistent daily precipitation that equal or exceed a certain region's average daily rainfall (Signh and Ranade, 2009). During wet spells period in South Africa, the pressure gradients over the Gough Island are high and low over the east and south-east of the subcontinent (Tyson, 1986). Stronger tropical easterlies are linked to extended wet spells over South Africa's summer rainfall region (Tyson, 1986). Tyson (1986) discovered that over the country's interior, wet spells are typically correlated with northerly wind directions, while southerly wind directions predominate at the coast.

2.4 Climate of South Africa

In a subtropical climate, South Africa’s climate is the product of atmospheric circulations from the tropical, subtropical and temperate worlds (Taljaard, 1996). Two lingering high-pressure systems (HPS) are another major driver of the nation’s weather (Tyson, 1986). South Indian Ocean HPS is on the eastern coast, South Atlantic HPS is on the western coast (Tyson, 1986; van Heerden and Taljaard, 1998; Boschat et al., 2015; Mbokodo, 2017). South Africa in general is a hot country with most of the provinces being around 17°C on average (Archer et al., 2010).

A significant variability in precipitation occurs both in spatial and temporal scales with the country often experiencing severe drought and floods (Tyson, 1986). The variation is due to the differences in topography (Figure 3), as well as the effects of the adjacent ocean currents, with the country's east coast receiving moist, warm air from the Agulhas current and its west coast receiving cold, dry air from the cold Benguela current (van Heerden and Taljaard, 1998). The majority of the country experiences summer rainfall (October to March), excluding for the south coast as well as the southwestern regions, which receive rainfall throughout the year and winter season respectively (Tyson, 1986; van Heerden and Taljaard, 1998; Phakula, 2016). The Intertropical Convergence Zone's (ITCZ) movement has a significant impact on South Africa's rainfall, during the summer season, the ITCZ moves southwards to the Tropic of Capricorn and during winter season, it is at the Tropic of Cancer in the Northern hemisphere. The vast majority of the summer's precipitation is convective, with the eastern escarpment receiving the most of it (Phakula, 2016; Dedekind et al., 2016; Tyson, 1986).

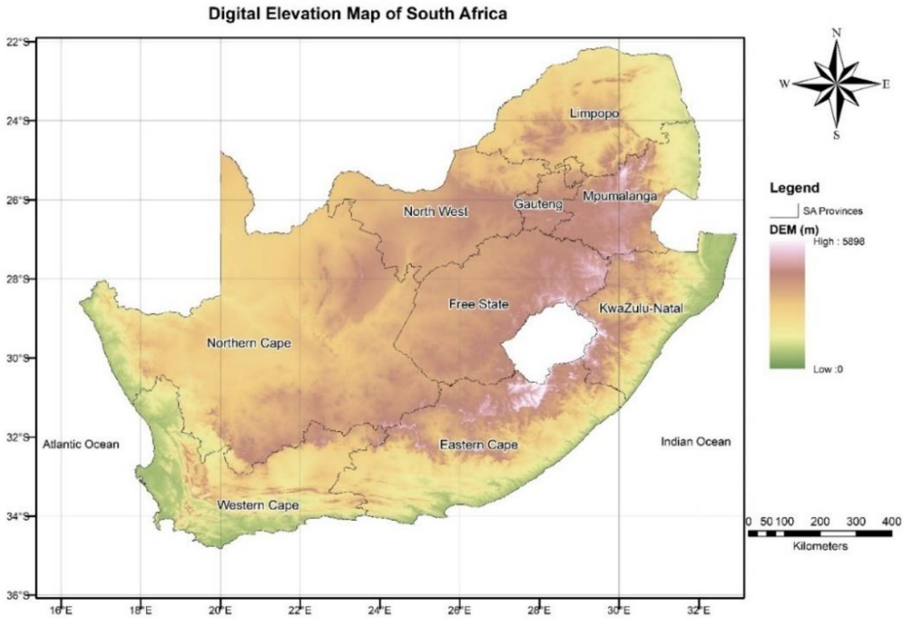

Figure 3: South Africa's topographical map in metres above sea level.

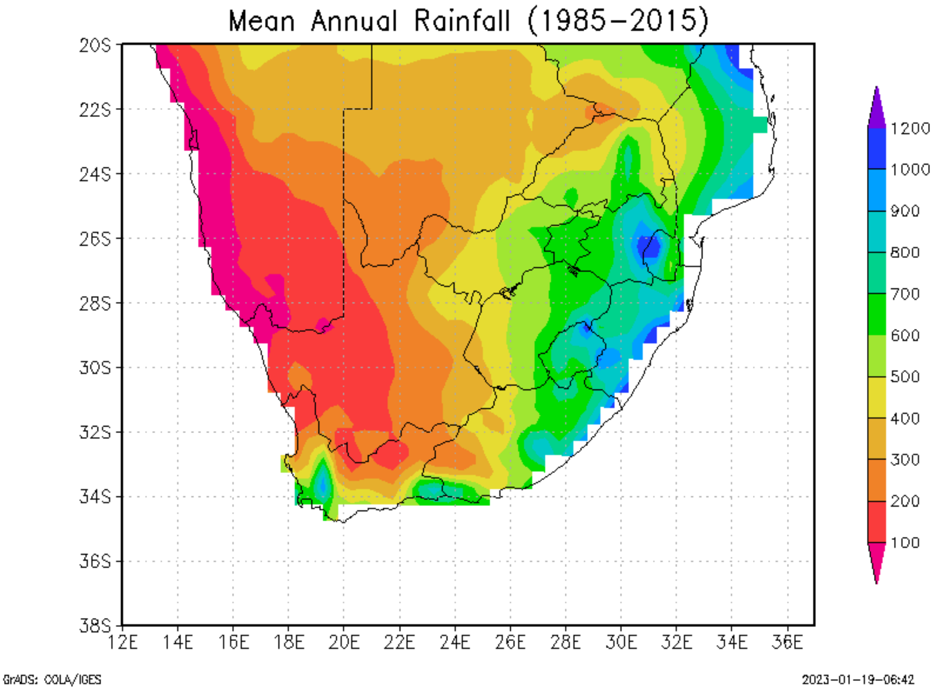

Figure 4: South African average annual rainfall for the period of 1985-2015.

The world's average rainfall is 814 mm per year; South Africa receives 450 mm, making it a semi-arid zone (Moeletsi, 2004; Botai et al., 2018; Nkosi et al., 2021). Rainfall variability is significant in this region, and this has a huge impact on sectors that rely on rainfall such as the agricultural and hydrological sectors (Jury, 2002; Midgley et al., 2007; Botai et al., 2018). The highest average annual rainfalls are found around the escarpments, namely in the Western Cape, eastern Drakensberg and along the eastern coastline. However, these regions are not the traditional maize production regions due to their climatic characteristics.

In regions where maize is grown, the average yearly rainfall differs from 400 mm in the western maize belt to 800 mm in the eastern maize belt region (Figure 4). The eastern maize belt area is often resilient to dry-spells, and it mostly produces yellow maize as opposed to the western part that produces mostly white maize (GrainSA and Agbiz research, 2019). This further illustrates that in periods of below normal rainfall, the western maize production region suffers enormously and because white maize is used to make maize meal in the country, there becomes a shortage in demand-supply process. This often affects the prices of maize meals and has dire impacts on the poor (GrainSA and Agbiz research, 2019).

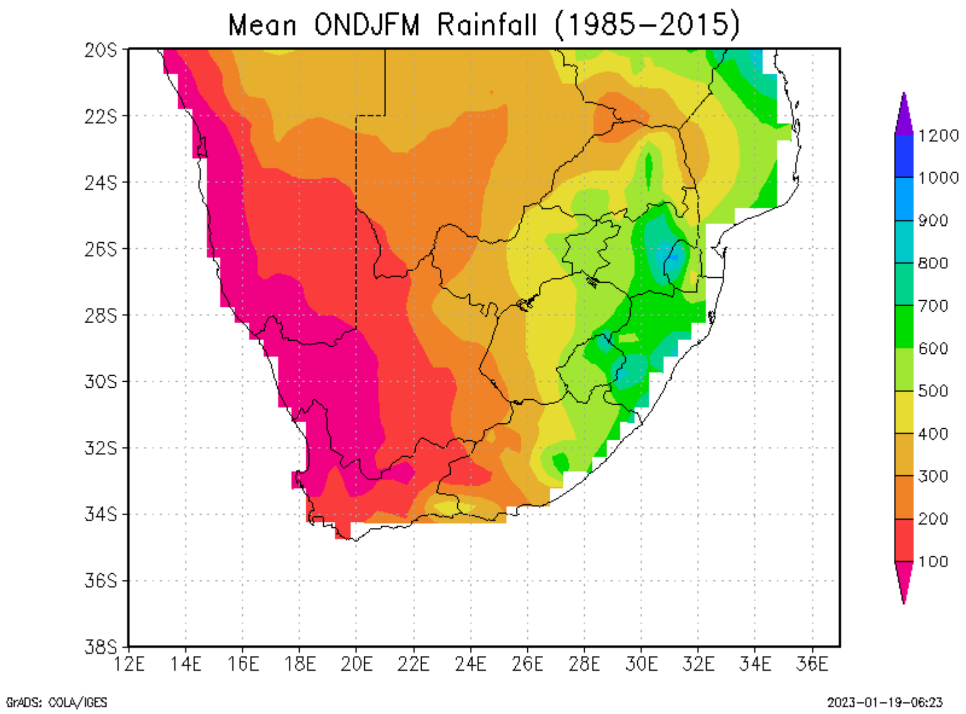

Figure 5: South African average total rainfall for October to March for period of 1985-2015.

During the first three months of the summer season, the eastern parts of the country receive sufficient rainfall, which replenishes soil moisture. This makes it favourable for planting to commence in October to November months (GrainSA and Agbiz research, 2019). The eastern and central maize triangle areas receive between 250 mm to 450 mm during the first trimester of the rainy season (Figure 6). The western maize production region of the country during the same period receives inadequate amounts of precipitation to supplement soil moisture with areas in the region receiving less than 200 mm.

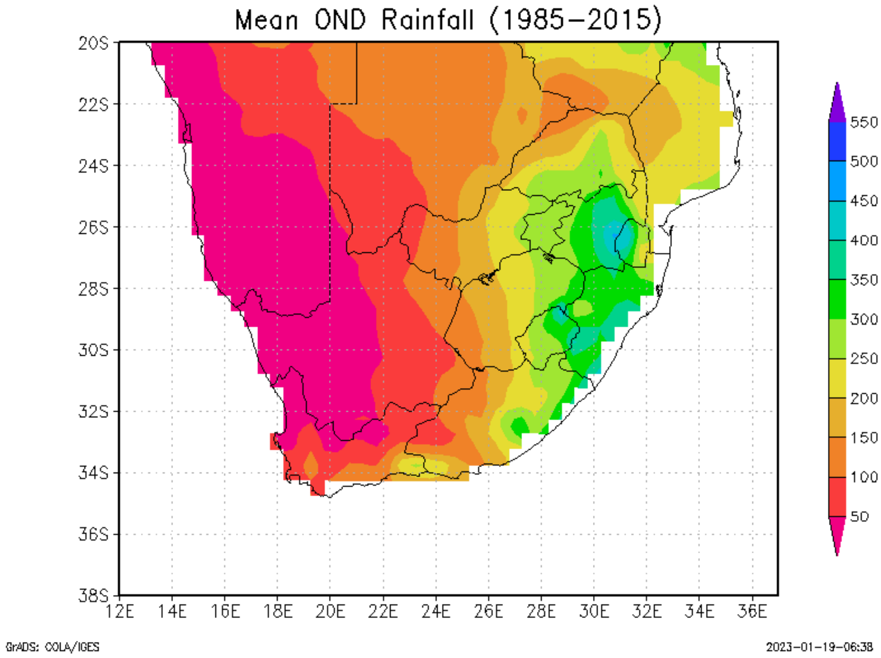

Figure 6: South African average total rainfall for October to December for period of 1985-2015.

The last trimester (JFM) of summer rainfall (Figure 7) reflects that the western maize production region of the maize triangle receives more than 200 mm of rainfall. The central and eastern parts of the maize belt receive 250 mm and 300 mm, respectively. This implies that the western regions of the country are drier compared to the eastern regions. This factor plays a crucial role in the region when there is below normal rainfall in a specific season. It increases the chances of delayed planting because of insufficient soil moisture. In some cases, farmers choose to plant different crops due to the prevalent heatwaves in the region (GrainSA and Agbiz research, 2019).

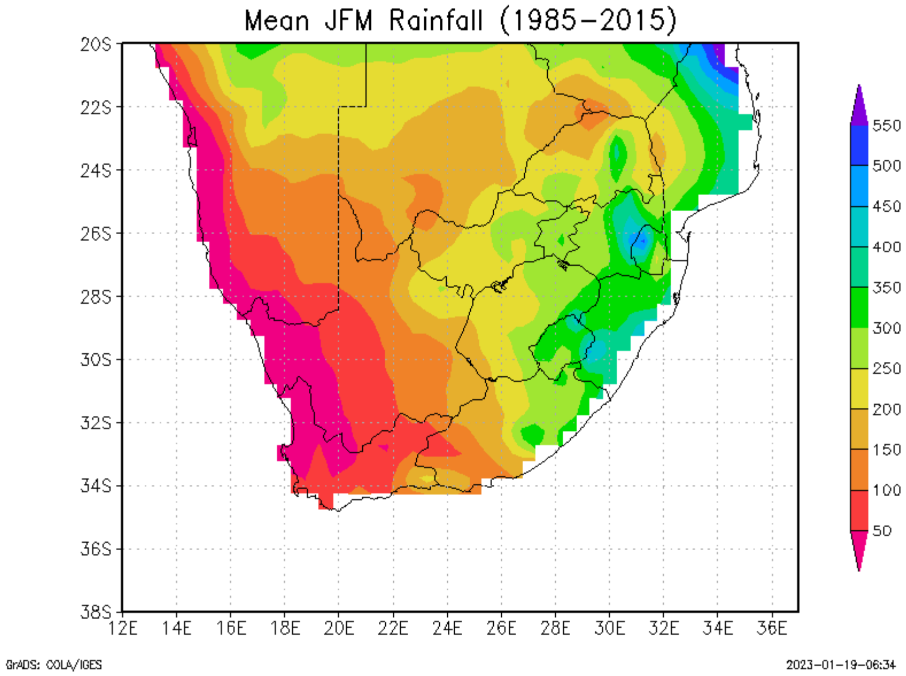

Figure 7: South African average total rainfall for January to March for period of 1985-2015.

2.5 Maize Production

The majority of South Africans rely mostly on maize (*Zea mays L*) as their staple diet, which is grown in a variety of climates (Du Plessis, 2003; Walker and Schulze, 2006). With abundant water supply and optimum temperatures, maize is a fast-growing crop (Aldrich et al., 1986). Maize cultivars differ in sizes and growing seasons; they range from 2 m to 8 m in height; and some have a noticeably short growing season of 70 days, whilst others grow for a longer season of over 140 days (Sprague and Dudley, 1988). Maize is a warm climate crop that develops well under temperature conditions of not more than 30°C with photosynthesis coming to a halt at temperatures below 6°C and above 45°C (Du Plessis, 2003). Smaller and lighter grain yields are caused by high temperatures, and these result in lower crop yields and poor grain quality (Molua and Lambi, 2006). Rainfall is the other significant climate factor that affects the yield of rain-fed maize in South Africa (Molua and Lambi, 2006).

For a vegetative crop, factors such as: precipitation; soil moisture; and plant population can influence the crop growth up to the silking stage (Sangoi, 2001). Drought stress can affect maize yield when higher temperatures, low humidity and dry conditions prevail which are common during periods of dry-spells (Sangoi, 2001). During the growing stages such as flowering and kernel set, deficits in water supply can severely reduce crop yield (Sangoi, 2001). Water availability can also affect the plant densities for maize when it is cultivated under rain-fed conditions (Loomis and Connors, 1996). Roughly 400 to 600 mm of rain per growing season is required for maize to reach optimum yields, and it is primarily extracted from the root zone (Du Plessis, 2003).

2.5.1 Factors Affecting Maize Production

Maize yield is affected by a number of factors such as the air temperature, rainfall and planting dates.

2.5.1.1 Air Temperature

Maize is a warm climate crop which requires a base temperature of 10°C or more and with mean daily temperatures of 19°C (Du Plessis, 2003). The optimum air temperature for a successful growing season of a maize crop ranges between 18°C and 30°C (Du Plessis, 2003). Early developing cultivars can reach maturity in 80 - 110 days when air temperatures rise above 19°C (Whitmore, 2000). As maize is a warm climate crop it is extremely sensitive to frost, thus caution must be taken when choosing a location for production, as conditions must be at least 140 days frost free (Du Plessis, 2003).

2.5.1.2 Rainfall

In dryland farming, rainfall is regarded as the most crucial factor that affects maize production (Ramos, 2001). Maize is mostly produced under rainfed conditions in the country. Thus, availability of water is crucial in the production cycle, therefore water in maize production is a yield limiting factor. Although maize can grow in regions with as little as 300 mm of rainfall per season, a range of 400 to 600 mm is needed for sufficient soil moisture (Du Plessis, 2003).

Soil moisture is vital in maize growth stages as the moisture content permits the soil to absorb nutrients and transfer to the crop (Tidsale et al., 1990). Low levels of soil moisture affect maize in a negative way as the processes such as diffusion that are basic for nutrient uptake are compromised and on the other hand excessive soil moisture limits ion absorption and respiration (Tshililo, 2017). In the event that maize experiences a dry-spell during growing stages, it may recover following a period of substantial rainfall (Whitmore, 2000). However, a mid-season drought is more detrimental to the crop than a drought event or dry-spell that occurs in the beginning or end of a season (Whitmore, 2000).

2.5.1.3 Planting Dates

One of the key factors influencing maize productivity is the timing of planting. The mid-summer drought, commonly experienced across much of the country between mid-December and mid-January, plays a crucial role in determining optimal planting dates (Kgasago, 2006). Farmers should ensure that the flowering stage of maize does not correspond with the occurrence of mid-summer drought, as the crop is extremely sensitive to water stress and heat conditions during this phonological stage (Du Plessis, 2003).

The four main regions in South Africa where maize is planted are KwaZulu-Natal, the cold eastern region, the temperate eastern region, and the western region. Each region has a different optimum planting date (Figure 8). The optimum dates to plant in the KwaZulu-Natal region are from 1 October to 30 November and 1 October to 15 November for the cold eastern region. However, in the southern region, the dates start later and run from 25 October to 30 November. The temperate eastern region's optimum planting dates are from 1 November to 10 December, while the western region is divided into three optimum dates. The eastern parts of the western region have optimal planting dates from 15 November to 25 December, while the western parts' planting dates are from 30 November to 7 January and lastly, the southern parts of the western region from 20 November to 31 December.

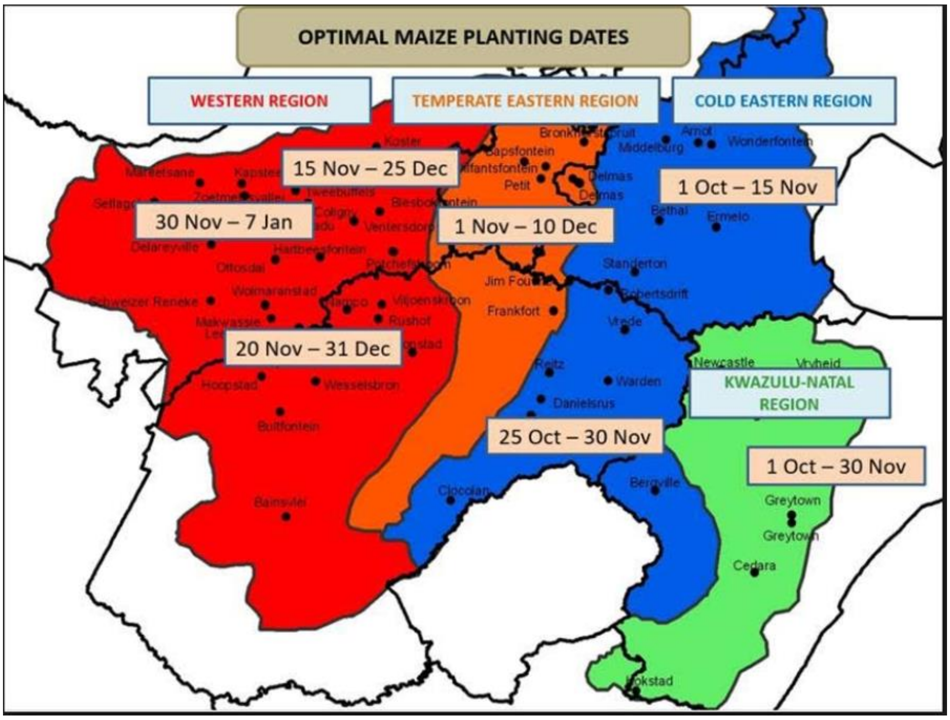

Figure 8: South Africa's Optimal Maize Planting Dates (GrainSA and Agbiz Research, 2019).

2.6 AquaCrop model

The AquaCrop model, developed by the FAO, estimates crop yields and water requirements by modelling the relationship between biomass accumulation and water loss via transpiration (Steduto et al., 2009; Hsiao et al., 2009). This crop simulation tool requires minimal input parameters, striking a balance between simplicity, robustness, and accuracy, making it both accessible and user-focused (Heng et al., 2009). Unlike leaf area index-based models, AquaCrop simulates crop growth by modelling green canopy cover from emergence to senescence (Heng et al., 2009).

A dataset for six growing seasons from the University of California, Davis, was used to validate the model for maize (Hsiao et al., 2009). Results showed that the model successfully simulated grain yields, biomass accumulation, and canopy development for four maize cultivars across six seasons under different planting dates and plant densities (Heng et al., 2009). AquaCrop is a useful tool for practical planning purposes in the context of management decisions under both rainfed and irrigated farming conditions (Raes et al., 2017). Using daily data on weather, crops, soil, and management, it simulates crop growth and soil water balance (Heng et al., 2009). However, it is more suited to herbaceous crops than perennial tree crops, particularly in simulating growth, biomass, and harvestable yields (Steduto et al., 2012).

The model has been adapted for various C3 and C4 crops (Greaves and Wang, 2019). Hsiao et al. (2009) emphasised the potential of AquaCrop to simulate the development, yield, and water metrics of maize under optimal conditions, such as evapotranspiration and water-use efficiency. However, its performance reduces under severe water stress when it comes to the estimation of some variables. Karteji et al. (2013) and Toumi et al. (2016) have reported this. The model best suits scenarios where water is the primary limiting factor. Successful model parameterisation requires site-specific data on climate, soil, irrigation, and field management for reliable outputs (De Casa et al., 2009; Farahani et al., 2009; Garcia-Vila et al., 2009).

The AquaCrop model is based on the yield-response-to-water approach of Doorenbos and Kassam (1979). Two key concepts make it different from other models (Steduto et al., 2009; Raes et al., 2012). Firstly, it separates productive and non-productive water use by dividing actual evapotranspiration into soil evaporation and crop transpiration (Steduto et al., 2009). Additionally, it uniquely represents vegetation growth using green canopy cover rather than leaf area index (Greaves and Wang, 2019). Under non-stress conditions, the model estimates transpiration through canopy cover and evapotranspiration, while daily soil evaporation is calculated using a soil evaporation coefficient (Heng et al., 2009). Then again, crop yield is modelled as the product of biomass and harvest index, which is dynamically varied based on water or temperature stress. That is what Greaves and Wang 2019 say.

Other than simulating crop growth, AquaCrop further performs yield simulation and retention of water in the soil along the root zone. Greaves and Wang (2019). The model performs a daily water balance, considering water fluxes such as deep percolation, infiltration, runoff, transpiration, and evaporation to estimate the root-zone water dynamics. It uses four water-stress response parameters: harvest index, stomatal conductance, canopy senescence, and canopy expansion. These parameters identify the impact of water deficits on crop performance. Agronomic factors are simulated using either daily or growing degree-day time steps based on temperature variables (Adeboye et al., 2020).

The model has been applied across various agro-ecological zones and crops, including maize (Hsiao et al., 2009; Abedinpour et al., 2012), Bambara groundnut (Karunaratne, 2011), soybeans (Adeboye et al., 2019), amaranthus (Bello and Walker, 2017), rice (Amiri, 2016), cabbage (Wellens et al., 2013), barley (Araya et al., 2010), sugarcane (Bahmani and Eghbalian, 2018), and cotton (Khoshravesh et al., 2012). For instance, Khoshravesh et al. (2012) assessed its capability in modelling irrigated soybeans' canopy cover and water productivity. They found the model could adequately simulate water productivity and canopy development for the different irrigation and nitrogen conditions at a Willmott index of agreement of 0.95.

Indeed, the model has been demonstrated by Adeboye et al. (2019) to be reliable for conditions under rainfed and conservation methods. Besides, it was shown to simulate seed production, biomass, and canopy cover effectively. It was very efficient in carrying out strategic planning for Miscanthus giganteus at different nutrient and climatic regimes by Striević et al. (2015). Mbangiwa et al. (2019) also confirmed that under dryland conditions, its predictions of soybean growth and yield are very accurate. Paredes et al. (2015) outlined that the model requires good parameterization to perform well, citing the low percentage of errors in simulating soybean yield by AquaCrop.

To effectively use AquaCrop, you need specific data inputs to configure the model accurately. (Hsiao et al., 2009; Heng et al., 2009). Hsiao et.al (2009) determined that the data requirements for AquaCrop can be categorized into the following key areas:

a) Crop Data:
    - Crop Type: Information about the specific crop species you want to model (e.g., wheat, rice, and maize).
    - Variety: Crop variety or cultivar information, as different varieties may have varying growth characteristics.

b) Climate Data:
    - Weather Data: Historical or current weather data for the location of interest. This includes the daily levels of humidity, wind speed, solar radiation, precipitation, and temperature. Accurate simulations require long-term climate data.
    - Climate Scenarios: Projections of future climate conditions if modelling for future scenarios.

c) Soil Data:
    - Soil Type: Information about the soil type and classification at the location. This covers the depth, organic matter content, and soil type such as sand, silt, and clay.
    - Soil Hydraulic Properties: Parameters related to soil water retention and hydraulic conductivity curves, which describe how the soil holds and releases water.

d) Crop Management Data:
  - Planting Date: The date when the crop is sown or transplanted.
  - Planting Density: Information about the spacing and density of crop plants.
  - Management Practices: Information regarding crop management techniques, including when to schedule irrigation, apply fertilizer, and manage pests.

e) Irrigation Data (if applicable):
  - Irrigation System: Information about the type of irrigation system used (e.g., furrow, drip, sprinkler).
  - Irrigation Amount and Timing: Data on when and how much irrigation water is applied during the growing season.

f) Carbon Dioxide Concentration Data (for advanced modelling):
  - Carbon Dioxide (CO_2) Levels: Information about atmospheric CO_2 concentration, especially if modelling for future scenarios considering the impact of elevated CO_2 levels on crop growth.

g) Management Scenarios:
  - Data for various scenarios you want to model, such as different irrigation strategies, fertilizer applications, or climate change scenarios.

h) Initial Conditions:
  - Initial soil moisture content if modelling from a specific point in time.

i) Crop Growth Parameters:
  - Parameters related to crop growth and development, including coefficients for crop growth stages, crop-specific constants, and crop stress thresholds.

j) Simulation Period:
  - The time frame for which you want to run the simulation, including the start and end dates of the crop growth cycle.

2.7 Conclusion

Late mid-summer droughts are a significant threat to agricultural production in the western maize production region of South Africa. The pentad rainfall of a location is a suitable method to determine the trends in late mid-summer droughts and the optimal planting dates. The dry-spells that occur during this period can be detrimental to maize production if they coincide with the flowering stage. The AquaCrop model is a suitable model to simulate crop yield, demonstrating the optimal growing periods and which planting dates result in better production outputs.

CHAPTER 3: STUDY AREA AND DATA METHODOLOGY

3.1 Study Area

The study focuses on Rainfall Districts 82, 83, 84, 85, 89, 90, 91, 92, and 93, which are located in the western maize-growing zone of South Africa. As defined by the South African Weather Service (SAWS) many years ago (South African Weather Bureau, 1972) (Figure 9), these districts are crucial to our research. The study area lies within the dry Highveld climatic zone. By selecting nine specific Rainfall Districts from the SAWS classification, the study targets key regions within the broader maize-growing area for a more detailed analysis.

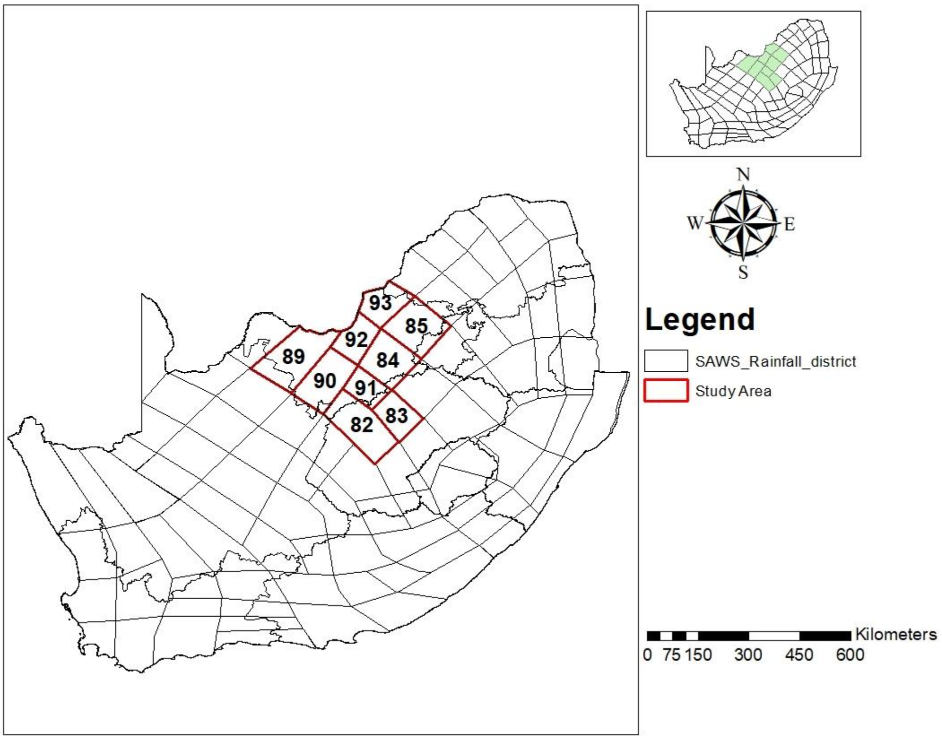

Figure 9: Study area showing the Rainfall Districts of South Africa, with provincial borders (SAWB, 1972) and the selected Rainfall Districts are in red polygons.

3.2 Data

Using daily rainfall data from the SAWS database, this study investigated how the late mid-summer drought affected yields of maize. Rainfall was recorded using either an automatic weather station (AWS) or a manual rainfall station. Measurements were performed at 08:00 South Africa Standard Time (SAST) at all stations, with both manual and automatic stations representing the accumulated rainfall over 24 hours, that is the time range from 8:00 SAST on the day before to 8:00 SAST on the present day (Kruger and Nxumalo, 2017). The automated weather stations were configured to record data in a data logger and transmit it to the SAWS database. In contrast, manual stations relied on hosts to record water levels, with SAWS collecting the data daily during rainfall events. The study utilized a total of fourteen weather stations (eleven automated and three manual rainfall stations) distributed across nine rainfall districts. To qualify for inclusion in the rainfall analysis, the stations needed to be active throughout the study period (1985–2015) and have at least 90% of daily rainfall measurements available.

The study used sandy clay loam soil with moderate fertility from the Harmonized World Soil Database (HWSD v2.0). A planting density of 20,000 plants per hectare was set for dry conditions, using a medium-growing cultivar maturing in 120 days. Climate data included daily rainfall, temperatures, reference evapotranspiration, and atmospheric CO_2 concentration to improve simulation accuracy for each Rainfall District.

3.3 Methodology

Late mid-summer drought occurs between mid-January and mid-February in the western maize production region. In South Africa, summer lasts a period of seven months (October to April). The summer Rainfall Districts in the western maize region that get more than 300 mm of total rainfall on average between October and March were considered for this study. Long-term monthly rainfall averages across the reference period of 1981 to 2014 were used to calculate areas that receive greater than 300 mm, this data was obtained from the Global Precipitation Climatology Centre (GPCC) (Becker et al., 2013: Schneider et al., 2016). A map illustrating the average rainfall of South Africa over the period of October to March is represented in Figure 10 (A). While Figure 10 (B) illustrates areas that receive average rainfall totals of greater 300 mm over the summer period and that are ideal for maize production. This region is limited to the eastern regions of South Africa. It encompasses the whole provinces of KwaZulu-Natal, Mpumalanga, and Gauteng, as well as most parts of the Limpopo, North West, and Free State, as well as roughly half of the Eastern Cape Province.

From the 40 stations that received average rainfall totals of greater than 300 mm over the summer season, only 9 districts with homogeneous rainfall and seasonality (Kruger, 2011) were used for further analysis. These 9 districts were selected as they are located within the western maize production region. Rainfall stations are numbered according to SAWS District Rainfall reference (Figure 9). Pentad summations (totals) were calculated using the Grobler (1993) methodology from the daily district rainfall data. Pentads were measured in Julian days; for example, pentad 1 covers the period from January 1–5, while pentad 73 is equivalent to December 27–31. The 10th pentad was extended to include the additional leap year day, February 29. Pentads 2 to 12 indicate the eight pentads that comprised the study period, which ran from mid-January to the end of February. A dry-spell is considered to be a pentad with less than 15 mm of rainfall.

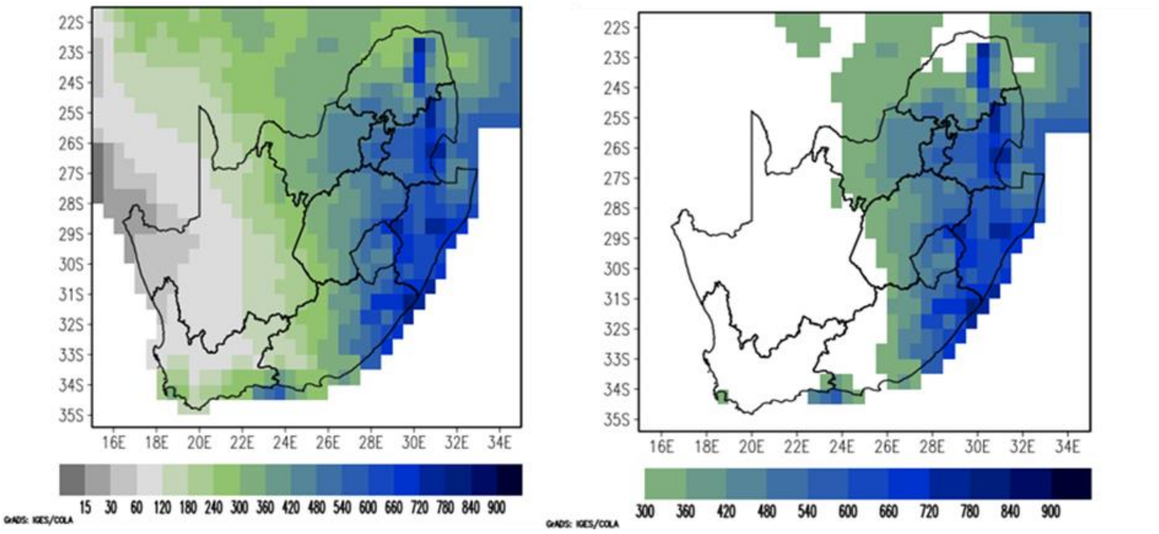

Figure 10: Maps indicating the average rainfall between the months of October and March obtained from the Global Precipitation Climatology Centre. A). Illustrates the average rainfall for the country. B). Illustrates the study areas with >300 mm of rainfall during the same period (Schneider et al., 2016; Becker et al., 2013).

In Chapter 4, the daily district rainfall dataset was sourced from the South African Weather Service (SAWS) rainfall database for the 30-year period from 1985 to 2015 (Kruger and Nxumalo, 2017). The data for the summer rainy season (October to April) were assessed (Kruger and Nxumalo, 2017). Pentad (defined as a period of five days) total rainfall values were used to investigate the wet and dry-spells by using the Markov chain probability model. A threshold of 3 mm rainfall depth per day (15 mm per pentad) was used in this study, which is the minimum threshold value for crops to satisfy their water requirements during a growing season (Dabral et al., 2014). A dry-spell is considered to be a pentad with less than 15 mm of rainfall and a pentad with 15 mm or more rainfall to be a wet pentad.

In Chapter 5, only weather stations with at least 21 years of continuous data, and up to 30 years in some cases, were included. A 15 mm rainfall threshold was applied uniformly across all districts, with analysis conducted for seasons representing low, medium, and high dry-spell frequencies. Using Grobler's (1993) methodology, pentad (five-day) rainfall totals were calculated from daily data, ensuring consistency by using Julian days (e.g., January 1–5 as pentad 1, December 27–31 as pentad 73). Leap years included an extra day in pentad 10. Dry spells were defined as pentads receiving less than 15 mm of rainfall. The study analysed eight critical pentads (January 16–February 24), a period when maize is highly sensitive to mid-summer droughts. One to two weather stations per Rainfall District were selected based on operational status and at least 21 years of continuous data to ensure robust analysis.

CHAPTER 4: SCIENTIFIC ARTICLE

Analysis of dry-spells in the western maize growing areas of South Africa

Siphamandla Daniel [1,2*], Michael Mengistu [1,2], Cobus Olivier[1] and Alistair Clulow[2]

South African Weather Service, PO Box X097, Pretoria 0001; [redacted]
[redacted]za
Discipline of Agrometeorology, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa; Clulowa@ukzn.ac.za

* Correspondence: [redacted]; Tel: +2[redacted]

Abstract: Crop yield in rainfed agriculture is directly influenced by rainfall patterns, which vary from one growing season to another. The failure or success of such crops can depend on the amount and distribution of the rainfall and, particularly, on the occurrence of dry and wet spells during the growing season. The aim of this study was to investigate the initial and conditional probabilities of dry-spell pentads using the Markov chain model in the western maize-growing region of South Africa, as well as to determine the direction and magnitude of dry-spell trends using the Mann-Kendal monotonic trend test and Sen's slope estimator. The results revealed that all the Rainfall Districts are affected by dry-spells during the mid-January-to-end-of-February period. This finding is significant because maize is usually planted during late November to late December in this region, and dry-spells may coincide with the flowering stage of the maize crop. When dry-spells occur during the flowering stage of maize, they significantly affect yield. The Mann-Kendal analysis revealed that most of the districts (7 out of 11 districts) have a decreasing trend in dry-spell occurrences except for districts 86, 87, 91 and 93. However, the decreasing trend is statistically insignificant in all the Rainfall Districts, and, thus, this reveals that there is no change or there is a minor change in dry-spell occurrence across all the districts. Furthermore, Sen's slope estimator signalled a decrease in dry-spell magnitude or occurrence over the study period. Information from this study will inform farmers of the various districts regarding changes in their particular risk profile for dry-spells.

Keywords: Dry-spell, wet spells, maize, crop yield, Markov chain model, pentad rainfall, rainfed.

4.1 Introduction

Maize is one of the most important summer staple grain crops produced in South Africa for both human and animal consumption (DALRRD, 2020). The crop is produced throughout the country, with Free State, Mpumalanga and North-West provinces being the major producers and accounting for over 85% of the national output (Diko and Jun, 2020). Most of the production is commercialised in these provinces, and small-scale farming is predominant in the rural provinces of Limpopo, KwaZulu-Natal, and the Eastern Cape. Around 90% of the production of maize in the country is under dry-land production (Du Plessis, 2003). Maize needs around 400 mm to 600 mm over the growing season for optimal production, and with South Africa being a semi-arid region, maize is generally exposed to water stress and drought conditions (DARDLEA, 2017). One of the major limiting factors in dryland production is, therefore, water stress, the consequences being delayed maturity and low crop yield (Mengistu *et al*., 2021). This is especially important during the flowering stage when maize is most sensitive to water stress conditions (Mzezewa et al., 2010).

In addition to the semi-arid rainfall pattern, southern Africa has a high rainfall unpredictability at various temporal and spatial scales and experiences extreme droughts and floods (Tyson, 1986). Drought is a natural phenomenon that occurs when there is below average rainfall over a period (Pereira et al., 2009). The lack of rainfall can cause reduced groundwater levels, soil moisture and stream levels. South Africa is a semi-arid country with rainfall averages of less than 500 mm (Taljaard, 1986: Mengistu et al., 2021). Much of the country receives summer rainfall, which starts from October, and cessation occurs in April (Mengistu et al., 2021). The southwestern parts of the country receive winter rainfall, and the southern coast receives rainfall throughout the year (Mengistu et al., 2021; Engelbrecht, 2014).

Rainfall is the most key factor affecting crop production, especially in dry land farming (Ramos, 2001). In semi-arid regions, the yield parameters depend on the amount and temporal distribution of rainfall (Munodawofa, 2012). Maize requires a minimum of 300 mm per annum to grow and yield (Belfield and Brown, 2008); however, for optimal yields, 400 to 700 mm of rainfall is required annually (DAFF, 2008; Tshililo, 2017). As South Africa is relatively dry, monitoring of drought, dry-spells as well as wet spells is vital for agricultural planning. For crop production, the timing of rainfall is more vital than the amount received. Thus, crops tend to do well when precipitation is spread uniformly over a growing season rather than with a few occasions of heavy rains intercepted by dry conditions (Sifer et al., 2016). The study area is regarded as a warm western production region subjected to persistent dry-spells and drought conditions, hence the desire to investigate the trend in dry-spells in this production area.

A dry-spell is a period where dry conditions persist for days to weeks but are shorter and less severe than drought conditions (Schulze, 1997). As dry-spells do not occur at the same time each year, it is important to understand the trend in these phenomena. Dry-spells are characterised by a reduced flow of moist warm air from the southwestern Indian Ocean over South Africa with a dominant high-pressure system over the interior (Ray et al., 2018) and inflow of some moisture from the South Atlantic Ocean, which is less moist and cooler than that from the Indian Ocean (Ray et al., 2018). Wet spell conditions dominate when there is a ridging high-pressure system along the coast and an easterly low over the northern interior (Tyson, 1986). Wet spells are defined as a continuous period of daily rainfall equating to, or greater than, the daily mean rainfall of a particular area (Pereira et al., 2009). Consecutive wet spells signal excessive surface run-off, which has benefits for water harvesting but requires mitigation measures to avoid soil erosion and potential flood damage. Farmers can ease runoff by applying mulch or organic manure on their fields.

The Markov chain model has been extensively used to study spell distribution and other properties of rainfall occurrence and long-term frequency behaviour of wet and dry-spells (Usman and Reason, 2004). Gabriel and Neumann (1957) first introduced the use of the Markov chain probability model in the analysis of wet spells and dry-spells, using 27 years (1923–1950) of rainfall data with a threshold of 0.1 mm from November to April in Tel Aviv, Israel (Gabriel and Neumann,1957). The Markov chain probability model was introduced in transitional probability where conditions change between two states (Usman and Reason, 2004; Dabral et al., 2014). The Markov chain model is widely used to determine the relative chance of occurrence of a given rainfall, to characterize a rainfall period as a dry- or wet spell (Usman and Reason, 2004). This model is also useful in assessing the onset and cessation of the wet season, which largely determines the success of rainfed agriculture (Usman and Reason, 2004). In the past decades, several studies used the Markov chain probability model to fit statistical distributions to meteorological observations (Sifer et al., 2016).

Climatologically, the western maize production region has a drier climate than the other maize production regions in South Africa (Mengistu et al., 2021). This region experiences late onset of the rainfall season, which leads to late planting of summer crops such as maize and sorghum. Mengistu et al. (2021) performed a dry-spell frequency analysis on the three maize production regions of South Africa, namely: cool eastern region, temperate eastern region, and parts of the warm western growing region during the conventional mid-summer period (mid-December to mid-January). A dry pentad was considered as a pentad with less than 15 mm of rainfall and a pentad with 15 mm or more rainfall as a wet pentad (Reddy, 1990). The investigation succeeded in detecting the occurrence of dry-spells in the cool and temperate growing regions and, to some extent, in parts of the western growing region during the mid-summer period which spans from mid-December to mid-January, as used in the study by Mengistu et al. (2021). However, the study highlighted that the western growing region experiences late onset of rainfall and maize is planted much later than in the other two growing regions. Therefore, the need to perform dry-spell analysis during the mid-January-to-end-of-February period was vital.

This study follows the investigation conducted by Mengistu et al. (2021) which focused on the spatial and temporal analysis of dry-spells during the mid-summer period (mid-December to mid-January) for parts of the western maize-growing region. However, for the western maize-growing areas, due to the late planting, the flowering stage, which is sensitive to water stress, occurs during January and February and not necessarily during the specified mid-summer period used in the study of Mengistu et al. (2021). Therefore, this necessitated that this study be conducted to investigate the occurrence of dry-spell frequency in the western maize-growing region during the mid-January-to-end-of-February period. Therefore, the aim of this study was to:

- Investigate the initial and conditional probabilities of dry and wet spell pentads using the Markov chain model in the western maize-growing region from mid-January to end of February.
- Determine direction and magnitude of trends of dry-spells using the Mann–Kendal monotonic trend test and the Sen slope estimator.

4.2 Study Area

The South African Weather Service (SAWS) Rainfall Districts 82, 83, 84, 85, 89, 90, 91, 92 and 93 (Figure 11) were selected for this study (South African Weather Bureau, 1972). These districts are most relevant to this study, as they fall under the dryland western maize production region as seen on Figure 12 (Grain SA and AgBiz, 2019). The study area falls under the dry Highveld climate region (Table 1) of South Africa. The boundaries of the climatic regions were determined by investigating the type of natural vegetation found in each region. The climatic conditions that are generally observed in these climatic regions are summarised in the table below.

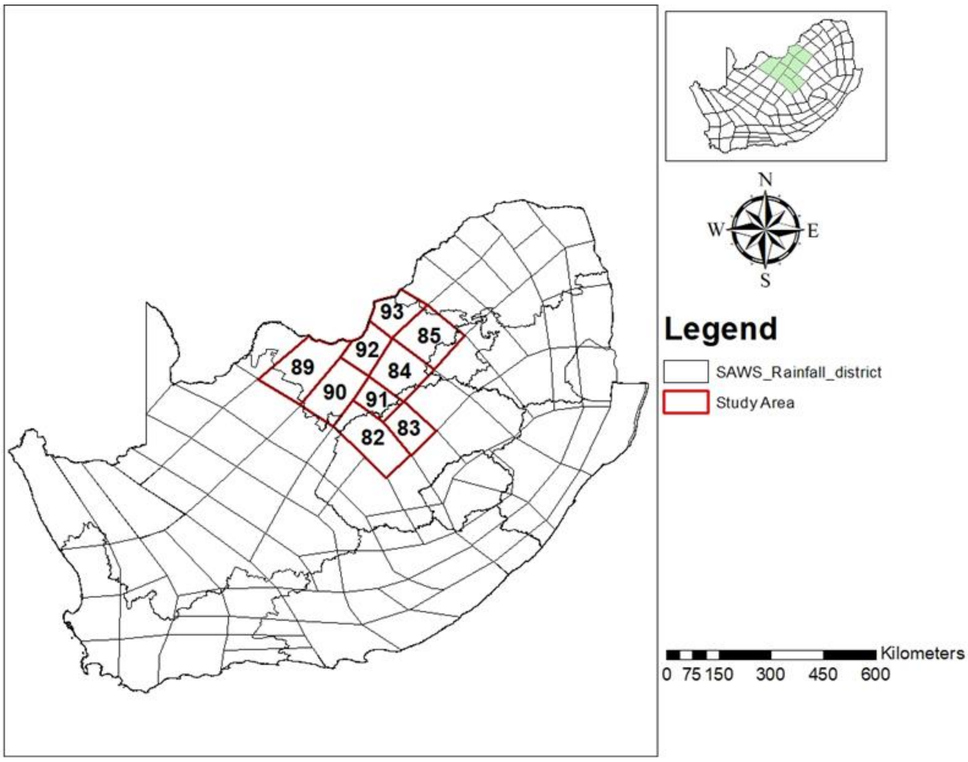

Figure 11: Study area representing SAWS Rainfall Districts, with province borders and the chosen Rainfall Districts indicated by red polygons (SAWB, 1972).

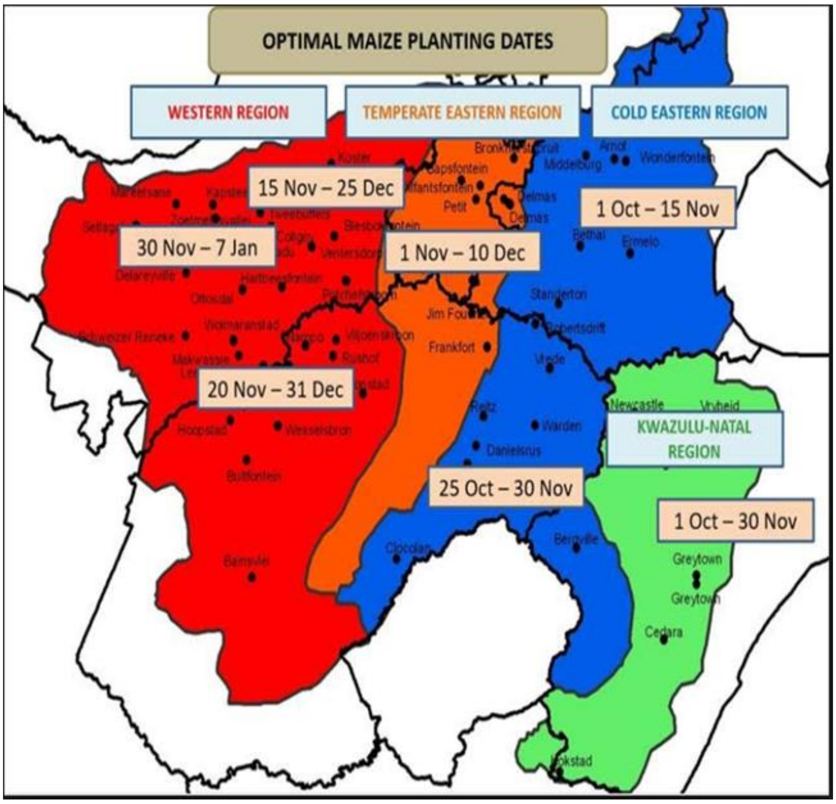

Figure 12: Maize growing regions and optimal maize planting dates (Grain SA and Agbiz Research).

Table 1. Summary of climate properties of dry highveld (Kruger, 2004).

Climate Region	**Climatic properties**	**Vegetation**	**Agricultural use**
Dry Highveld	Temperatures often exceed 30 °C in summer months and cool during winter months, with cold nights (<5 °C) observed. Over the high-lying areas, snow does occur in winter. Precipitation ranges from about 450 to 700 mm. The rainy season reaches its peak during mid-summer in the north and late summer in the south and west. Winds tend to be from the north to north–easterly direction	Vegetation consists mainly of grassland with some trees along streams.	Maize production, cattle, and sheep

4.3 Dataset

The daily district rainfall dataset was obtained from the South African Weather Service (SAWS) rainfall database for a period of 30 years (1985–2015) (Kruger and Nxumalo, 2017). The data for the summer rainy season (October to April) were assessed (Kruger and Nxumalo, 2017). Pentad (defined as a period of five days) total rainfall values were used to investigate the wet and dry-spells by using the Markov chain probability model. A threshold of 3 mm rainfall depth per day (15 mm per pentad) was used in this study, which is the minimum threshold value for crops to satisfy their water requirements during a growing season (Dabral et al., 2014). A dry-spell is considered to be a pentad with less than 15 mm of rainfall and a pentad with 15 mm or more rainfall to be a wet pentad.

4.4 Data Analysis

4.4.1 Calculation of the Wet and Dry-spells using the Markov Chain

Each year was divided up into consecutive pentads, with the first pentad being 1 to 5 July and the 73rd pentad from 26 to 30 June. This captures the whole summer rainfall season that commences in October and ends in April as a single period. The period of interest was mid-January to end of February, which is represented by pentads 40 to 48. This period is critical in the western growing region, as dry-spells tend to dominate in this period, and the crops planted in this region are usually in the water-stress-sensitive flowering stage (Diko and Jun, 2020).

In this study, a Markov chain probability model was used for analysing the wet and dry-spells. The probability of rainfall received during a pentad (PW/PD) was known as the "initial probability," and the probability of receiving rain in the following pentad (PWW/PDD) was termed "conditional probabilities." In the first order probability, the Markov chain assumes that the probability of an incident occurring in the pentad depends on the previous pentad only; thus, it is independent of the events beyond the previous pentad (Mengistu et al., 2021). Dry and wet spells for each pentad are calculated independently in the initial probability model. In the conditional probability model, dry-spells or wet spells that are followed by a dry/wet spell and vice versa were considered. The model probabilities are calculated in the following manner:

Initial Probability Percentage:
Initial probability of getting less or more than 15 mm of rainfall

$$P_D = F_D/N \tag{1}$$

$$P_W = F_W/N \tag{2}$$

Conditional Probability Percentage:

$$P_{DD} = F_{DD}/F_D \tag{3}$$

$$P_{WW} = F_{WW}/F_W \tag{4}$$

$$P_{DW} = 1 - P_{WW} \tag{5}$$

Consecutive dry and wet week probabilities:

$$2D = P_{Dp1}P_{DDp2} \tag{6}$$

$$2W = P_{Wp1}P_{WWp2} \tag{7}$$

$$3D = P_{Dp1}P_{DDp2}P_{DDp3} \tag{8}$$

$$3W = P_{Wp1}P_{WWp2}P_{WWp3} \tag{9}$$

where: *PD* is the probability of the pentad being dry, *PW* is the probability of the pentad being wet, *N* is the number of years of data, *FD* is the number of dry pentads, *FW* is the number of wet pentads, *PDD* is the probability of a dry pentad being preceded by a dry pentad, *PWW* is the probability of a wet pentad being preceded by a wet pentad, *PDW* is the probability of a dry pentad being preceded by a wet pentad, *FDD* is the number of dry pentads preceded by another dry pentad, *FWW* is the number of wet pentads preceded by another wet pentad, *2D* is the probability of 2 consecutive dry pentads starting with a particular pentad, *2W* is the probability of 2 consecutive wet pentads starting with the pentad, *3D* is the probability of 3 consecutive dry pentads starting with the pentad, *3W* is the probability of 3 consecutive wet pentads starting with the pentad, PD_{p1} is the probability of the pentad being dry (first pentad), PDD_{p2} is the probability of the second pentad being dry, given the preceding pentad dry, PDD_{p3} is the probability of the third pentad being dry, given the preceding pentad dry, PW_{p1} is the probability of the pentad being wet (first pentad), PWW_{p2} is the probability of the second pentad being wet, given the preceding pentad wet, and PWW_{p3} is the probability of the third pentad being wet, given the preceding pentad wet.

4.4.2 Trend Detection Using Mann–Kendall Test

The non-parametric Mann-Kendall (MK) monotonic trend test is commonly used to detect the increasing or decreasing trends in time series climate data or hydrological data (Ray et al., 2018). In this study, the MK test was used to detect the increasing or decreasing number of dry-spells per year. The number of dry-spells and the maximum length of a consecutive dry-spells for the time series data were assessed using Mann–Kendall's trend test statistics and Sen's slope test (Q2) at a 95% confidence level (Ramos, 2001).

The MK test is given by:

$$\boldsymbol{S} = \sum_{k-1}^{n-1} \sum_{j-k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{10}$$

where: xj and xk represents a rainfall variable and k is the total number of data points available in the time series for analysis.

The standard normal statistical test "*p-value*" helps determine the significance of results in relation to the null hypothesis. The null hypothesis states that there is no relationship between the two variables being investigated and that the results are due to chance and are not significant in terms of supporting the idea being investigated. Thus, the null hypothesis (H_0) assumes that that there is no trend existing in your time series. The alternative hypothesis (H_1) assumes existence of a trend in the time series. The level of statistical significance is a p-value between zero and one with a p-value of less than 0.05 being statistically significant and a *p-value* of greater than 0.05 not being +statistically significant.

4.4.3 Slope Estimator

While the MK-test gives the trend, the direction, and the p-value statistic, it does not give the frequency of change. The Sen Slope Estimator was used to calculate the magnitude of change providing a more robust estimation of the trend, especially when the trend cannot be estimated by other statistical approaches like MK test. The Sen Slope was estimated using the following:

$$Q = \frac{Yi-Yj}{Ni-i} \tag{11}$$

where: Q is the slope estimate, Yi and Yj are the values at times i and j, where i is greater than j, N' is all data pairs for which i is greater than j.

Positive results of Sen-slope in a number of dry-spells indicates an increasing trend and a negative result indicates a decreasing trend over a given time.

4.4.4 Spatial Analysis Interpolation

The spatial distribution of rainfall is often analysed using rain gauges, and they are typically the most reliable point data (Byakatonda et al., 2019). However, the network is sparsely distributed, and it is impossible to attain a compact data analysis using only the rain gauges that can be used to generate adequate spatial maps (Byakatonda et al., 2019). Therefore, to generate quality spatial maps, spatial interpolation was used. Several interpolation methods, deterministic and geostatistical are available to analyse rainfall data. In this study, the geostatistical method was favoured over deterministic methods, and Kriging was favoured (Adhikary, 2017). Kriging is a geostatistical method based on statistical models that have the capability of surface prediction and have been found to provide some measure of accuracy of prediction (Adhikary, 2017). Kriging has several advantages over traditional interpolation techniques such as inverse distance weighting or nearest neighbour:

- It provides a measure of uncertainty attached to the results (i.e., Kriging variance).
- It accounts for direction-dependent relationships (i.e., spatial anisotropy).
- Weights are assigned to observations based on the spatial correlation of data instead of assumptions made by the analyst for IDW.
- Kriging predictions are not constrained to the range of observations used for interpolation.
- Data measured over different spatial supports can be combined, and change in support, such as downscaling or upscaling, can be conducted.

Kriging can use a limited set of data points to estimate the variable over a continuous spatial field (Usowicz et al., 2021). Kriging assumes that the interpolation is stationary (joint probability is the same across the study area) and isotropic (uniform in all directions) (Carrat and Valleron, 1992).

4.5 Results

4.5.1 Total Annual Rainfall

As mentioned, South Africa is a semi-arid region and its average rainfall is less than 500 mm, this says that some regions may not meet the minimum water requirements of maize which is 300 mm. When looking at figure 13, during La Nina period such as 1988 and 2000, all the districts had over 500 mm of rainfall, however, during normal years such as 2003 and 2012, most Rainfall Districts had less than 500 mm. With drought years such as 1992 and 2015 having Rainfall Districts that have less than 300 mm. When analysing figure 13, it is evident that the western production region’s rainfed production is at a risk due to more years that have less or just enough rainfall to meet the water requirements of maize. Furthermore, this annual rainfall may not be uniformly distributed during the planting season and that has an impact on maize yield. As having events with intense rainfall or lack of rainfall have a negative effect on maize yield.

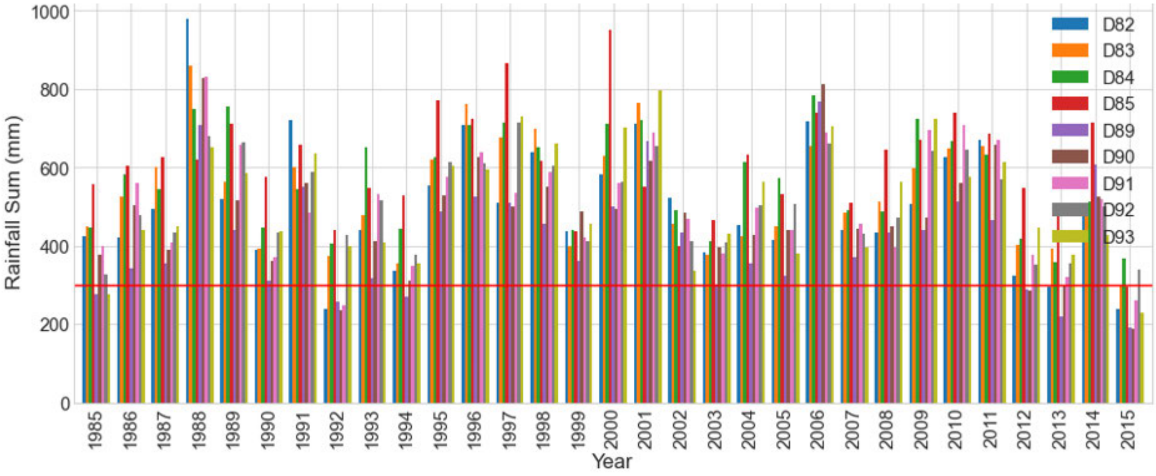

Figure 13: Total Annual Rainfall for Rainfall Districts (82,83,84,85,89,90,91,92,93) from 1985 to 2015.

4.5.2 Dry-spell occurrence

Analysis of rainfall for 30 years showed that for all Rainfall Districts, pentads 40 to 48 (mid-January to the end of February) were affected by dry-spells (Table 2). Rainfall District 84 had the lowest average initial dry-spell frequency over the period, with Rainfall District 93 having the highest initial dry-spell probability during the same period. Pentad 41 (18-22 January) had the lowest average percentage of initial dry-spell probability across all districts, whereas pentad 48 (22-26 February) had the highest percentage. The conditional dry-spell probability results indicate that the district with the lowest probability was Rainfall District 84, while district 89 was the highest.

The pentad with the highest conditional dry-spell probability was pentad 44 (2-6 February), and the lowest was pentad 41 (18-22 January) as illustrated in Table 3. Figures 14 and 15 are schematic results of the initial and two consecutive dry-spell probabilities. The probability of having a dry-spell is at its lowest during pentad 41 (orange colour) for most districts, with the highest probability of occurrence being in pentad 48 (black colour).

Table 2. Initial dry-spell probability (%) of saws Rainfall Districts during the mid-January to end of February period (pentads 40 to 48) from 1985 to 2015.

District	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**
82	64.5	58.1	71.0	80.7	71.0	54.8	51.6	64.5	77.4
83	67.7	54.8	54.8	83.9	67.7	61.3	61.3	64.5	80.7
84	48.4	41.9	58.1	77.4	64.5	61.3	61.3	48.4	71.0
85	41.9	38.7	64.5	67.7	77.4	64.5	71.0	58.1	80.7
89	77.4	67.7	77.4	77.4	77.4	71.0	74.2	64.5	87.1
90	71.0	51.6	64.5	74.2	67.7	67.7	58.1	67.7	83.9
91	67.7	48.4	71.0	74.2	71.0	64.5	67.7	58.1	77.4
92	54.8	41.9	64.5	74.2	61.3	61.3	64.5	61.3	83.9
93	51.6	61.3	74.2	74.2	67.7	64.5	71.0	74.2	74.2

Pentads 40 to 48 showed the highest probabilities of dry-spell occurrence during the study period. The occurrence of two consecutive dry pentads was low to moderately high, as shown in Figure 15. However, there is an increased risk that the study area will experience two consecutive dry-spells due to the continued lack of rainfall. The increased risk of two consecutive dry pentads will likely lead to water stress that could negatively affect the yield of summer grain crops.

Table 3. Conditional dry-spell probability table (percentage) of SAWS Rainfall Districts during the mid-January to end of February period (pentads 40 to 48) from 1985 to 2015.

District	40	41	42	43	44	45	46	47	48
82	38.7	41.9	54.8	54.8	64.5	48.4	25.8	38.7	51.6
83	48.4	45.2	38.7	45.2	61.3	41.9	41.9	41.9	54.8
84	35.5	25.8	29.0	45.2	51.6	41.9	41.9	32.3	38.7
85	25.8	19.4	25.8	51.6	58.1	51.6	41.9	41.9	45.2
89	58.1	58.1	54.8	67.7	67.7	58.1	54.8	54.8	58.1
90	58.1	45.2	35.5	48.4	61.3	48.4	35.5	45.2	61.3
91	54.8	35.5	38.7	61.3	54.8	54.8	41.9	41.9	48.4
92	29.0	25.8	25.8	48.4	45.2	38.7	38.7	45.2	51.6
93	25.8	41.9	45.2	54.8	54.8	48.4	45.2	61.3	58.1

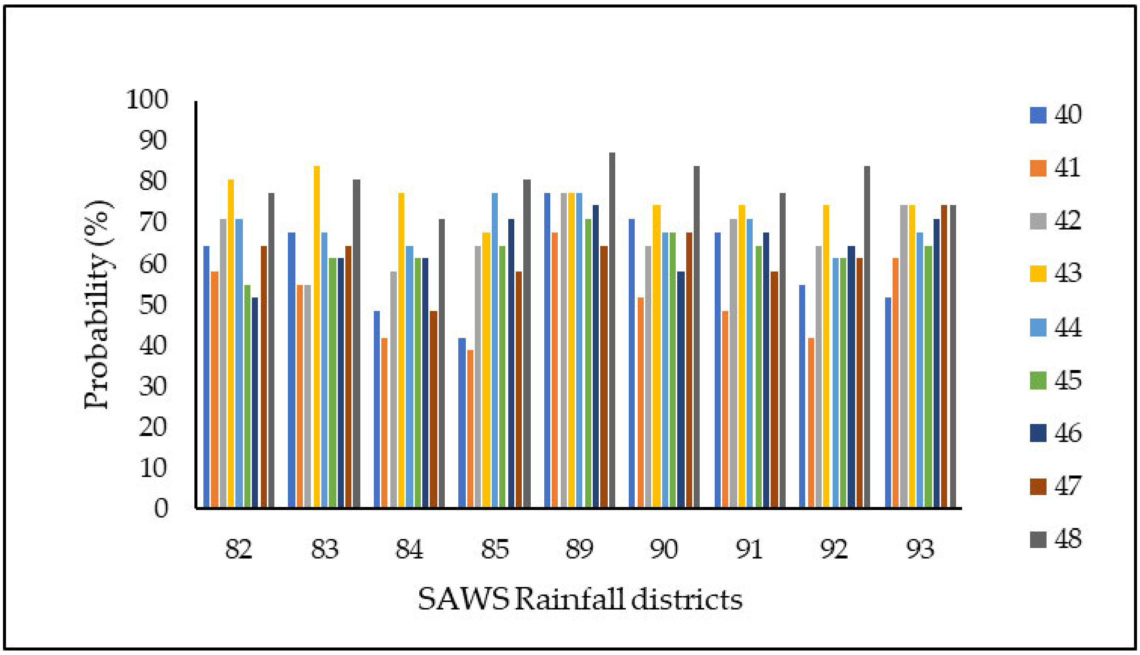

Figure 14: Initial dry-spell probability for selected SAWS Rainfall Districts from 1985 to 2015 during Pentad 40 to 48.

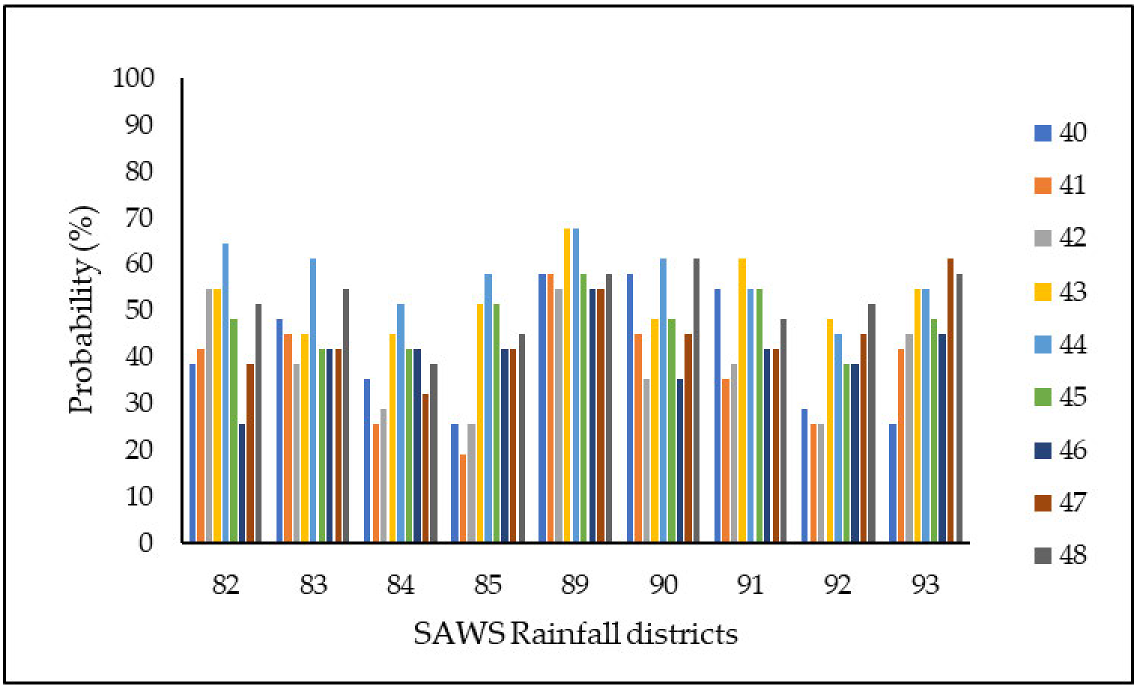

Figure 15: Probability of experiencing two consecutive dry-spells for selected SAWS Rainfall Districts from 1985 to 2015 during Pentads 40 to 48.

The spatial analysis in Figures 16 and 17 shows that the dry-spell and wet spell occurrences within the study area are erratic. In Figure 6, the spatial analysis of initial dry-spell probability is shown for pentads 40, 44, 46 and 48. These pentads were selected because the 40th pentad is the first pentad of the analysis period, the 44th pentad has the highest probability, while the 46th pentad generally has an average probability, and, lastly, the 48th pentad is the end of the analysis period. For pentad 40, the highest initial dry-spell probabilities were observed for the west and southwestern parts. High initial dry-spell probabilities were also noticed in the northeastern part for pentad 44, in the western, north, and northeastern parts for pentad 46, and only the western area for pentad 48. For example, for pentad 44, the highest probability is 77% for districts 89 and 85, while districts 84 and 92 have the lowest probability of 61%. This indicates that all districts experienced dry-spells. For pentad 46 (12-16 February), the highest probability of initial dry-spell was 77%, and the lowest was 51%, with districts 85, 89 and 93 showing the highest initial probability and district 82 the lowest. For pentad 48 (22-26 February), the highest initial dry-spell probability was 87%, and the lowest was 70%, with districts 89, 90 and 92 showing the highest risk of dry-spell occurrences and district 84 the lowest. These spatial initial dry-spell probability results, presented in Figure 6, show that the probabilities are high and that the whole study area is affected by dry-spells.

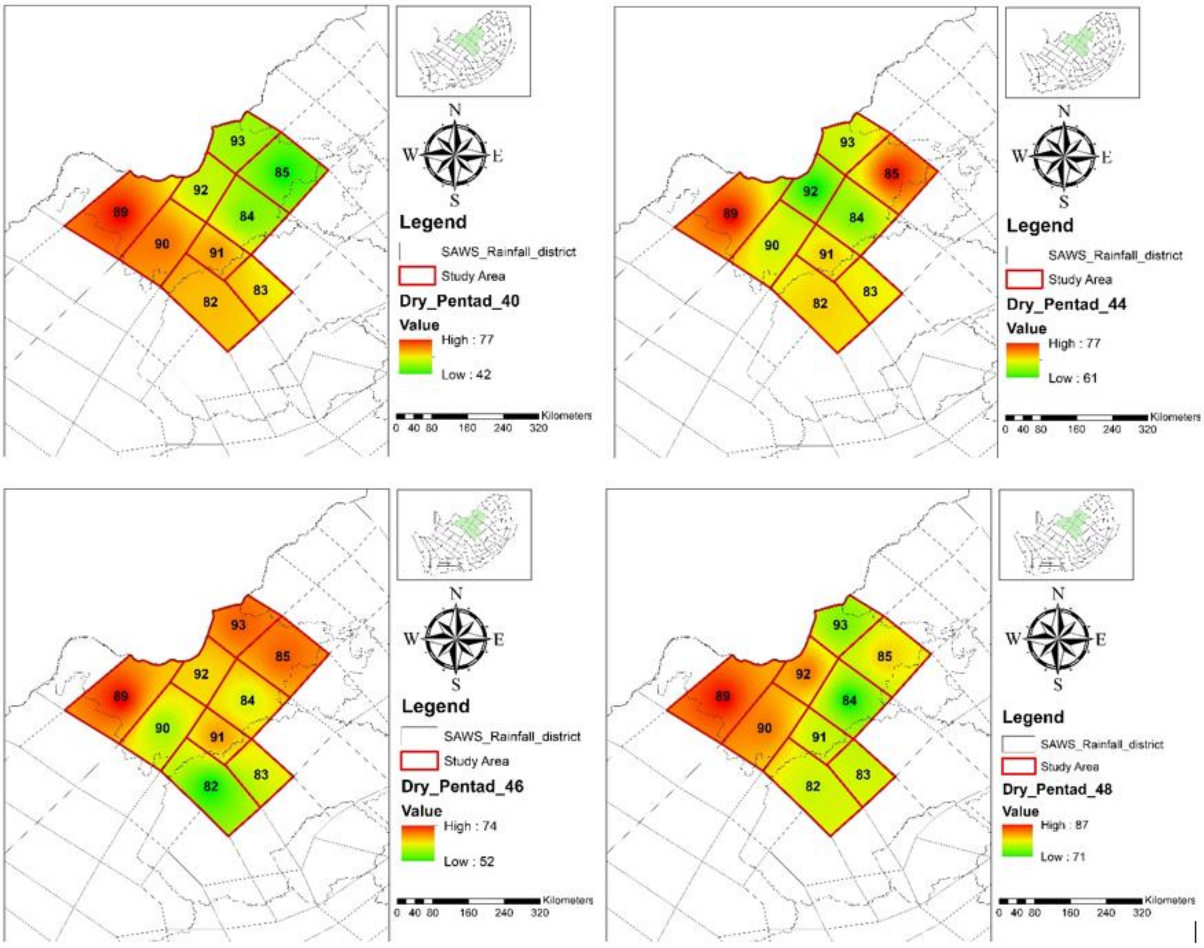

Figure 16: Spatial analysis of initial dry-spell probability (Pd) for pentad 40, 44, 46 and 48.

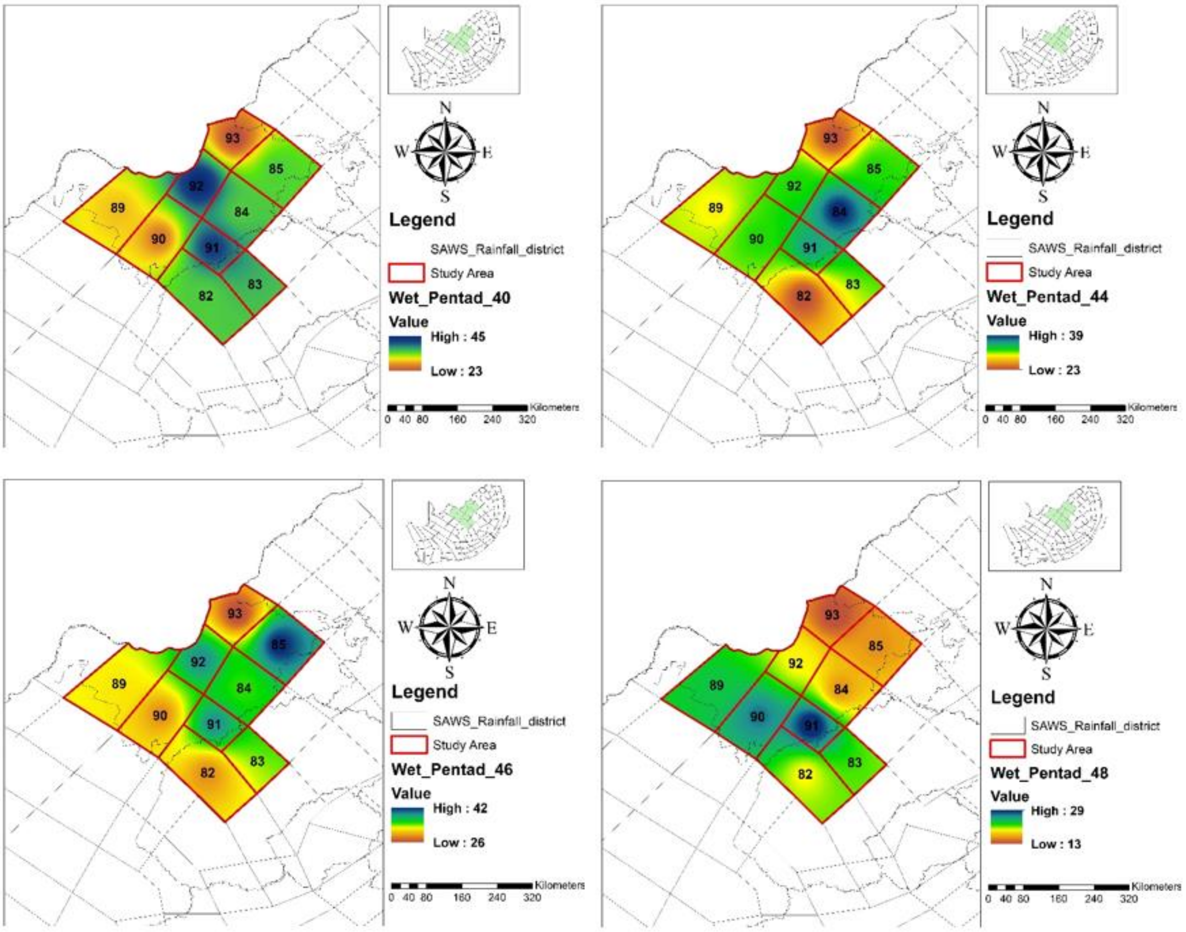

Figure 17: Spatial analysis of initial wet spell probability (Pw) for pentad 40, 44, 46, 48.

4.5.3 Trend Analysis of Dry-spells

The results of MK and Sen Slope trend analysis results, at 95% confidence interval for SAWS Rainfall Districts in the study area for Pentads 40 to 48 (Table 4), indicates that there was no statistically significant trend detected in any of the Rainfall Districts. A detectable change in the trend was noticed for district 92, with a magnitude of -0.03 per year indicating a decrease in the occurrence of dry-spells over the 30 years study period (1985 to 2015). The other Rainfall Districts: 82, 83, 84, 85, 86, 87, 89, 90, 91 and 93 showed no significant detectable magnitude of change in the trend. The magnitude of the trend (Sen-slope) was provided and showed that there is no change in the dry-spell magnitude over the years. Rainfall Districts 83 and 84 show a stable trend (in dry-spell < 15 mm) with the MK statistics at -0.12 and -0.04 respectively. The p-values of 0.91 for district 83 and 0.97 for district 84, reveal that the trend is not statistically significant and thus the trend is inconsistent.

Table 4. Mann-Kendal and Sen Slope analysis at 95% confidence interval for SAWS Rainfall Districts during Pentads 40 to 48 (1985 to 2015).

District	Dry-spell < 15 mm		
	MK Stat	**p-Value**	**Sen-Slope**
82	-0.37	0.71	0
83	-0.12	0.91	0
84	-0.04	0.97	0
85	-0.14	0.89	0
86	0.38	0.71	0
87	0.27	0.78	0
89	-0.99	0.32	0
90	-0.54	0.59	0
91	0.75	0.45	0
92	-1.42	0.16	-0.03
93	**0.62**	**0.53**	**0**

95% Confidence level - Pentads 40 to 48 (Mid-January - End February)

Districts 86 and 91 showed an upward trend in the number of observed dry-spells (<15 mm dry-spell) over the 30-year period. District 86 has an MK statistic value of 0.38, with a p-value of 0.71. This indicated that there was an increasing trend in the number of dry-spells occurring over the years; however, the trend was not significant, and the Sen slope is at 0.00. An MK value of 0.75 and p-value of 0.45 were found for district 91. Although there was no significant trend, the upward trend may be of concern, as the region is already dry, and this will further aggravate the conditions faced by dryland producers. Rainfall Districts 89 and 92 had the highest MK values, and they are -0.99 and -1.42, respectively. This is evident in the charts in Figure 18, where the trend line clearly showed a decreasing trend in dry-spells for both districts. Furthermore, district 92 had a Sen slope magnitude of -0.03; this further suggests that there was a decreasing trend in this district during the study period. The lack of significance in the direction of the trends for the individual Rainfall Districts within the study area, indicated that the occurrence of dry-spells is normal during the study period in this study area.

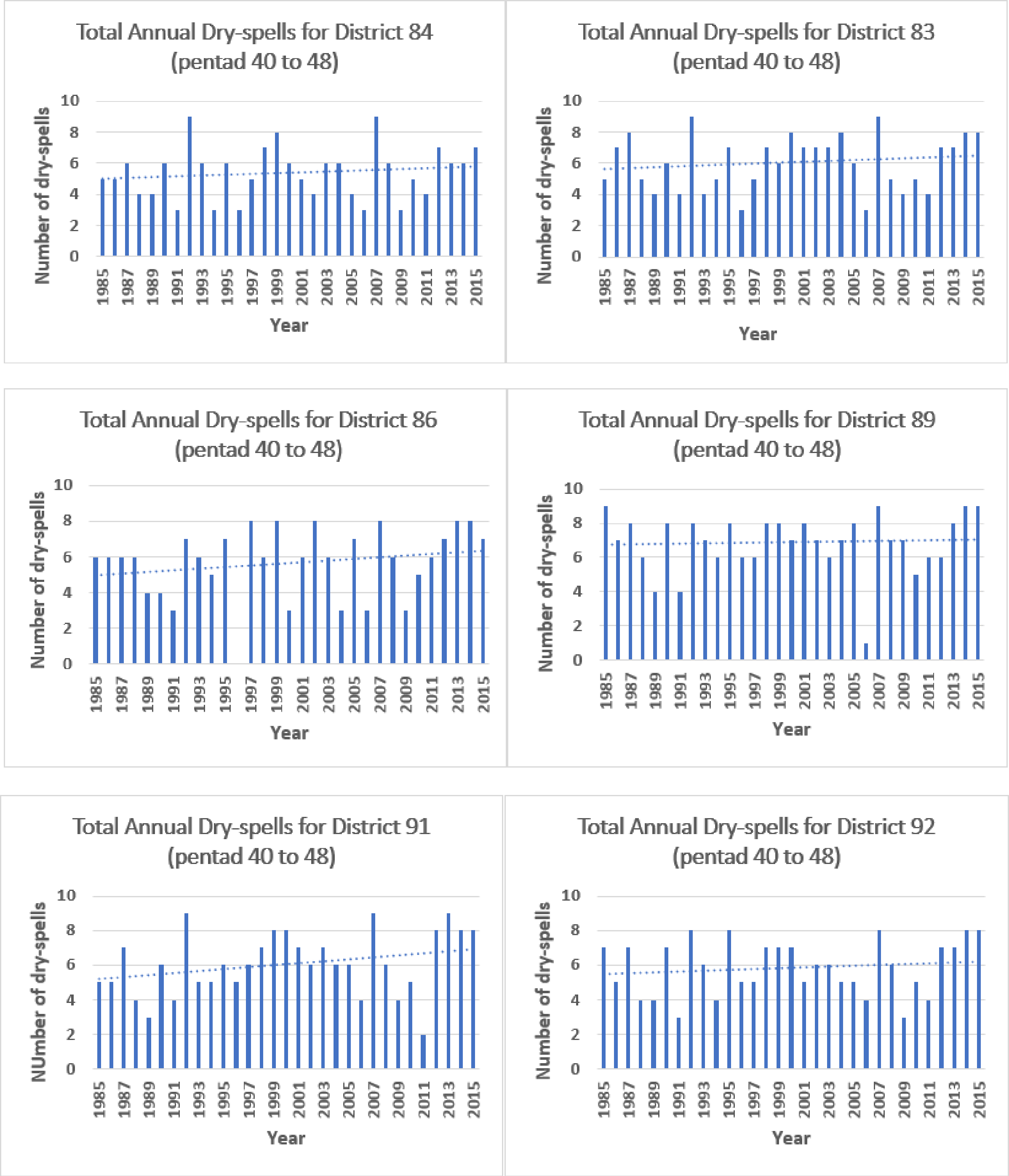

Figure 18: Trend analysis of the number of dry-spells per year in SAWS Rainfall District 83, 84, 86, 89, 91 and 92 during pentad 40 to 48.

4.6 Discussion

The occurrence of wet- and dry-spells is an important phenomenon for summer crops, as it may signal a "good or a bad" season, depending on when they occur. Grobler 1993, illustrated that, during the mid-summer period, Dry-spells tend to dominate in the major maize production areas. In the study carried out by Mengistu et al. (2021) it was discovered that dry-spells occur at different frequencies and magnitudes during mid-summer in the major maize production areas of South Africa. The western maize-growing region experiences late onset of the rainfall season, which leads to late planting of summer crops. However, for the western maize-growing areas, due to the late planting, the flowering stage, which is sensitive to water stress, usually occurs during the end of January to February and not necessarily during the specified mid-summer period used in the study of Mengistu et al. (2021). Findings from this study revealed that dry-spells still occur at a relatively frequent rate during the mid-January-to-end-of-February period, and their occurrence might have an adverse effect on the summer grains if the flowering stage coincides with the dry-spell.

This is not favourable for dryland farming, which only relies on rainfall for crop production. A season with poor rains and a higher-than-normal dry-spell frequency will lead to crops being water-stressed and result in lower crop yields. Most of the Rainfall Districts have a neutral trend in dry-spell frequency; the unpredictable nature of the occurrence of this dry-spell has a negative impact on the annual planning of crop production. Information on dry-spell characteristics such as frequency, duration, and intensity with respect to maize crop phenology is particularly important for dryland maize production. Therefore, planting dates should be chosen to ensure that the flowering stage coincides with normally favourable growing conditions and does not coincide with mid-summer dry-spell periods (Diko and Jun, 2020). Knowledge on the length of dry-spell can be used for selecting drought-tolerant varieties and can be used in irrigation planning during the critical dry period. Thus, the investigation of dry-spells is critical in this region, as the impacts of water stress have dire consequences on grain crop production, especially those produced under dryland conditions.

The results of this study reveal that the occurrence, as well as the intensity, of dry (wet) spells is variable. This poses a serious risk to farmers that rely on rainfed agriculture, especially in the western region where these dry-spells occurred more often during the study period. The neutral trend in dry-spell frequency in much of the study area is a sign that dry-spells have been occurring continuously during the study period. It is worth noting that the occurrence of dry-spells in the Western part are attributed to the characteristics of the dry climate of the region. As dry-spells have an impact in reducing maize crop yield if they coincide with the flowering stage, it is therefore vital that more research is carried out on introducing strategies to minimise risk and avoid production losses.

The knowledge of dry and wet spell probability prepares agricultural advisors with a tool to equip the farmers in gaining knowledge, understanding the risks, and potentially improving production. Critically analysing spells and planting dates in a district can assist farmers with deciding when to plant and avoid the dry-spell period by predicting when it is likely to occur. Knowledge of dry and wet spells can also assist researchers in breeding new crop varieties that mature at various stages, when they know the general occurrence of the dry-spell. Monitoring dry and wet spells coupled with the onset and cessation of the rainy season is vital information, as it equips role-players with the knowledge of what to generally expect in each region or Rainfall District.

Furthermore, the findings from this study show that dry-spells occur frequently during the study period, and this has adverse effects on crop production. As most districts in the study area illustrate, no changes were observed in the trends of dry-spell frequencies, except for one (district 92), which showed a decreasing trend in dry-spell occurrence. However, this observed decreasing trend in dry-spell frequency for district 92 was not statistically significant.

4.7 Conclusion

Rainfall patterns directly affect the crop yield in rainfed agriculture; hence, it is significant to monitor the probability of wet and dry-spell. The success and failure of crops in a planting season is directly influenced by the occurrence of wet and dry-spells. Dry conditions are beneficial during the ripening stage of crops. The Rainfall Districts that were analysed in this study reveal that the occurrence of dry-spells is a major threat to crops, where most summer crops in this region are at the flowering stage as they are planted later than in the eastern regions. The Markov chain model proved to be the most accurate method of analysing the dry-spell occurrence.

It is evident from the results that all Rainfall Districts in the study area are subjected to dry-spells. It is therefore crucial that future research focus more on the effects of dry-spells on different varieties of maize. This will allow farmers to select cultivars that can withstand these dry conditions.

The recommendations from this study are as follows:

1. An investigation into optimum planting dates by using crop models to avoid the occurrence of dry-spells should be conducted, which is crucial to assist farmers and decision makers in preventing production losses and other adverse effects of dry-spells.
2. The impact of climate change on future projections of dry-spells should be investigated.

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Conflicts of Interest: The authors declare no conflict of interests.

CHAPTER 5: SCIENTIFIC ARTICLE II

The effects of different planting dates on maize yield: simulations using the AquaCrop model in the western maize-growing region of South Africa

Siphamandla Daniel [1,2*], Michael Mengistu [2,3] and Alistair Clulow [3]

[1]Department of Mineral Resources and Energy,192 Visagie Street, Pretoria, South Africa; [redacted]
[2]South African Weather Service, PO Box X097, Pretoria 0001
[redacted]
[3]School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa;
Clulowa@ukzn.ac.za
*Correspondence: [redacted]

Abstract: Dryland maize yield is influenced by both the amount and distribution of rainfall during the growing season, as well as the occurrence of frost. Planting dates are crucial because they help prevent crop failure due to frost or dry-spells. In the western maize-growing region of South Africa, maize is typically planted in late November or December to avoid frost and take advantage of the soil moisture from the first rains. This study aimed to investigate the effects of different planting dates on maize yield using the AquaCrop model. The historically available daily rainfall dataset (spanning between 21 and 30 years) was simulated for three distinct dry-spell frequencies (low, medium and high) where dry-spell occurrences are considered a norm and have significant impacts. A two-way ANOVA test revealed a statistically significant relationship between maize yield and planting dates in some Rainfall Districts. Planting maize from 20 December resulted in the highest yields compared to other planting dates across most Rainfall Districts. In conclusion, the study highlights the critical role that planting dates play in optimizing dryland maize yield, particularly in regions prone to dry-spells. It also highlights that low dry-spell frequency seasons tend to produce higher yields compared to medium and high dry-spell frequency seasons. Furthermore, long-term data records are vital for crop modelling, which are essential for simulating various yield scenarios and informing planting strategies.

Keywords: Planting dates, dry-spell occurrences, crop failure, maize yield.

5.1 Introduction

South Africa is characterised by dry conditions and has a significant variation of inter-annual rainfall (Cook et al., 2004). This has a significant impact on water resources as well as the agricultural and socio-economic sectors of the region. Drought is a natural phenomenon, manifested when there is a temporary disparity in the amount of water available as a result of consistently receiving less precipitation than usual for a certain amount of time (Pereira et al., 2009). Therefore, drought is part of the natural climate variability and can be observed through all the climate regimes. Drought has been well researched and documented, with the focus areas having been on the occurrence, impact, intensity, and duration (Mengistu et al., 2021).

When precipitation is consistently below average for a given period of time, it causes a temporal imbalance in the water supply and potentially a long-term drought (Pereira et al., 2009). Short-term droughts, also referred to as "dry-spells," can be just as significant to the farming industry since the timing and severity of the dry-spell is more important than periodic rainfall deficits because when dry-spells coincide with sensitive stages of crop growth, they can lead to substantial damage and yield loss (Usman and Reason, 2004; Mengistu et al., 2021; Daniel et al., 2023). Usman and Reason (2004) noted that uneven distribution of rainfall across space and time can result in an agricultural region experiencing less benefit from an above-average rainfall season compared to a below-normal rainfall season. Thus, a uniform rainfall distribution over time is more likely to benefit crops than strong, sporadic showers interrupted by persistent dry-spells (Usman and Reason, 2004).

The agricultural production of an area is influenced by natural factors such as the soil features and climatic variables, which continuously change with time (Moeletsi, 2004). The yield of crops is adversely affected by a number of climatic conditions, including variable rainfall patterns, high temperatures, high evapotranspiration, mid-summer droughts, and low humidity levels during the growing season (Du Plessis, 2003). Therefore, it is essential to maintain ongoing investment in agrometeorological research in various regions to assist farming communities in making well-informed decisions regarding crop management (Moeletsi, 2004).

Monitoring mid-summer dry-spells is essential for the agriculture sector, since the intensity and timing of the dry-spell is more significant than periodic rainfall deficits or droughts (Mengistu, 2021). Mid-summer droughts usually occur in the mid-summer months (December and January) in the summer rainfall regions, because of a change in the atmospheric circulation from baroclinic (circulation dominated by southern systems) to barotropic (circulation dominated by tropical systems) (Bhalotra, 1984). This period coincides with the flowering stage of maize and sorghum, which typically occurs in mid-summer. Therefore, it is important to study the patterns of mid-summer drought during this critical stage in order to minimize negative impacts on dryland maize crops (Du Plessis, 2003). It has been observed that the flowering stage is most vulnerable to water stress, which can lead to a reduction in crop development, biomass production, and yield in the final stages of development. Planting dates should therefore be chosen such that the flowering stage coincides with optimal growing conditions to avoid mid-summer droughts (Du Plessis, 2003). However, the western maize growing region experiences dry-spells during the months of January and February when the maize crop is flowering, due to the typical late planting in the region (Masupha et al., 2016; Mengistu et al., 2021; Daniel et al., 2023). The planting season in this region is delayed because it typically receives rainfall later than other planting regions (Tsubo et al., 2003; Tadross et al., 2005; Daniel et al., 2023).

Various crop models are used in agriculture for planning and management decisions. These models are useful as they minimise the need of implementing field experiments, which are expensive and time consuming (Whisler et al., 1986; Jones et al., 2017: Babel et al., 2019). These models also serve as analytical tools to assess yield gaps between the actual and potential productivity of various crops (Van Ittersum et al., 2013; Grassini et al., 2015; Babel et al., 2019). The Decision Support System for Agrotechnology Transfer model and the AquaCrop model are amongst the most widely used crop models in the southern African region. Crop models may be impacted by high levels of uncertainty in their structure and input parameters (Van Ittersum et al., 2013; Grassini et al., 2015; Babel et al., 2019) and model calibration and evaluation for different crops for different areas are recommended.

The Food and Agriculture Organisation (FAO) developed AquaCrop model uses the link between biomass accumulation and water lost through transpiration to estimate crop production and determine water requirements (Steduto et al., 2009; Hsiao et al., 2009). The AquaCrop model maintains an ideal balance between simplicity, accuracy, and resilience. It is user-friendly and accessible for crop modelers (Heng et al., 2009). AquaCrop simulates the crop green foliage canopy cover instead of leaf area index from crop emergence through to crop senescence (Heng et al., 2009). This is on the basis that the model calculates transpiration and separates soil evaporation from evapotranspiration (Steduto et al., 2009).

The AquaCrop model has been tested on maize utilising data from the University of California Davis's six consecutive seasons of maize production (Hsiao et al., 2009). The experiment showed that, despite differences in planting dates and plant density over the course of six seasons, the model was able to accurately replicate the crop canopy, biomass development, and grain production of four different maize cultivars (Heng et al., 2009). In both rainfed and irrigated agriculture, AquaCrop has been utilised as a planning tool for management decisions (Raes et al., 2016). On a daily timestep, the model simulates crop growth stages and soil water balance as a function of crop, weather, soil, and management data. (Heng et al., 2009).

AquaCrop was chosen for this study due to its simplicity, user-friendly design, and fewer input requirements compared to models such as DSSAT. Its suitability for use in water-limited regions, particularly in developing countries like South Africa, makes it ideal for environments with lower data availability. AquaCrop’s adaptability to various crops, along with its free access, regular updates, and ease of use, make it a valuable tool for assessing crop yield in water-scarce areas.

The aim of this study was therefore to investigate the impact of dry-spells experienced during late mid-summer (January and February) on maize yield in the western maize growing region of South Africa and to determine the optimum planting dates for maize in the region.

5.2 Study Area

The study area includes SAWS Rainfall Districts 82, 83, 84, 85, 89, 90, 91, 92, and 93 (Figure 19). The western maize growing region is known for its maize production under dry land conditions with optimum planting dates varying across the region (Figure 20).

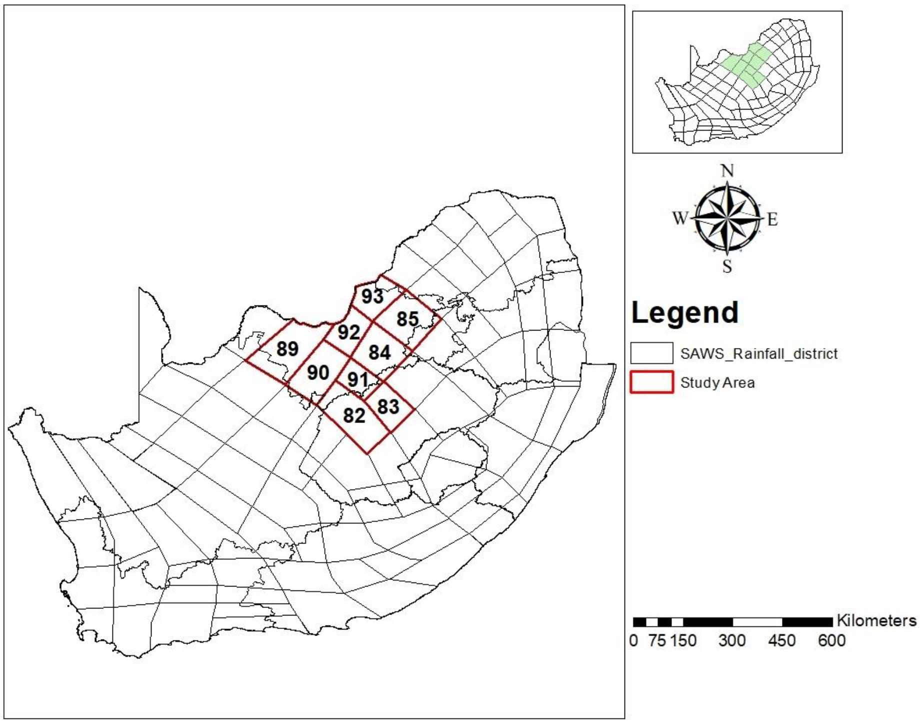

Figure 19: Study area representing SAWS Rainfall Districts, with province borders and Rainfall Districts indicated by red polygons (SAWB, 1972).

The western maize-growing region is comprised of agricultural towns such as Bothaville, Bultfontein, Kroonstad and Henneman in the Free State Province as well as Christiana, Ottosdal, Delareyville and Schweizer-Reneker in the North West. The western region is known for its significant agricultural production output, producing mostly white maize which is used primarily for human consumption (Grain SA and Agbiz Research, 2019).

The dominant soil type of sandy clay loam with moderate fertility was sourced from the Harmonized World Soil Database v2.0 (HWSD v2.0), a global inventory providing detailed soil properties at a 1 km resolution. Researchers recommended a planting density of 20,000 plants per hectare, considering dry climate conditions that limit optimal growth. The study utilized a medium-growing cultivar maturing in 120 days. In addition, the average atmospheric CO_2 concentration was applied, alongside daily minimum and maximum temperatures from stations within each Rainfall District. To enhance simulation accuracy, daily reference evapotranspiration and atmospheric CO_2 concentration (ppm) were also incorporated. The climate file for each Rainfall District was constructed using daily rainfall (mm/day), minimum and maximum temperatures (°C), reference evapotranspiration (ETo) (mm/day), and CO_2 concentration (ppm).

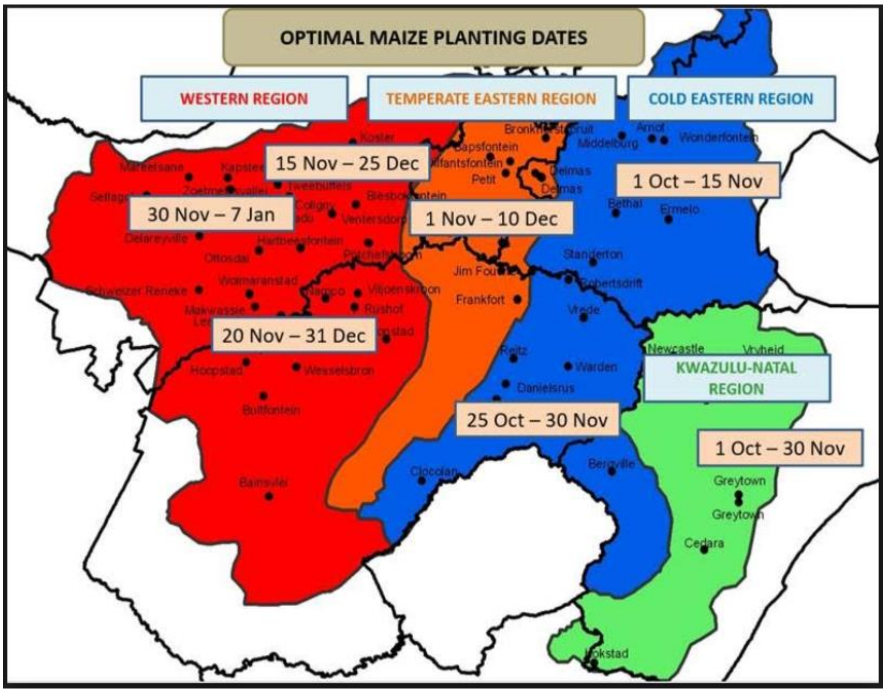

Figure 20: A map presenting the major maize-growing regions with optimum planting dates (Grain SA and Agbiz Research, 2019).

5.3 Data and Methodology

5.3.1 Daily Rainfall Dataset

Climate data was obtained from the SAWS climate database. Nine stations from the SAWS Rainfall Districts (Figure 19) were used for further analysis, which are defined as homogeneous rainfall areas (Kruger, 2011). The number of stations per Rainfall District as well as the data length per station differ; however, only stations with at least 21 years of data were used in this study, with some up to 30 years of data. Daily rainfall was defined as the total accumulated over the preceding 24 hours (Kruger and Nxumalo, 2017) and can be measured manually or at Automatic Weather Stations (AWS) at 08:00 SAST. The study employed a 15 mm threshold across all Rainfall Districts, and the analysis was carried out in selected seasons represented varying levels of dry-spell frequency: low, medium, and high.

It is worth noting that due to South Africa's complex rainfall patterns and topography make it challenging to ensure consistent quality control of rainfall data (Kruger and Nxumalo, 2017). Cases where zero rainfall was recorded during periods of significant surrounding rainfall were flagged and removed (Kruger and Nxumalo, 2017). SAWS divided the country into 94 Rainfall Districts, which are updated monthly and represent areas with distinct rainfall characteristics. Rainfall totals are calculated as averages from available station data, but the number of stations used varied over time, particularly in districts with denser networks (Kruger and Nxumalo, 2017). Therefore, rainfall within many districts was not homogeneous, especially in areas with complex topography, leading to potential biases in trend analysis (Kruger and Nxumalo, 2017).

Table 5. The length of the district climate data set used for yield analysis.

Rainfall District	Start Date	End Date	Number of Station used for yield analysis	Number of Years
82	1985	2015	1	30
83	1991	2015	2	24
84	1992	2015	1	23
85	1994	2015	2	21
86	1994	2015	1	21
87	1994	2015	1	21
90	1985	2015	1	30
91	1994	2015	1	21
92	1985	2015	2	30
93	1985	2015	1	30

The 5-minute average air temperature from the available stations was used to calculate the daily maximum and minimum air temperatures. Thus, air temperatures were averaged from available stations in the district to create a district average daily maximum and minimum air temperature. Solar radiation (R_s) was estimated using the Hargreaves and Samani (1982) method:

$$R_s = (KT)*(R_a)*(TD)^{0.5} \qquad (1)$$

where: KT is an empirical coefficient, R_a is extra-terrestrial radiation (mm/day), TD is maximum minus minimum daily temperature (°C).

Using the methodology of Grobler (1993), pentad summations (5-day totals) were computed from the daily Rainfall District data. Julian days were used to calculate pentads; for instance, January 1–5 represented pentad 1, and December 27–31 represented pentad 73. The tenth pentad included the extra day for leap years on February 29. A dry-spell was considered to be a pentad with less than 15 mm of rainfall. Eight pentads, over which the maize crop is most sensitive to late mid-summer droughts, were chosen, spanning from January 16 (the beginning of pentad 4) to February 24 (the end of pentad 11). The number of weather stations used in a Rainfall District ranged from one to two (Table 5). The stations were chosen based on two requirements: they had to be operational and have had continuous data for at least 21 years. The number of years in the dataset varied from 21 years to 30 years.

5.3.2 Maize Yield Estimation

The AquaCrop model employs green canopy cover (CC) to simulate crop development and models crop growth and yield response to varying water availability. Within AquaCrop, yield is divided into two components: harvest index (HI) and biomass (Raes et al., 2009b). Biomass accumulation is determined through transpiration (Tr) and water productivity (WP). In this study, AquaCrop utilized default values of 32.0 g m^{-2} for biomass water productivity and 40% for harvest index when simulating maize yield. It is worth noting that water productivity values ranging from 30 to 35 g m^{-2} are generally accepted for C4 cereal crops within the AquaCrop framework (Steduto et al., 2009; Raes et al., 2018).

The canopy growth coefficient within the AquaCrop model undergoes multiplication with the water stress coefficient to simulate the effects of water stress on canopy growth. As root zone depletion (Dr) fluctuates above and below the upper threshold, the stress coefficient diminishes to values below 1, resulting in a reduction in canopy expansion (Raes et al., 2018). The frequency and intensity of dry-spells have profound repercussions on maize production in South Africa, affecting yield, soil health, pest and disease dynamics, loss of income, and food security.

The impact of mid-summer dry-spells on maize yield was estimated using the FAO AquaCrop simulation model. The AquaCrop model is a water-driven simulation model (Steduto et al., 2009; Raes et al., 2018). The model is able to simulate the yield response to water for most primary field and vegetable crops with a varying number of inputs and has been reported as having an appropriate balance of robustness, simplicity, and accuracy (Raes et al., 2018). Its parameter guidelines are clear and primarily basic (Steduto et al., 2009; Raes et al., 2018). Since AquaCrop uses water productivity, which is adjusted for climate, it can be used in a variety of locations and seasons (Karunaratne et al., 2011).

Using canopy ground cover (CC) instead of leaf area index (LAI), the AquaCrop model determines transpiration and makes the distinction between transpiration and soil evaporation. Subsequently, biomass was determined by multiplying transpiration by a water productivity indicator:

$$B = WP \times \Sigma \, Tr \qquad (2)$$

where: B is living vegetation above the soil (t ha^{-1}), WP is water productivity (Mg ha^{-1}), and Tr is crop transpiration (mm d^{-1}).

Crop yield was then calculated as the product of above-ground dry biomass and harvest index (HI):

$$Y = B \times HI \tag{3}$$

where: Y is crop yield (Mg ha^{-1}), and HI is harvest index (%).

AquaCrop needs input data files and parameters for soil, crop, and atmosphere. For the climatic component, daily meteorological data such as the maximum and minimum air temperatures, rainfall, ETo, and CO_2 concentration were required (Hsiao et al., 2009). The soil profile file incorporated basic soil parameters such as volumetric water content at saturation, field capacity, permanent wilting point, and saturated hydraulic conductivity of the various soil profile depths (Heng et al., 2009). Water stress categories, phenology, development, canopy senescence and maturity time, flowering period and yield formation duration, plant density, rooting depth, reference HI, and development are among the crop input data (Steduto et al., 2009; Hsiao et al., 2009). Information about irrigation, field management, and ground water are other sources of input data (Steduto et al., 2009).

Due to the variation in the soils across which maize is grown, a dominant sandy clay loam soil with moderate soil fertility was used for the simulations. For the crop input data, the optimal planting dates for maize in drier areas ranged from the last week of November to mid-December. These dates included 20 November, 30 November, 05 December, and 20 December, (ARC-GCI, 2002; Du Toit et al., 2002). For each area, the planting density was determined mainly by the desired yield in each of the producing areas. In the western region, to achieve a maize yield of 3 tonnes per hectare (t ha^{-1}), a plant density of 20 000 plants per hectare was used (Du Plessis, 2003). The maize cultivars grown in each region also differed, and a medium cultivar with 120 growing days was used for the simulations. Three planting dates for the warm and dry western maize production region were used in the AquaCrop simulations (Table 6).

Table 6. The planting density and range of planting dates for the western maize growing areas of South Africa used to model maize yield using the AquaCrop model.

Production Region	**Planting density (plants ha^{-1})**	**1st Planting date**	**2nd Planting date**	**3rd Planting date**
Warm and dry Western Region (Districts 82, 83, 84, 85, 89, 90, 91 92, 93)	20 000	30-Nov	05-Dec	20-Dec

Three distinct growing seasons with high, medium, and low frequencies of mid-summer dry-spells were utilised in the study since the objective of the research was to determine the effect of dry-spells on maize yield. They were chosen particularly for their overall dry-spell frequency: low (2004/2005), medium

(2003/2004), and high (2000/2001). The frequency of dry-spells over the sensitive flowing period between pentad 4 to 12 was assessed and the crop yield was modelled for each of these three seasons across a range of planting dates.

5.3.3 Statistical Analysis

To determine whether planting dates and crop yield are related, a two-way ANOVA test was employed in this investigation. The two-way ANOVA tests two null hypotheses:

H_0: Planting dates have no significant effect on maize yield,

H_1: Planting dates have a significant effect on maize yield.

In an ANOVA, several components were considered to assess the data. The source of variation identifies factors contributing to data differences, while the sum of squares (SS) measures the total variation. Degrees of freedom (df) indicate how many values are free to vary, and mean square (MS) is the ratio of sum of squares to degrees of freedom, representing the average variance. The F-value compares the variance between and within groups, with a higher value indicating a greater effect. The p-value shows the probability of observing the result if the null hypothesis is true, and a smaller p-value suggests stronger evidence against it. Lastly, the critical F-value (F crit) is used to assess the importance of the F-value, with significance determined if the computed F-value exceeds the critical value.

5.4 Results and Discussion

5.4.1 Frequency of Dry-Spell Occurrence during the flowering period

Results from Rainfall District 82 were comparable to those from Rainfall District 83, while Rainfall District 84 had similarities to Rainfall District 91. Rainfall District 85 has unique rainfall characteristics rainfall characteristics including an above-average rainfall compared to other districts. Rainfall District 90 had similarities to Rainfall Districts 89, 92, and 93. Therefore, one Rainfall District (82, 85, 90 and 91) from each of these four groupings is presented (Figures 21 to 24) over the sensitive flowering period (pentad 4 to 12) to minimize repetition.

5.4.1.1 Rainfall District 82 analysis (comparable with Rainfall District 83)

In Rainfall District 82, the 2000/2001 high frequency dry-spell season, eight out of nine pentads did not meet the required 15 mm threshold between pentads 4 to 12 (Figure 21). Such conditions are likely to be harmful to maize crops, especially if the dry period aligns with the crop's flowering stage, negatively impacting maize yield. Equally, the medium frequency season exhibited a similar scenario, where eight out of nine pentads did not meet the required 15 mm threshold with pentad 10 exceeding 30 mm (Figure 21). However, conditions were notably favourable during the low-frequency dry-spell season of 2004/2005 (Figure 21). Throughout this growing season, six out of nine pentads failed to meet the 15 mm threshold.

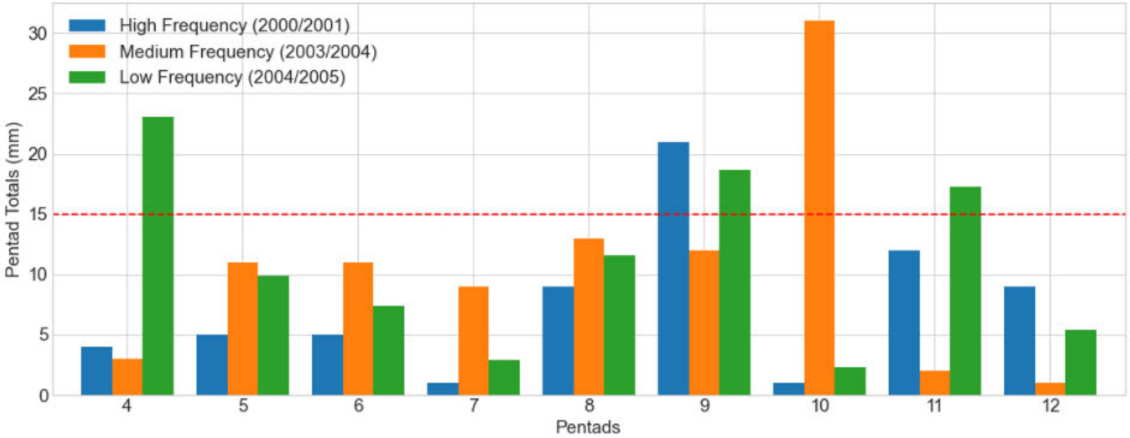

Figure 21: Total pentad rainfall for different dry-spell occurrence frequencies in Rainfall District 82, where dry pentads are defined as those receiving less than 15 mm of rainfall.

5.4.1.2 Rainfall District 85 analysis

In Rainfall District 85, in the high frequency dry-spell season of 2000/2001, five out of nine pentads did not meet the 15 mm threshold, though pentads 8 and 9 exceeded 80 mm (Figure 22). Similarly, in the medium frequency dry-spell season of 2003/2004, six out of nine pentads did not exceed the 15 mm threshold, with pentads 5 and 10 surpassing 40 mm and pentad 11 reaching above 25 mm (Figure 22). On the other hand, during the low frequency dry-spell growing season of 2004/2005, at least four pentads did not meet the 15 mm threshold (Figure 22). This illustrates that that regardless of the dry spell seasonal frequency, consecutive dry-spells can occur during the sensitive flowing period, increasing the risk of negative impacts on maize production.

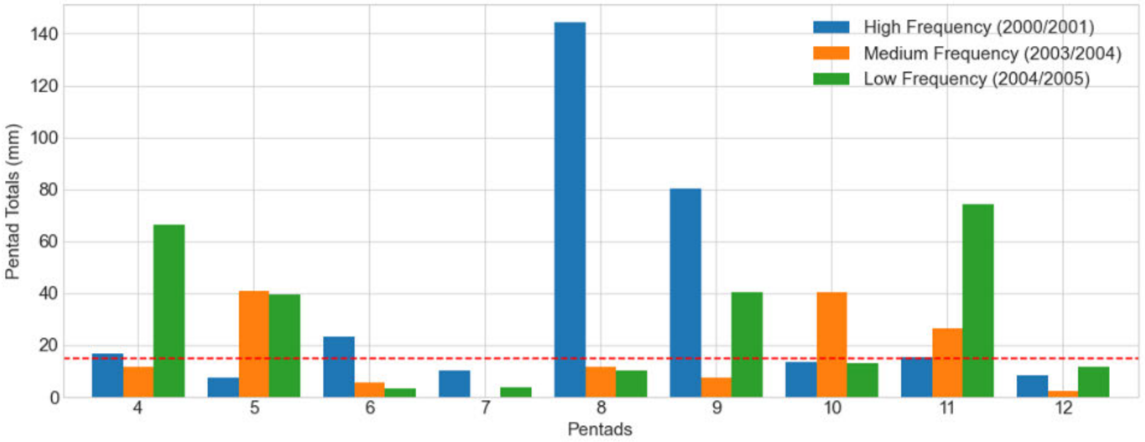

Figure 22: Total pentad rainfall for different dry-spell occurrence frequencies in Rainfall District 85, where dry pentads are defined as those receiving less than 15 mm of rainfall.

5.4.1.3 Rainfall District 90 analysis (comparable with Rainfall Districts 89, 92, and 93)

In Rainfall District 90, during the high-frequency dry-spell season of 2000/2001, all the pentads failed to reach the 15 mm threshold (Figure 23). Similarly, in the medium frequency season of 2003/2004, six out of nine pentads did not reach the 15 mm threshold (Figure 23). While in the low-frequency season of 2004/2005, four out of nine pentads failed to reach the 15 mm threshold, though pentads 4 and 11 experienced rainfall accumulations exceeding 30 mm (Figure 23). In this Rainfall District, the late mid-summer drought was prevalent in all seasons, which may have contributed to low maize yields, as the dry-spells likely coincided with the maize flowering period.

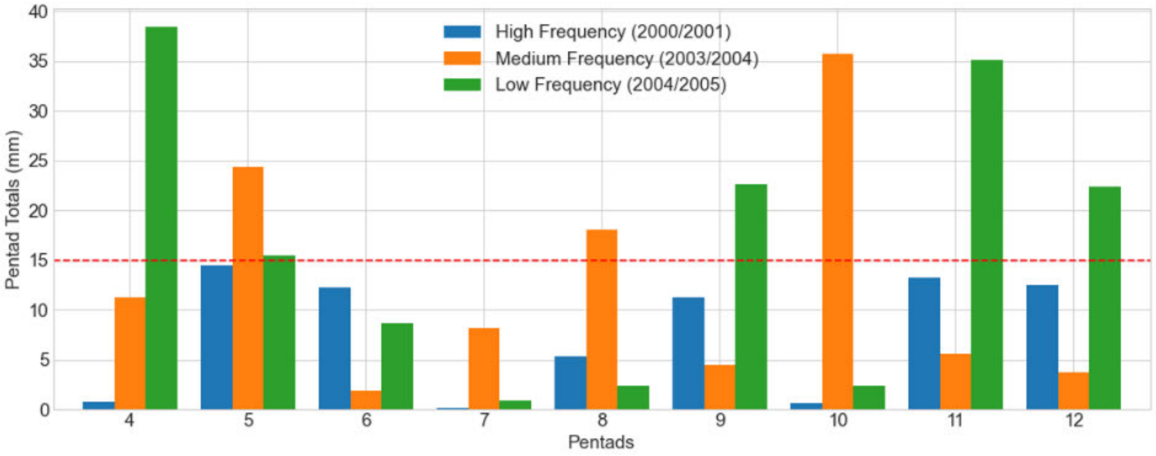

Figure 23: Total pentad rainfall for different dry-spell occurrence frequencies in Rainfall District 90, where dry pentads are defined as those receiving less than 15 mm of rainfall.

5.4.1.4 Rainfall District 91 analysis (comparable to Rainfall Districts 84)

In Rainfall District 91, during the high frequency dry-spell season of 2000/2001, eight out nine pentads did not exceed 15 mm (Figure 24). Similarly, in the medium frequency season of 2003/2004, seven out of nine pentads failed to meet the 15 mm threshold during the study period (Figure 24). In the low frequency season of 2004/2005 (Figure 24), six pentads out of nine pentads did not meet the 15 mm threshold.

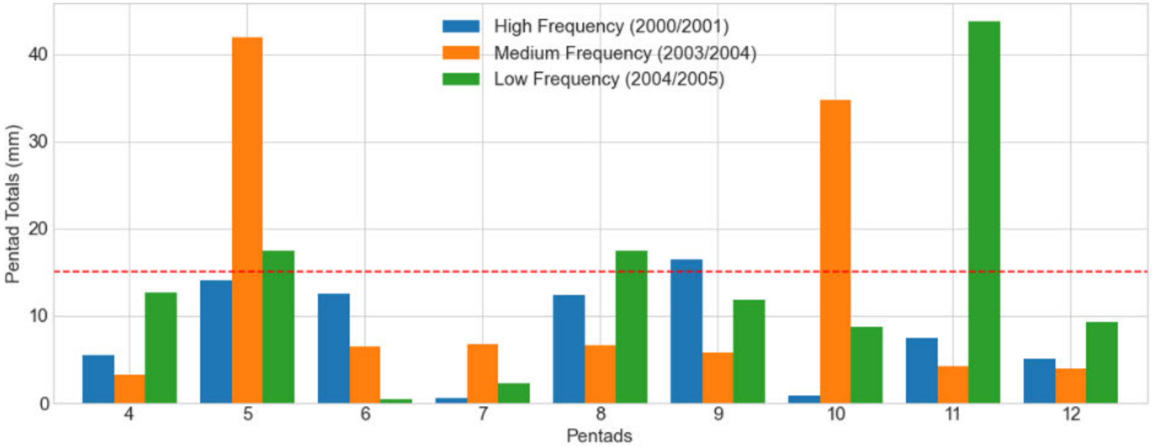

Figure 24: Total pentad rainfall for different dry-spell occurrence frequencies in Rainfall District 91, where dry pentads are defined as those receiving less than 15 mm of rainfall.

It is worth mentioning, in all the Rainfall District analyses above, none of the dry-spell frequency seasons during Pentad 7 exceeded the 15 mm threshold. Furthermore, the high frequency dry-spell seasons generally corresponded to a greater number of dry pentads. However, in some instances, medium and low dry-spell frequencies had the same number of dry pentads.

Dry-spells during key stages of maize growth such as the flowering stage can have significant negative impacts (Du Plessis, 2003). During flowering, water stress can render pollen non-viable and delay silk emergence, leading to poor kernel fertilization and reduced pollination (Masupha, 2016). As water stress continues, plant growth is stunted, limiting photosynthesis and resulting in weaker plants with lower yield potential. In addition, prolonged dry conditions can disrupt grain filling, leading to kernel abortion, especially if the stress extends into this critical stage. The occurrence of frequent dry-spells during pentads 4 to 12, particularly in medium and low-frequency season, signals an increased risk to maize flowering and grain filling. This highlights the importance of drought-resistant maize varieties, enhanced irrigation strategies, and improved climate adaptation measures to safeguard yields against mid-summer droughts.

5.4.2 AquaCrop Yield Estimation

The AquaCrop model was run for all districts under the high, medium and low frequency dry-spell seasons with three different planting dates for each scenario to determine the optimum planting dates in terms of yield for the three different dry-spell frequencies. A yield of 3 t ha^{-1} is considered a reasonable yield for maize (Du Plessis, 2003) and this was used as a threshold in the analysis.

In Rainfall District 82 (Table 7) , maize yield was consistently above 3 t ha^{-1} across all dry-spell frequencies. The highest yield was achieved with a planting date on 20 December across all three dry-spell frequencies. The higher yield may be attributed to maize flowering outside the late-midsummer drought period, which occurs from mid-January to the end of February. In contrast, district 83 showed variability in yields. During high frequency dry-spells, yields fell below 3 t ha^{-1}. Medium frequency seasons generally produced yields above 3 t ha^{-1}, except for the 20 November planting date. Under low frequency seasons, all planting dates achieved yields exceeding 3 t ha^{-1}. These findings are consistent with the analysis done by Adisa et al 2018, which revealed mean maize yield of 3 t ha^{-1} in the western maize production region. The study by Adisa et al (2018) sought to assess the impacts of agro-climatic variable such as precipitation, evapotranspiration, minimum and maximum temperatures on maize yield in different regions of South Africa from 1986 to 2015.

In Rainfall District 84 (Table 7), maize planted on 05 and 20 December consistently produced yields over 3 t ha^{-1} across all dry-spell frequencies. In district 85 (Table 7), only the 20 December planting date achieved yields above 3 t ha^{-1} in high and medium dry-spell frequency, while all the planting dates in low frequency season achieved the minimum threshold or exceeded it. In Rainfall District 89 (Table 7), during the high-frequency season of 2000/2001, only the planting date of 20 December surpassed the minimum threshold, while in the medium frequency season, all the planting dates achieved the minimum threshold, whereas in the low frequency season, only the 20 November planting date yielded more than 3 t ha^{-1}. This suggests the need for a more in-depth analysis to identify the underlying factors contributing to the failure of planting dates during low-frequency seasons to meet the minimum yield threshold. In Rainfall District 90, 91, 92 and 93 (Table 7), during the high-frequency seasons, all the planting dates failed to meet the minimum yield threshold, whereas in the low frequency seasons, all the Rainfall Districts achieved the minimum yield threshold.

The results illustrate that if the minimum yield threshold was not met, then certain agro-climatic factors may be limiting maize yield (Table 7). The deviations from the threshold may highlight unfavourable rainfall distribution and sensitivity to dry-spell frequencies. These variances highlight the need for localized analysis to address these constraints. It is worth mentioning that the model analysis revealed that there was excessive rainfall modelled in Rainfall District 89 during the low-frequency season where on 5 and 20 December planting dates, there was a decline in crop yield.

Table 7. AquaCrop maize yield estimates in tons per hectare (t ha^{-1}) using three planting dates (PD) and three seasons of varying dry-spell (DS) frequencies for Rainfall Districts within the study area.

Rainfall District	**Maize Yield (t ha^{-1}) 2000/2001**			**Maize Yield (t ha^{-1}) 2003/2004**			**Maize Yield (t ha^{-1}) 2004/2005**		
	High Frequency Dry-spell Season			**Medium Frequency Dry-spell Season**			**Low Frequency Dry-spell Season**		
	PD (20 Nov)	**PD (5 Dec)**	**PD (20 Dec)**	**PD (20Nov)**	**PD (5 Dec)**	**PD (20 Dec)**	**PD (20 Nov)**	**PD (5 Dec)**	**PD (20 Dec)**
82	4.5*	4.8*	5.4*	4.2*	5.1*	5.7*	4.7*	5.8*	6.1*
83	1.7*	1.2*	2.3*	2.2*	3.1*	4.0*	4.0*	3.9*	4.1*
84	2.5	3.8	4.2	2.9	3.9	4.4	3.8	4.9	5.1
85	2.0*	2.5*	3.8*	2.4*	2.8*	4.2*	3.9*	4.4*	4.9*
89	2.0*	2.9*	3.8*	3.4*	5.0*	5.5*	4.7*	1.8*	2.2*
90	0.7*	2.7*	2.7*	7.4*	7.2*	7.0*	7.5*	6.8*	6.7*
91	1.2	2.4	2.9	3.3	3.5	3.7	5.6	5.7	5.9
92	1.0*	2.1*	2.5*	2.9*	3.3*	3.5*	5.6*	5.8*	6.1*
93	1.1*	2.0*	2.4*	2.8*	3.2*	3.4*	5.5*	5.8*	5.9*

A two-way ANOVA without replication was carried out to assess the impact of two independent variables: planting date and maize yield, on the Rainfall Districts in the study area (Table 7). For ease of reference, an asterisk (*) is placed next to yield values that are significant at the 0.05 level in Table 7. The analysis showed that the difference in yields shown in Table 7 for Rainfall District 82 is statistically significant ($F = 3.59$, $F_{critical} = 3.44$, $p = 0.04$) at a significant level of 0.05. The difference in yields shown in Table 7 for Rainfall District 85 were found to be statistically significant ($F = 9.53$, $F_{critical} = 2.59$, $p = 8.2 \text{ x } 10^{-5}$) at a significance level of 0.05. The difference in yields for Rainfall District 90 were found to be statistically significant ($F = 4.99$, $F_{critical} = 2.36$, $p = 0.001$) at a significance level of 0.05. In addition, the impacts of planting dates on maize yield were found to be statistically significant in Rainfall Districts 82, 85, and 90. However, the impact of planting dates was statistically insignificant in Rainfall Districts 84 and 91, as the F-critical value exceeded the F-value, with p-values of 0.07 and 0.12, respectively. This further confirms that selecting planting dates that avoid dry-spells during the flowering stage significantly enhances maize yield. Furthermore, the frequency of dry-spells plays a crucial role in determining attainable yield, as planting dates with lower dry-spell frequency resulted in higher yields compared to those with medium or high frequencies. Seasons with high-frequency dry-spells modelled the lowest maize yields. Therefore, the model simulations validate that optimizing planting dates serves as an effective management strategy to mitigate risks associated with dry-spells and improve crop yield.

5.5 Conclusion

AquaCrop proved to be an ideal tool for this study due to its effectiveness with limited data and minimal input requirements for scenario modelling. Selecting planting dates that avoid dry-spells during the flowering stage significantly enhanced maize yield. In addition, the frequency of dry-spells played a crucial role in determining attainable yield, as planting dates with lower dry-spell frequencies resulted in higher yields compared to those with medium or high frequencies. Subsequently, seasons with high-frequency dry-spells modelled the lowest maize yields. AquaCrop accurately simulated optimal planting dates, identifying 20 December as the key planting day that produced the highest yields among the three dry-spell frequencies during the study period.

The ANOVA analysis proved that the variability in yield is statistically significant at the 5% level. Thus, the variability in yield is explained by different planting dates and it is not due to random chance but likely due to the actual effect of the planting dates. In addition, the yield factor showed a significant effect on the planting dates, this indicates that the observed differences at different yields are statistically significant but likely due to the impacts of different planting dates. It is noteworthy that in Rainfall District 91, the impacts of planting dates on yield were found to be statistically insignificant. This suggests that other factors may play a more dominant role in influencing yield within this specific district.

Furthermore, the results revealed that late planting dates resulted in higher yields depending on the dry-spell frequency when compared to earlier planting in the western maize production region. This is likely due to the presence of adequate soil moisture for germination and the onset of rainfall during the December planting period.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Maize is among the important summer staple grain crop in South Africa, which is used for both human and animal consumption. To achieve its optimal yield during the growing season, maize typically requires between 400 and 600 mm of rainfall. Located in a semi-arid region, South Africa is prone to droughts, rendering drought and water stress common challenges impacting maize production. The flowering period is particularly concerning, where maize presents heightened vulnerability to water stress. Consequently, water stress emerges as a primary limiting factor in dryland productivity, resulting in diminished crop production and delayed maturity.

While previous research has extensively examined the frequency, severity, effects, and forecasting of drought on a seasonal and annual basis, the significance of short-term droughts, known as "dry-spells," cannot be undermined in the agricultural sector. This is because the timing and severity of dry-spells often have a more profound impact than periodic rainfall deficits. Given that the occurrence of dry-spells varies annually, understanding their patterns becomes crucial. The Markov chain model provides insight into the rainfall distribution pattern, such as the frequency and duration of wet and dry spells, which are very important in understanding their impact on crop production. In this context, the analysis distinguishes between initial probabilities (PW/PD), which measure the likelihood of receiving rainfall during a pentad, and conditional probabilities (PWW/PDD), which indicate the likelihood of rainfall continuation based on the previous pentad's conditions. The first-order Markov chain assumption simplifies the modelling by considering that the occurrence of rainfall in a pentad depends solely on the immediately preceding pentad. This assumption helps to correct the characterization of the stochastic nature of rainfall patterns without necessarily invoking historical dependencies beyond one pentad. The study highlights the key role wet and dry spells play in affecting crop performance during a planting season. For maize, the timing of dry spells is especially critical. Although dryness is ideal during the maturity stage, dry spells occurring at the flowering stage can really hamper crop development because maize is highly sensitive to water stress during this growth stage. This is really a problem in areas where plantings are later than in eastern parts, which are more exposed during this stage to dry spell events.

The findings emphasize the regionalisation of planning in agriculture concerning planting dates or irrigation strategies to avert or diminish the risks from adverse occurrences of dry spells. The application of Markov chain analysis in this paper will provide a robust framework that will help anticipate and deal with rainfall variability in better crop management and yield optimisation. This study emphasises how crucial it is to monitor dry-spells and rainfall patterns in rainfed agriculture due to their direct impacts on crop yield. Dry-spells, in particular, pose a significant risk to crops, especially maize during its flowering stage. In addition, the Markov chain model was effective in analysing the frequency of dry-spells.

The AquaCrop model was employed to assess the impact of late mid-summer dry-spells on maize yield within the western growing region of South Africa. This investigation focused on three years characterised by varying frequencies of dry-spells: high, medium, and low. To probe deeper into these occurrences, three distinct growing seasons were selected for further investigation within the AquaCrop simulation: those with low (2004/2005), medium (2003/2004), and high (2000/2001) frequencies of dry pentad occurrences. The analysis was conducted on the total pentad rainfall for nine pentads in late mid-summer, covering January and February. Seasons with frequent dry-spells during flowering stage produced lower yields than those with moderate or fewer occurrences.

The study showed that in the western maize production region, planting dates in December generally generated higher yields than those in November. Relating this phenomenon to adequate soil moisture during the December period is possible. This study did address the research question, “What planting dates minimise the risks associated with the late mid-summer drought in the western maize-growing region of South Africa?”. The planting dates of the 20 December had high yield outputs in all three dry-spell frequencies; thus, these dates minimise the risk of the flowering stage coinciding with water stress conditions caused by the late mid-summer drought.

The study aimed to investigate the impact of late mid-summer drought on maize yield in the western maize growing region of South Africa using the AquaCrop model. The results showed that high-frequency dry-spells resulted in lower maize yields compared to medium or low-frequency dry-spell seasons. Notably, seasons with low-frequency dry-spells produced the highest maize yields. In addition, the ANOVA analysis proved that the variability in yield is statistically significant at the 5% level. Thus, the variability in yield is explained by different planting dates and it is not due to random chance but likely due to the actual effect of the planting dates.

In conclusion, this study emphasises the importance of tracking rainfall patterns and the occurrence of dry-spells in rainfed agriculture due to their direct and significant effects on crop productivity. The analysis revealed that all the Rainfall Districts in the study experienced dry-spells, posing a significant risk to crops, especially maize during its crucial flowering stage. The application of the AquaCrop model proved valuable insight in identifying the timing of dry-spells and their impact on various stages of crop growth.

6.2 Recommendations

In light of the findings and conclusions of this study, the following recommendations are made:

- Future research studies should focus on investigating the impacts of dry-spells on different maize varieties.
- Investigate the impact of early (November) and late (January) planting dates, particularly during La Niña, on maize production in the western region.
- Investigate the impact of climate change on dry-spells and its influence on maize production.

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