USING THE STANDARDISED PRECIPITATION INDEX TO DETERMINE THE SEVERITY, DURATION, AND FREQUENCY OF DROUGHT EVENTS IN THE WESTERN CAPE WATER SUPPLY SYSTEM AREA

by

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DECLARATION

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ABSTRACT

Droughts are significant climate events, that can have severe consequences and impacts on the planning and operation of water supplies, but the lack of consistent quantification and monitoring of droughts means that water resource managers often do not have information readily available to inform and assist with decision making in responding to droughts.

The drought experienced in Cape Town, South Africa, during 2015 – 2020 saw storages rapidly depleting and severe restrictions needing to be implemented to ensure that water supplies did not fail. Additional information to understand the onset and severity of the drought as early as possible could have assisted with water resource management.

This research focused on adapting quantification methods and indices to assess and analyse droughts in the Western Cape Water Supply System (WCWSS) area.

Suitable rainfall station data from the South African Weather Services, City of Cape Town and Water Research Commission was selected to form a dataset for use in the research. Rainfall records were corrected, and missing data filled in where required.

Precipitation data for each rainfall station was converted into a Standardised Precipitation Index (SPI), which allows for the occurrence, duration, and magnitude of historical droughts to be assessed for each rainfall record.

Threshold precipitation values were determined, from the SPI values developed, for each rainfall record, which allows the onset and end of droughts to be determined from rainfall measurements only. Threshold precipitation isohyets were mapped for the WCWSS area.

Severity, duration, and frequency (SDF) curves were produced, after deriving SDF relationships for each rainfall station from the SPI values. The SDF curves allow for the probability of a drought with a certain severity and duration to be determined. SDF relationships were also mapped as isohyets across the WCWSS area.

As a case study, these methods were applied to the rainfall stations indicative of the precipitation in the catchments of the major dams of the WCWSS, to study the droughts experienced during 2015 – 2020. The case study showed that the return periods for droughts during this period varied between 1:5 to 1:100 years, with the most significant impacts seen in the catchments of the Theewaterskloof, Steenbras and Voëlvlei Dams. It also showed that four of the five catchments were still in drought by the end of the analysis period in 2020.

OPSOMMING

Droogtes is beduidende klimaatsgebeure, wat ernstige gevolge kan inhou en die beplanning en werking van die watervoorraad beïnvloed, maar die gebrek aan konsekwente kwantifisering en monitering van droogtes beteken dat waterhulpbronbestuurders dikwels nie geredelik oor die inligting beskik om besluitneming in reaksie op droogtes te staaf nie.

Die droogte wat Kaapstad, Suid-Afrika, van 2015 tot 2020 getref het, het veroorsaak dat opgaarvoorraad vinnig verminder het en streng beperkings nodig was om te verseker dat die watervoorraad nie heeltemal uitgeput word nie. Bykomende inligting om die aanvang en felheid van die droogte, so vroeg as moontlik te verstaan, kon gehelp het met die bestuur van die waterhulpbronne.

Hierdie navorsing het gefokus op die toepassing van kwantifiseringsmetodes en -indekse om droogtes in die gebied van die Wes-Kaapse Watertoevoerstelsel (WKWTS) te assesseer en te ontleed.

Geskikte reënvalstasiedata van die Suid-Afrikaanse Weerdiens, Stad Kaapstad en die Waternavorsingskommissie is uitgesoek om die datastel vir die navorsing te vorm. Reënvalrekords is, waar nodig, reggestel en aangevul.

Neerslagdata vir elke reënvalstasie is omgeskakel na ŉ gestandaardiseerde neerslagindeks (GNI), wat assessering van die voorkoms, duurte en omvang van historiese droogtes vir elke reënvalrekord moontlik maak.

Uit die GNI-waardes wat ontwikkel is, is neerslagdrempelwaardes vir elke reënvalrekord vasgestel, wat dit moontlik maak om die aanvang en einde van droogtes uit slegs reënvalmetings te bepaal. Neerslagdrempel-isohiëte is vir die WKWTS-gebied gekarteer.

Felheid-, duurte- en frekwensiekrommes (FDF-) is opgestel, nadat die FDF-verwantskappe vir elke reënvalstasie uit die GNI-waardes afgelei is. Uit die FDF-krommes kan die waarskynlikheid van ŉ droogte van ŉ sekere felheid en duurte bepaal word. FDF-verwantskappe is ook as isohiëte vir die hele WKWTS-gebied gekarteer.

Hierdie metodes is op die reënvalstasies, wat die neerslag in die opvanggebiede van die hoofdamme van die WKWTS aantoon, toegepas om die droogtes wat van 2015 tot 2020 ervaar was, as ŉ gevallestudie te bestudeer. Die gevallestudie het getoon dat die herhaalperiodes vir droogtes tydens hierdie periode gewissel het van 1:5 tot 1:100 jaar, met die mees beduidende invloed wat in die opvangsgebiede van die Theewaterskloof-, Steenbras- en Voëlvleidam gesien kon word. Dit het ook getoon dat vier uit die vyf opvangsgebiede teen die einde van die ontledingstydperk in 2020 steeds n droogte ervaar het.

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LIST OF ABBREVIATIONS

AWA	Australian Waterworks Association
AWWA	American Water Works Association
CCT	City of Cape Town
CDF	Cumulative distribution function
DELWP	Victorian Government Department of Environment, Land, Water and Planning
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
ENSO	El Niño/La Niña Southern Oscillation
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization of the United Nations
GCM	Global Circulation Model
GHG	Greenhouse Gases
Gℓ/year	Gigalitres per year
IPCC	Intergovernmental Panel on Climate Change
m^2	Metre square
mm	Millimetre
NASA	National Aeronautics and Space Administration
NOAA	National Oceanographic and Atmospheric Administration
PDF	Probability density function
PDSI	Palmer Drought Severity Index
%	Percentage
RCP	Representative Concentration Pathway
SAWS	South African Weather Service
SDF	Severity, duration, and frequency

SPI	Standardised Precipitation Index
SPI-12	12-month cumulative Standardised Precipitation Index
UNDRR	United Nations Office for Disaster Risk Reduction
UNESCO	United Nations Educational, Scientific and Cultural Organization
W	Watts
WCWSS	Western Cape Water Supply System
WRPM	Water Resource Planning Model
WRYM	Water Resource Yield Model
WMO	World Meteorological Organization

1. INTRODUCTION

1.1 Context of the research

Droughts are significant climatic events, that can have severe consequences and impacts on the planning and operation of water supplies, but the lack of consistent quantification and monitoring of droughts means that water resource managers often do not have information readily available to inform and assist with decision making in responding to droughts.

1.2 Motivation for the research

The drought experienced in Cape Town, South Africa, during the period from 2015 – 2020 saw storages rapidly depleting and a period of severe restrictions required to ensure that water supplies did not fail. A lack of consensus and delayed decision-making on a drought response by authorities contributed to the rapid decline of storages.

The motivation for this research was to provide additional information to water resource managers to assist with drought management by informing responses to drought events.

1.3 Aim and objectives of the research

The aim of this research was to develop information on droughts and dry conditions in the supply area of the Western Cape Water Supply System (WCWSS), to provide water resource managers with additional information on the start and end of dry condition and drought periods, and to index and quantify the severity droughts. The scope of the research was on adapting quantification methods to assess and analyse rainfall records in the supply area of the WCWSS, to give water resource managers sufficiently detailed information at a catchment level to better plan and manage the WCWSS.

The research focused on calculating index values to develop severity, frequency, and duration (SDF) relationships, and mapped these across the WCWSS region. This would ideally add to existing models and information available to facilitate timely and appropriate decision-making on managing dry conditions and drought. A case study was done, to illustrate the use of the methods and information developed, and to quantify the droughts experienced in the WCWSS area during 2015 – 2020.

The objectives of the research were to:

1. Identify suitable rainfall records in the catchment area of the WCWSS, to use for analysis and statistically analyse these rainfall records.

2. Use a drought index to determine the occurrence and severity of droughts in the historic records for the selected rainfall stations.
3. Develop threshold precipitation graphs to allow the start and end of droughts to be determined directly using rainfall data.
4. Develop SDF curves for the rainfall records for return periods of 5, 10, 20, 50 and 100 years, to understand the relationships between drought severity, duration, and frequency.
5. Graphically map the SDF information across the region of the WCWSS, to understand the regional distribution of drought impacts and allow these to be assessed in locations that do not have long-term rainfall data.
6. As a case study, quantify and index droughts experienced during 2015 – 2020 in the WCWSS area.

1.4 Significance of the research

Decisions on responses to a drought often have significant consequences on people, communities, economies, and the environment. Information that can assist decision makers in timely and appropriate responses can lessen the impact of the consequences: however, information on severity, duration, and frequency of historical droughts to detect and index droughts are not readily available without specialised knowledge of drought and frequency analysis theory. Decisions that need to be made can range from imposing water restrictions, which can have severe economic and societal impacts, to constructing emergency water supply schemes, which often have significant capital costs and long-term operating costs. These are impacts and costs that must ultimately be borne by water customers. Additional information can assist authorities to make more timely and appropriate decisions to minimise adverse impacts on water utilities and the public.

1.5 Layout of the thesis

This thesis is structured as follows:

- **Section 1** introduces the study by summarising the motivation for, context, aim, scope and significance of the research.
- **Section 2** presents the literature review and covers the background to the research, including the impact of droughts, how droughts are defined, the significance of droughts in water supply management and how droughts are quantified and indexed.

- The methods that were used to calculate the drought index values and develop the threshold precipitations and severity, duration, and frequency relationships, and how these were mapped across the region are covered in **Section 3**.
- The calculation of the drought index values, development of the threshold precipitations and SDF curves, and mapping of this information across the WCWSS area are discussed in **Section 4**.
- **Section 5** illustrates the application of this information based on a case study, where droughts experienced in the WCWSS area during 2015 – 2020 were indexed and quantified.
- Finally, **Section 6** presents the conclusions and recommendations of the research.

2. LITERATURE REVIEW

This section provides background and context to the research presented in this research. In Sections 2.1 – 2.5, the literature is reviewed and concepts are discussed on: droughts as a natural disaster; climate change and its impacts on drought occurrence; water resource management and droughts; droughts around the world; and the drought during the 2015 – 2020 period in Cape Town. Section 2.6 explores how droughts are defined, the common drought indices used, and the concept of severity, duration and frequency relationships used to quantify droughts. Section 2.7 concludes with a summary of the literature review.

2.1 Droughts as a natural disaster

Droughts have significant impacts on people, communities, economies, and the environment. Unlike other natural disasters such as floods, hurricanes, and earthquakes where impacts and damages happen rapidly, droughts often start slowly, and can last for long periods of time with the impacts felt over large regions. For this reason, droughts are often referred to as a “creeping phenomenon” (Mishra & Singh, 2010).

Droughts have occurred throughout recorded human history. It is postulated that droughts in ancient Egypt, Greece and South America contributed to the decline, and even complete collapse, of entire civilisations (Sheffield & Wood, 2011). The collapse of the Maya empire in South America is an example of this (Haug, Günther, Peterson, *et al.*, 2003). It is interesting to note that it is hypothesised that it was not drought itself that caused the decline or collapse of these societies, but rather famine, competition for resources and war as a result of droughts that lead to political and social upheaval.

Even with the less immediate impact and a smaller number of occurrences of events than other natural disasters such as flooding, droughts continue to have a significant impact on societies and countries around the world. The United Nations Office for Disaster Risk Reduction (UNDRR) estimates that between 1995 and 2015, even though droughts only accounted for 5% of the number of natural disaster events globally, it had an impact on 1.1 billion people, or 26% of the number of people affected by all natural disasters over the 20 year time period studied (UNDRR, 2015). During this period, droughts also resulted in approximately 22,000 deaths, which the UNDRR also believes is under-estimated as it does not consider indirect fatalities due to factors resulting from droughts, such as malnutrition, populations fleeing drought-stricken areas, and related illnesses.

The World Meteorological Organisation (WMO) estimates that globally between 1970 and 2012, droughts caused the deaths of approximately 680,000 people, and resulted in damages totalling around US$191 billion, while only accounting for about 6% of the number of weather-related disasters during the period (WMO, 2014). The higher number of fatalities was mainly due to the severe droughts experienced in Ethiopia, Sudan, and Mozambique during the 1980s. This again underlines the large scale, severe impacts of single drought events.

It should be noted that there is a difference between droughts and arid climates. Droughts are temporary reductions in rainfall from normal or average conditions. Droughts can therefore happen in any climate, including equatorial monsoon type climates, temperate climates in the mid-latitudes, as well as arid climates. Arid climates themselves have permanently lower levels of rainfall than other climates. However, arid climates can also experience periods of droughts when rainfall is temporarily lower than average.

While there is no universal definition of a drought, it is generally accepted to be caused by lower-than-normal precipitation. This lack of a universal definition of a drought has often been problematic in the identification, planning and management of droughts by policy and decision makers (Wilhite, 2000). Added to this is the challenge that the onset of droughts can be difficult to detect, and that the impacts of droughts, such as reduced stream flow and groundwater levels, can last for long periods after a drought has ended.

The lack of rainfall experienced during a drought progresses though the water cycle, through reduced soil moisture, runoff, flow in streams and rivers, and groundwater levels (Van Loon, 2015). This impacts on societies and communities, economic activities, and the environment reliant on water and water supplies from these sources, including: water restrictions placed on urban communities; reduced agricultural production, and in extreme droughts the devastation of crops and livestock; increased cost of production of goods requiring water; decrease of environmental water quality; the drying of the natural environment that increases the risk of fires, with the resulting damage to property, infrastructure and the environment; and the reduced ability to generate electricity through hydropower.

Droughts are one of the natural disasters where the impacts can be exacerbated by human activities. As human populations have grown, so has the demand for water increased, and this has placed additional demands on water resources. Water supply systems come under more pressure during dry periods and droughts. As more water is abstracted from the environment for human and economic use, and water resource are placed under strain even during normal rainfall conditions, any shortages in water availability due to dry conditions and droughts can quickly result in severe impacts on human activities.

The impacts of the extreme drought in the southern areas of South Africa during 2015 – 2020 were no more starkly illustrated than the situation in Cape Town, where it was being predicted and extensively reported around the world that it would become the world’s first major city to run out of water. While a number of factors contributed to the crisis (Ziervogel, Franklin & Thorson, 2019), it can be argued that a contributing factor was that water demand had started approaching the availability of water from the system, increasing the magnitude and speed of impact on water resources with the occurrence of a severe drought event (DWS, 2016).

It is therefore clear that droughts can cause significant loss of life, political and social upheaval, economic losses, and environmental damage, and while not occurring as often as other natural disasters such as flooding and storms, can have widespread and long-lasting impacts.

2.2 Climate change

The term ‘global warming’ is the name given to the measured increase in temperature of the Earth’s surface and oceans over the last century. The Earth’s average temperature has increased by approximately +0.85ºC from 1850 to 2012. This increase in temperature is shown in Figure 2.1, which illustrates the deviation of average combined surface and ocean temperatures over the long term, compared to the period from 1986 to 2005 (IPCC, 2014). Three datasets are graphed, showing both annual and decadal averages.

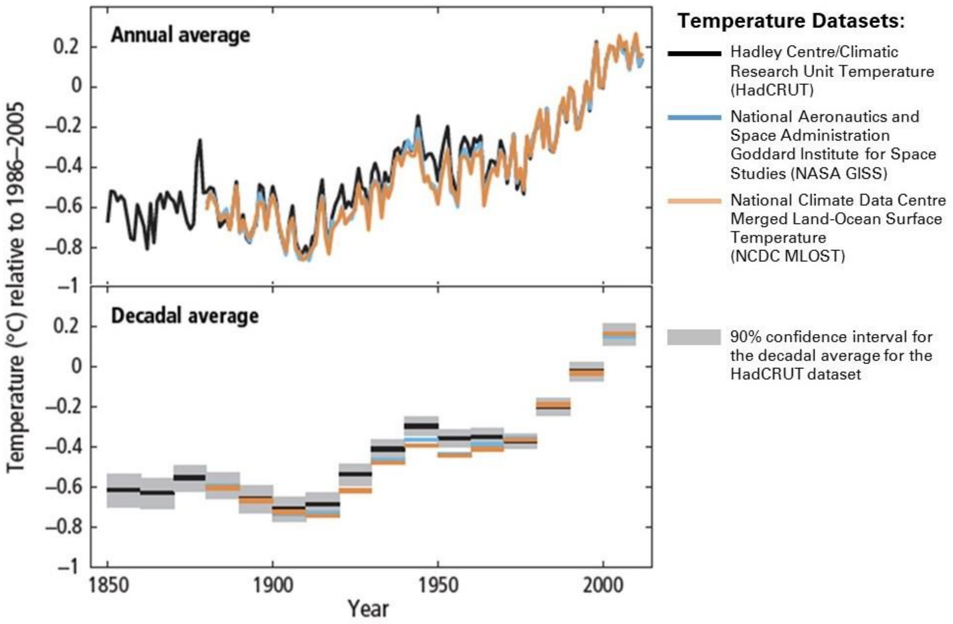


Figure 2.1: Observed land and ocean temperature variation (IPCC, 2014)

The rate of global warming is also increasing. Over the last 20 years, average global temperatures have increased by a rate equivalent to 1ºC per century. The Intergovernmental Panel on Climate Change (IPCC) considers it very likely that the 30 years from 1983 to 2012 was the warmest period in the Northern Hemisphere compared to the previous 800 years.

Data analysis in 2017 by the National Aeronautics and Space Administration (NASA) and the National Oceanographic and Atmospheric Administration (NOAA) indicated that 16 of the warmest 17 years on record since 1880 have occurred in the period from 2001 to 2016.The phenomenon of global warming, and the resulting impacts on the Earth's atmosphere, weather systems, oceans, and natural environment is referred to as climate change. It should be noted that there is a difference between the meanings of weather and climate. Weather refers to the random day-to-day natural atmospheric phenomena such as temperature, wind, humidity, cloud cover, and precipitation, and by its definition is a short-term measurement. Climate is a longer-term measure of weather and refers to the seasonal patterns in weather or the trends (both past and projected into the future) of atmospheric conditions (UNESCO, 2011).

The Earth's atmosphere, oceans and land surface all play a role in regulating the temperature of the planet. The Earth receives solar radiation from the sun - part of this reflected away from the Earth by the atmosphere, while the remainder reaches the Earth's surface. Some of the solar radiation absorbed by the Earth's surface is radiated into the atmosphere as heat – part of this heat is radiated into space, but part of the heat is trapped in the atmosphere, primarily through the action of greenhouse gases (GHGs) such as carbon dioxide, methane and nitrous oxide. This system of heat reflection and absorption is illustrated in Figure 2.2. This greenhouse state is critical to maintaining a temperature at the Earth's surface that makes existing life on the planet possible.

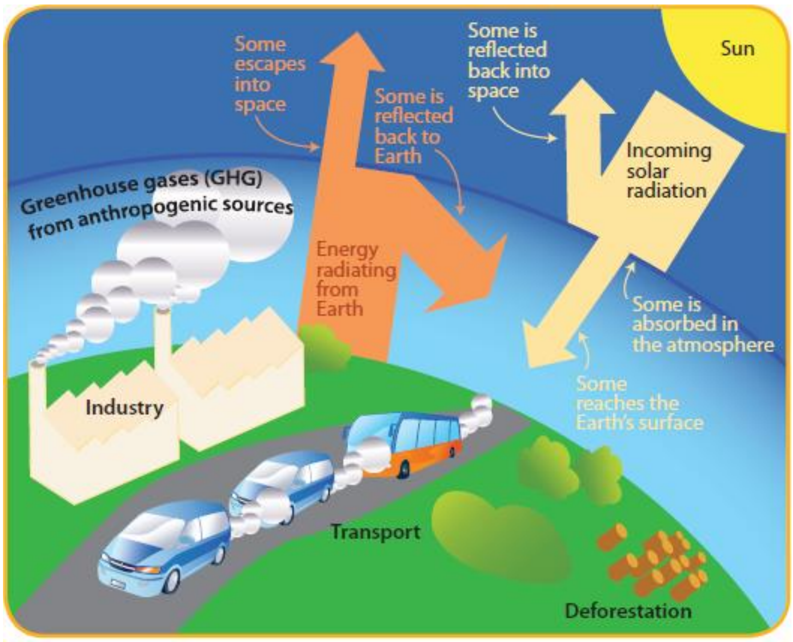


Figure 2.2: The greenhouse effect of the Earth's atmosphere (UNESCO, 2011)

Because of the shape of the Earth and its position on its axis relative to the sun, the equatorial regions receive a higher intensity of solar radiation than the poles. The Earth's atmosphere, oceans and land surface all play a role in distributing heat from the equatorial regions towards the polar regions. This distribution of heat is illustrated in Figure 2.3. Without these mechanisms, the equatorial regions would be excessively hot while the polar regions would be excessively cold, and it would be difficult for existing life to thrive in these regions.

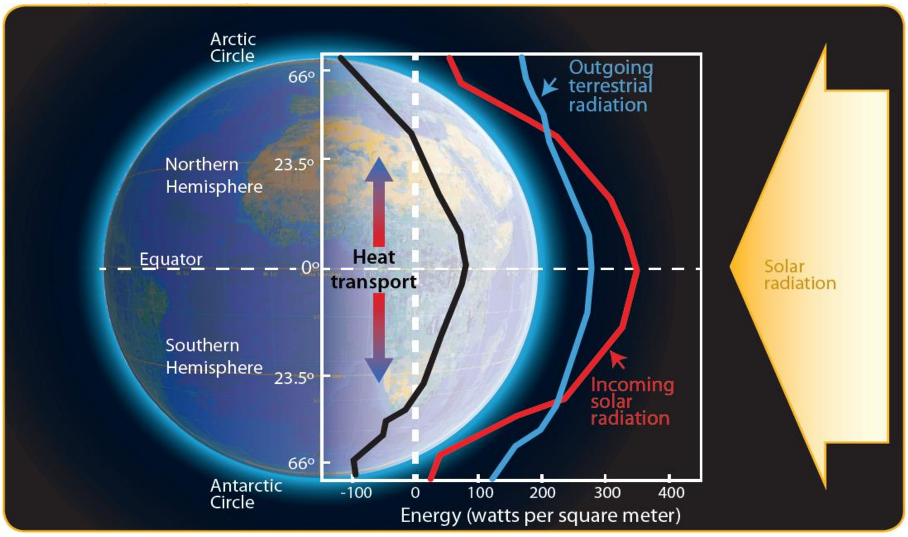


Figure 2.3: Distribution of heat around the Earth (UNESCO, 2011)

These mechanisms of regulation of temperature and the distribution of heat drives much of the planet's climate systems. These systems are complex and large-scale, and there are also interactions between the systems which can have impacts across the globe. An example of this is El Niño/La Niña Southern Oscillation (ENSO), a climate cycle determined by the periodic warming or cooling of the tropical Pacific Ocean. This climate variation occurs approximately every five years and can result in droughts or floods in regions around the world, including Cape Town and the south-western region of the Western Cape, that receives rainfall predominantly from cold fronts originating in the Southern Ocean and travelling in an easterly direction. It is understood that global warming will have an impact on these mechanisms, and in turn this will affect the Earth's climate systems and hydrological cycle.

The increase in temperature over the last century, including the more rapid increase over the last 50 years, has coincided with a significant increase in GHG emissions from human activity since the beginning of the industrial revolution. These have mainly resulted from the burning of fossil fuels for activities such as transportation, heating, electricity generation, and industrial processes. Agricultural activities also emit GHGs such as methane and nitrous oxide. Figure 2.4 indicates the annual levels of CO_2 emissions from human activities from 1850 to 2011.

This illustrates the significant increase in CO_2 emissions since the middle of the twentieth century. It is estimated that CO_2 comprises around 77% of the GHG emissions from human activities. Figure 2.5 shows the total GHG emissions from human activities from 1970 to 2010.

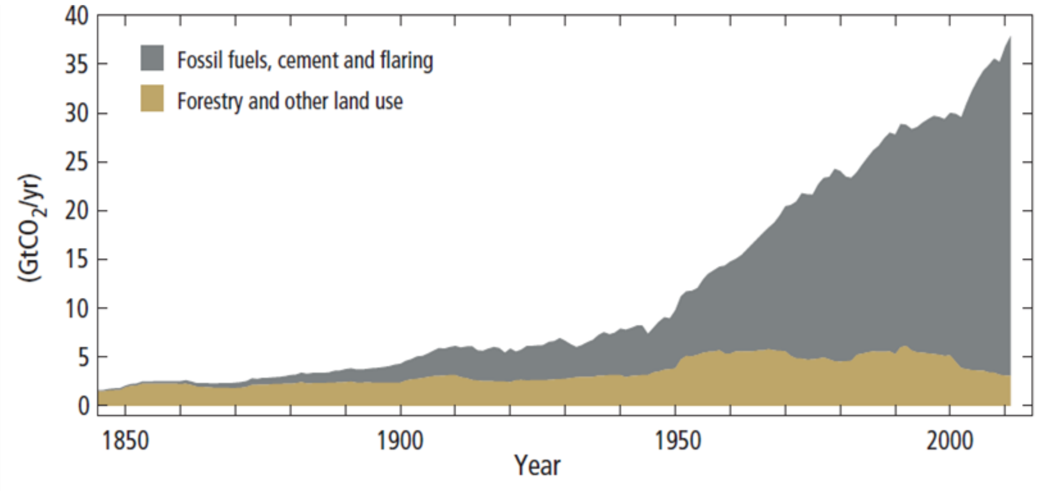


Figure 2.4: Global annual CO_2 emissions from human activities (IPCC, 2014)

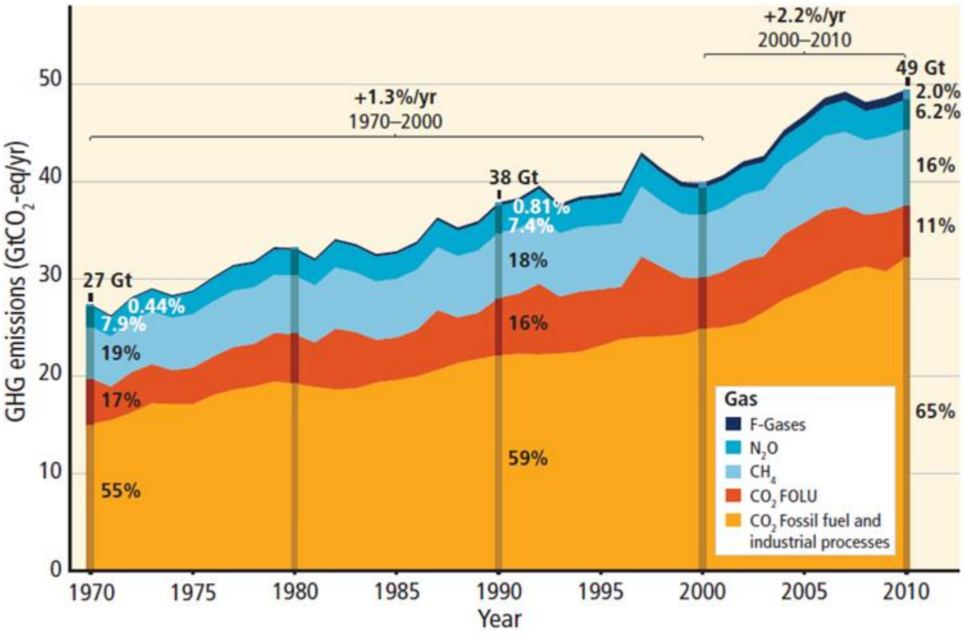


Figure 2.5: Annual GHG emissions from human activities (IPCC, 2014)

Most climate scientists agree that global warming is a result of human activities. A study by Cook, *et al.* (2016) found that there was a 90% - 100% consensus in scientific publications on human-caused global warming, although there is some debate on this level of consensus amongst scientists (Tol, 2016). The IPCC, in its Climate Change Synthesis Report (2014) stated that there is a clear link between human activity and climate change, and that climate change has already affected the Earth's natural environment.

General Circulation Models (GCMs) are used to project future climate trends and the impacts of climate change decades into the future (IPCC, 2014). These complex computer-based models simulate various climate variables, such as atmospheric temperature; ocean temperature, currents, and ice; precipitation; wind; and clouds. Several variables are used in these simulations, including population growth, economic growth, energy generation, technology progress, land-use, environmental changes, and GHG emissions.

Representative Concentration Pathways (RCPs) are used to model scenarios of levels of GHG emissions. Currently, there are four different RCPs used in climate change modelling: RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The numbers in the pathways refer to levels of atmospheric radiative forcing, which is the difference between solar radiation received by the Earth that is radiated out into space and absorbed or retained by the atmosphere, and is measured in Watts/square metre (W/m^2) (IPCC, 2014). The pathways are used to model different climate futures: RCP2.6 represents an optimistic, low emissions pathway, where a rapid change in human activities and technological innovation allows an aggressive reduction in GHG emissions; RCP4.5 and RCP6.0 are intermediate scenarios; and RCP8.5 represents the least optimistic, high emissions pathway, where intervention in reducing GHG emissions from human activities is slow.

The IPCC in 2014 released its Fifth Assessment Report (AR5), a set of documents comprehensively covering the current state of climate change science, including analysis of observed historical changes and potential projected climate futures, incorporating quantitative assessment of the likelihood of trends in climate aspects such as land and ocean temperature, precipitation, and the occurrence of extreme weather resulting in flooding and droughts (IPCC, 2014). The IPCC in 2012 also published a special report, based on its 2007 Fourth Assessment Report (AR4), covering the management and adaption to extreme events resulting from climate change (IPCC, 2012). Some notable findings from modelling and projections, specifically related to precipitation in Southern Africa, are:

- Changes in precipitation are projected to vary for different regions around the world. While tropical regions may see an increase in precipitation, it is likely that average precipitation in subtropical dry regions will decrease.
- Under the RCP8.5 scenario, it is likely that average annual precipitation in Southern Africa will decrease.
- It is projected that winter rainfall areas in Southern Africa will have lower precipitation, due to GCMs predicting that climate change will result in the expansion of high-pressure systems over Southern Africa and cold fronts sweeping across the Southern Atlantic and Indian Oceans being pushed further southwards.

- It is projected that the intensity of variation in climate events related to the ENSO will increase.
- There is medium confidence that there will be an increase in the intensity and duration of droughts in Southern Africa. It is noted that trends in droughts need to be projected with a combination of results from both GCMs and localised drought indices, and there has been difficulty in projecting the trends in the occurrence of drought with certainty, especially at a local level, due to the lack of data or agreement on trends from models.

For the Western Cape, downscaled projections from GCMs show that it is almost certain that there will be an increase in temperatures over the region in future: in the order of 1.5 ºC to 3 ºC by 2040 - 2060 (WCG, 2016). However, the downscaling of projected precipitation is more complex and less certain. Most GCMs predict that there will be less rainfall over the region into the future, due to changes in mid-ocean high pressure systems and the movement and tracking of cold fronts further south. However, there is less consistency between models which downscale projections of rainfall across the region, due to the difficulty in modelling the impact of mountains and varying topography on rainfall. Resolving this will require further observation and research (WCG, 2016).

2.3 Droughts and water resource management

Droughts are one of the key issues of concern in water resources management. If not planned for or managed carefully, droughts can threaten water supply systems and result in supply failure, with severe consequences for the people and economies that rely on these systems. With rapid population and urbanisation globally, existing water supply systems are coming under increasing stress and there is a need to maintain reliable supplies in the face of increasing variability in climate and extreme weather events such as droughts. The ability to prepare for, manage, and prevent drought related water supply issues is therefore becoming increasingly important. Various aspects related to droughts and water resource planning and management are covered in the literature. This section outlines some of the main aspects.

2.3.1 Management aspects

Planning and management of water resources

Water resource systems which rely on surface water need to be designed and operated to manage the natural annual variation in inflows to storages. These systems should also be able to supply water during extended dry conditions, with stored water kept aside specifically for these drought periods.

Water rights and allocations from these systems should consider that some water needs to be reserved for use during dry periods. However, the drive for efficiency means that normal demand may utilise capacity reserved for dry conditions, or there may be hesitancy to augment a system when it is perceived that there is still excess water available in the current supply system (e.g., over-allocating a system instead of building a new water supply scheme).

Water supply systems also need to be built with operational redundancy and multiple sources to allow storages to be operated optimally, both in normal times to maximise storage, and during a drought to protect vulnerable sources.

Adequate planning and preparation for dry conditions or drought requires appropriate legislation and regulations to ensure that these plans and management principles are put together by water authorities, and that these plans can be implemented when droughts do occur.

Balancing supply and demand interventions

During a drought, it is important to consider both supply and demand-side measures in managing droughts (Turner, White, Chong, *et al.*, 2016; City of Cape Town, 2018). Sudden onset, severe droughts can cause water storages to deplete quickly, even if provision has been made for drought storage. New water augmentation schemes can deliver additional water at a large scale, but the design and construction of new infrastructure can have long lead times to implementation and first water delivery. Demand-side interventions therefore become critical as these can be implemented relatively rapidly, especially the reduction of discretionary usage normally targeted by water restrictions.

It can be difficult to decide on the approach to be taken in balancing of supply and demand-side interventions, especially at the start of a drought period. At this point, the magnitude and duration of the drought is unknown, and thus the level of intervention that will be needed to ensure that water supplies do not fail is also unknown. Deciding to build new supply infrastructure commits water authorities to often significant infrastructure capital and operating costs for many years into the future. There are many examples around the world of new supply infrastructure built in response to drought events, but were not finished before, or not required after, the drought ended. On the other hand, ongoing demand reduction measures, especially through restrictions, can have significant negative impacts on customers and economies.

These are difficult decisions that need to be made, especially when there are competing opinions and demands from politicians, the media, and the public. A combination of an approved clear drought response plan; demand-side measures; an adaptable plan for new supply infrastructure; clear communication with all stakeholders; and data and modelling, are all necessary for best managing the approach to responding to a specific drought event (Turner *et al.*, 2016).

Drought response plans and measures

In most locations around the world, droughts have occurred in history, and will likely occur again at some point in the future. The severity, duration and possible frequency of these events can be determined from an analysis of historical hydrological records. The likelihood of droughts occurring again at some point in the future can therefore be determined. Water authorities need to prepare drought response plans and have these ready for when a drought does occur. Politicians and the public often seem surprised when droughts occur, and about the measures that are needed to manage a drought. It is therefore important to communicate drought response plans to stakeholders when there is no drought, so that they are aware and agree with the measures that will be taken when droughts do occur (Santos Pereira, Cordery & Iacovides, 2009).

Without adequate drought management plans, responses to a drought will be chaotic and will take the form of crisis management, leading to ill-informed decisions on investment in supply and demand-side interventions that can have long term financial, societal, and economic costs. The lack of an adequate and coordinated response can lead to the failure of a water supply system, and a potential economic and humanitarian disaster (Santos Pereira *et al.*, 2009).

2.3.2 Supply aspects

Determining the onset of a drought

There is no standard definition of a drought. Several different drought indices have been developed to quantify and identify droughts. These indices often require specialist knowledge to develop, use and interpret. For these reasons, it is often difficult to determine when a drought has started and is occurring (Mishra & Singh, 2010).

This difficulty in determining the commencement, occurrence, extent, and severity of a drought can prevent timely, appropriate, or effective decisions being made on dealing with droughts, especially at the start of a drought period. A further complication is that during droughts and periods when there is a water crisis, decision making is generally made at a political level, and it can be difficult for non-technical decision makers to understand drought theory. During severe drought events, time lost in making appropriate decisions to augment supplies or reduce demand through restrictions can result in more extreme actions being required to ensure that water supplies do not fail, often at higher cost to water authorities and customers (American Water Works Association, 2017).

Diversification of water resources

Water supply systems have traditionally depended on surface or groundwater sources for drinking water supplies. In times of drought, the overreliance on these natural resources can become a major problem when these sources start depleting.

During the Millennium Drought in Australia, the water industry realised that water supply systems to the country's major cities were over reliant on surface water sources and therefore vulnerable to droughts. Water supply authorities invested significantly in alternative water supply schemes, and large-scale desalination plants were constructed in all the major cities. While this has reduced vulnerability to droughts in the short to medium-term, water charges to customers have increased to cover the costs of these non-surface water schemes, which are often more expensive to construct and operate compared to traditional surface water sources (Turner *et al.*, 2016). This underlines that diversification of resources to increase protection against the impacts of drought has a cost.

However, the construction of these diversified sources was not without controversy. An issue highlighted by the Australian experience during the Millennium Drought was that careful longer-term resource augmentation planning was disregarded by political decision-making in response to the drought crisis, and decisions were made to rapidly construct large-scale supply infrastructure, which ended up costing significantly more to implement, with many of the schemes not required after the drought had ended in 2010. This led to several of the plants being mothballed and only being required to start operating a few years later in response to growing demand and drier conditions (Turner *et al.*, 2016; DELWP, 2019; Seqwater, 2019).

There are a few interesting examples of countries and cities that have pursued the diversification of resources in response to water scarcity and security concerns.

The city of Perth, Australia, has experienced a clear, steady decrease in rainfall and streamflow into its surface water storages since the 1970's; the city now receives 20% less rainfall compared to averages before 1970. As part of a planned response to increase and diversify its resources, two desalination plants were constructed between 2004 and 2013, with a total production capacity of 195 Gℓ/year. Desalination now provides 47% of Perth's water requirements, significantly reducing its reliance on surface water and groundwater (World Bank, 2018). However, this significant decrease in reliance on rainfall dependent sources also reduces its vulnerability to rainfall variation and droughts. The costs of Perth's desalination plants were also lower per gigalitre than the plants built in the other capital cities of Australia, which suggests that a planned, measured approach to augmenting and diversifying water resources is a more cost-effective approach (AWA, 2014).

Singapore is another example of a city that has taken a planned approach to diversifying its water resources. One of the main reasons for this approach however is political – Singapore relies on the neighbouring country of Malaysia for a significant proportion of its water supplies through agreements, and this was considered a strategic vulnerability. As a result, Singapore took the decision to reduce its dependence on this imported supply by developing its own water sources. Singapore now has four different sources of water: seawater desalination; reclaimed water (called NEWater) from stormwater and wastewater; water from its own catchments; and water imported from Malaysia. By 2018, 55% of Singapore's water demand was provided by desalination and reclaimed water, and this is planned to increase to 85% by 2060 (World Bank, 2018). While Singapore has a tropical climate, it has also experienced periods of dry conditions and lower rainfall, and the increase in alternative water supplies also reduces its vulnerability to droughts and rainfall variation.

At the time of the start of the drought in Cape Town in 2015, the city received 98% of its allocated water from surface water sources and the balance from groundwater sources. With three years of low rainfall, and even with severe demand restriction measures in place, the capacity of the water storages supplying the city fell to just under 20% prior to the onset of the winter rainfall season in 2018. While dam levels have since improved, due to strict water restrictions and improved rainfall, the City of Cape Town has recognised that diversification of resources is key to increasing its water security, and the city plans to augment its supplies with a combination of desalination, water reuse for potable use, and groundwater schemes over the next decade (City of Cape Town, 2019).

2.3.3 Demand aspects

Water conservation and efficiency

Conserving water and improving the efficiency of water use and operation of water supply systems allows water authorities to maximise existing water resources, and to defer the need to augment water supply systems. The term *water use efficiency* refers to using less or the least amount of water possible for a particular purpose, while *water conservation* refers to reducing water usage or loss. Water conservation and efficiency initiatives differ from water restrictions; while all are intended to reduce water demand, water conservation and efficiency projects are more focused on the longer-term permanent reduction in water use, while water restrictions are short-term measures targeting rapid reduction in demand in response to droughts and other supply emergencies, such as infrastructure outages or water quality problems (AWWA, 2017).

Water efficiency and conservation measures can include:

- Leak detection and repair of water conveyance systems,
- Plumbing fittings and installations that use less water, such as pressure reducing, valves, low flow showerheads, and dual flush toilets,
- Use of water efficient appliances,
- More efficient irrigation practices, such as using drip irrigation systems,
- Using alternative water for non-drinking water purposes, including rainwater tanks, recycled wastewater and stormwater for irrigation and industrial use.

However, a concern with water efficiency and conservation is that it removes the seasonal, discretionary usage of water from drinking water demand, that is normally targeted by water restrictions during droughts (AWWA, 2017). Termed *demand hardening*, this reduces the ability to decrease demand through traditional water restriction measures in response to droughts and should be an important consideration in the drought response plans of water authorities.

Agricultural water use and efficiency

Agriculture is the largest user of water globally – estimated at about 70% of the total water use around the world. With population and economic growth, it is anticipated that agricultural output will need to increase by up to 70% by 2050 to meet the increased demand for food and agricultural products (FAO, 2011).

With the key role of water in agriculture, and the significant volume of water required, the sector is particularly vulnerable to drought, extreme weather, and variation in rainfall. This will be further exacerbated by the pressure that will be placed on water resources in future, with the combination of the impacts of climate change and the competing demands on water resources by a growing population for drinking water use. In the future, the agricultural industry will have to focus on more efficient irrigation methods; using technology to improve efficiencies; more co-ordinated use of surface and groundwater storages; and use of alternative or recycled water for irrigation. Improved use of rainfall and seasonal forecasting techniques could allow for more efficient use of water and appropriate crop selection (FAO, 2011). Improved collection and access to soil moisture data from drones and satellites could also aid more efficient irrigation.

2.4 The impacts of droughts around the globe

The United Nations Office of Disaster Risk Reduction (UNDRR) in its report The Human Cost of Weather-Related Disasters (2015), assessed the global impact and cost of natural disasters, including floods, storms, earthquakes, extreme temperature, landslides, droughts, wildfires and volcanic activity. Impacts and costs were assessed over a 20-year period from 1995 to 2015. The following were noted on the occurrence of natural disasters, and specifically on droughts:

- Of the 7130 natural disasters documented from 1995 – 2015, only 5% were due to droughts.
- By far, flooding and storms were the highest proportion of the number of natural disasters during this period, accounting for 71% of the events.
- However, drought events affected 1.1 billion people, which was 26% of the number of people affected by all natural disasters.
- Drought events resulted in the deaths of 22,000 people, which represented 4% of the total number of deaths due to natural disasters.
- Droughts accounted for economic damages of US$100 billion, or 4% of the total estimated damages over the period.

The World Meteorological Organization (WMO) in its publication, the Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (2014), assessed the impact and cost of weather and climate related natural disasters during the period 1970 to 2012, in six continental regions. The study ranked, per continental region, the ten natural disasters that caused the greatest number of deaths, as well as the ten disasters that caused the most economic damage.

Figure 2.6 indicates globally the number of events, deaths and estimated economic losses per disaster type.

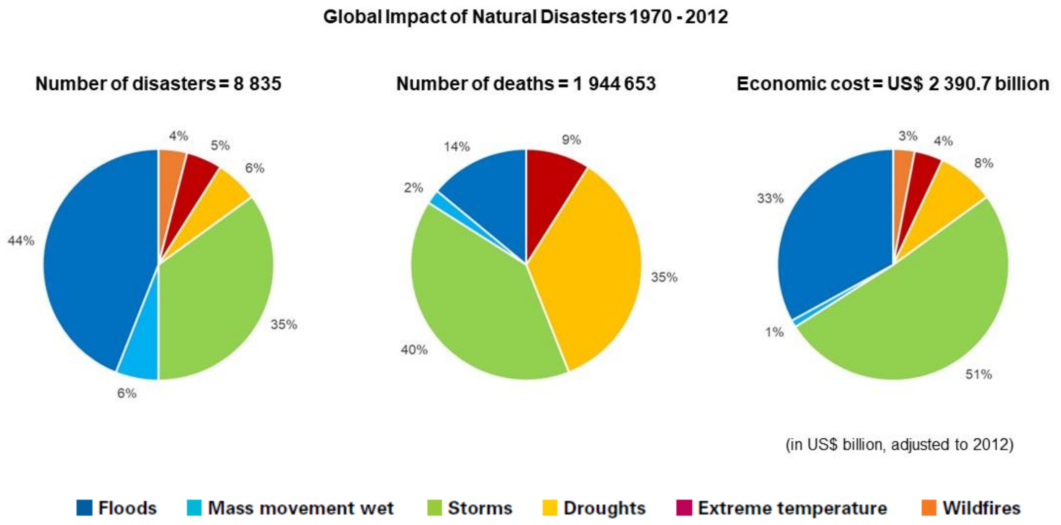


Figure 2.6: Global impact of natural disasters 1970 - 2012 (WMO, 2014)

A disproportionate number of the fatalities due to droughts occurred in the African countries of Ethiopia, Sudan, Mozambique, and Somalia during the 1970s and 1980s. While resulting from droughts experienced, it also suggests that these countries did not have the necessary systems in place to manage the drought and its impacts on their affected populations.

Besides some regions being more prone to droughts than others, the results of this study also illustrate that the social, infrastructure and governance systems of a country are critical in being able to manage a severe drought.

These statistics indicate that while storms and flooding result in significant human and economic costs, droughts impact on a significant number of people per event. This is likely due to droughts, and the effects of these events, lasting for months to years, with the impacts often being felt over large regions.

2.5 The 2015 – 2020 droughts in Cape Town

Cape Town, and the south-western region of South Africa, during 2015 – 2020 experienced severe droughts which rapidly depleted its water supply system storages and resulted in crisis management of the event. After three consecutive years of low rainfall and inflows into water storages from 2015 to 2017, the storages of the WCWSS declined rapidly, falling to around 20% before the start of winter 2018. The three years of declining storages triggered a significant response, that included an emergency augmentation build program, the implementation of water restrictions to curtail demand, operational and customer water conservation and efficiency measures, a steep increase of water tariffs, and an extensive communications campaign (City of Cape Town, 2018). There was significant concern amongst politicians, the media, and the public about Cape Town becoming the first major city in the world to run out of water. Improved rains from 2018 to 2020 resulted in storages recovering, and restrictions were progressively lifted. However, the event should serve as a good learning experience on drought preparedness and the appropriate response to a severe drought event.

Rainfall and inflow

While there were various causes of the water crisis itself, the primary cause was a period of low rainfall and inflows into the major storage dams of the WCWSS.

For the Steenbras and Wemmershoek catchments, where three of the six major storage dams of the WCWSS are situated, the rainfall averages over the three hydrological years from 2014/15 to 2016/17 were 38% and 26% lower than the long-term averages. These are illustrated in Figures 2.7 and 2.8.

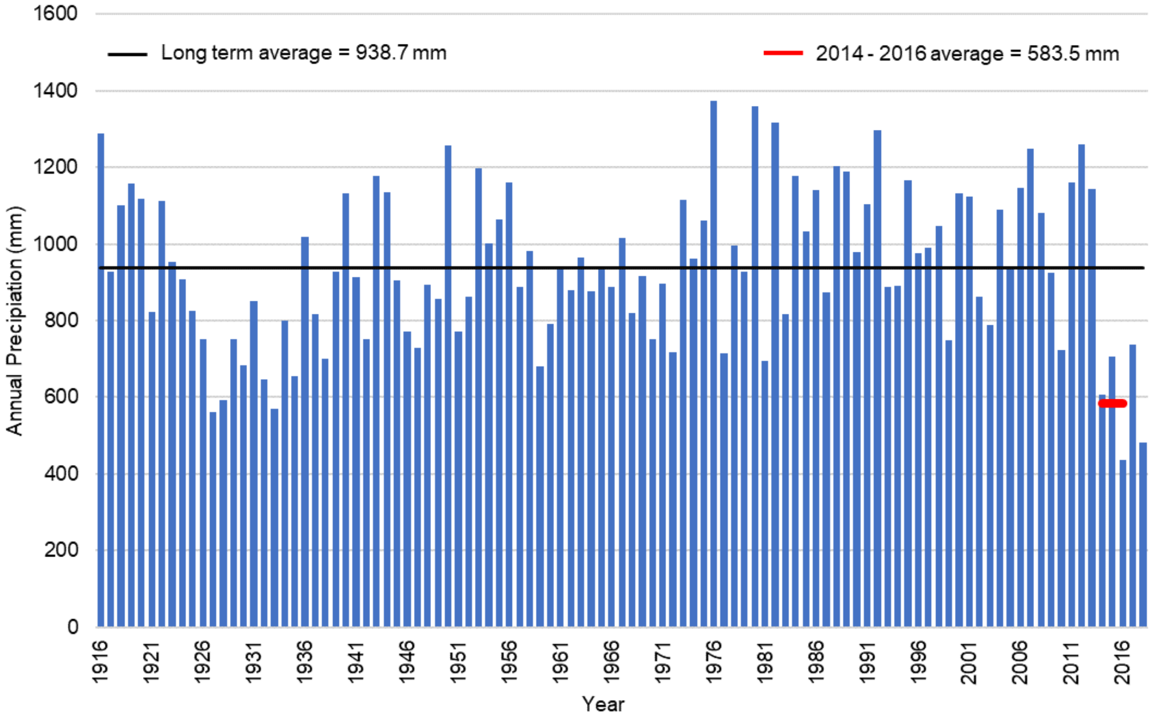


Figure 2.7: Steenbras catchment annual precipitation 1916 - 2018 (CCT, 2018)

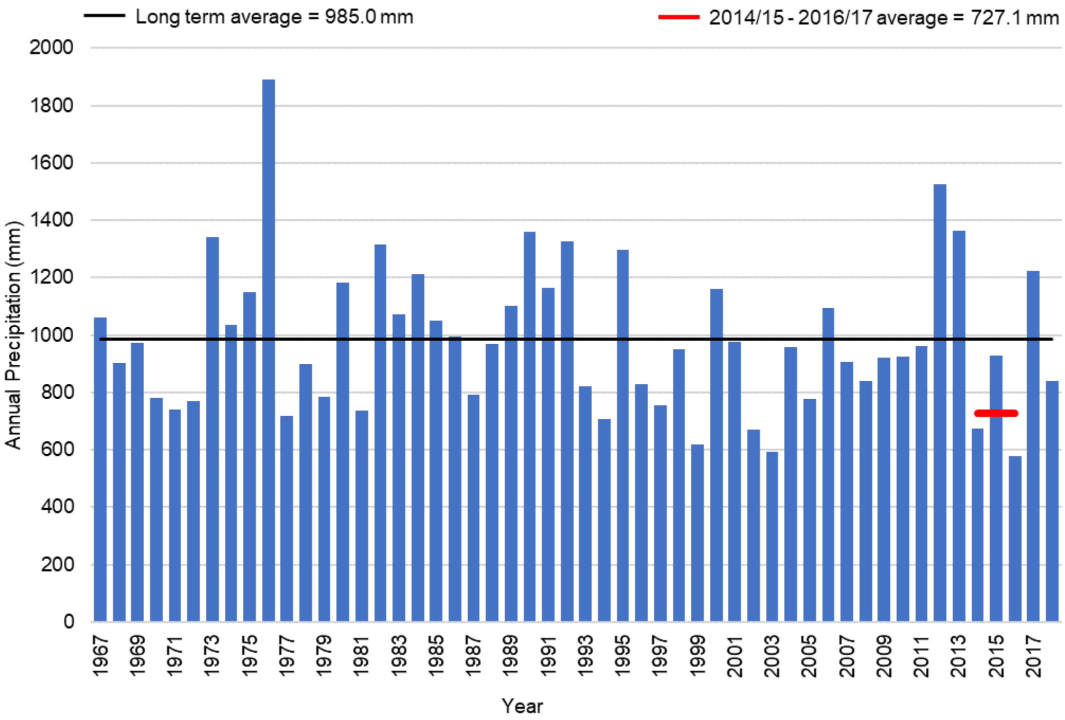


Figure 2.8: Wemmershoek catchment annual precipitation 1967 - 2018 (CCT, 2018)

The consecutive years of lower-than-average rainfall resulted in a 46% decrease in the inflows into the major storage dams over the 2014/15 – 2016/17 hydrological years. Figure 2.9 shows the low inflows into the storage dams of the WCWSS during these years (City of Cape Town, 2018).

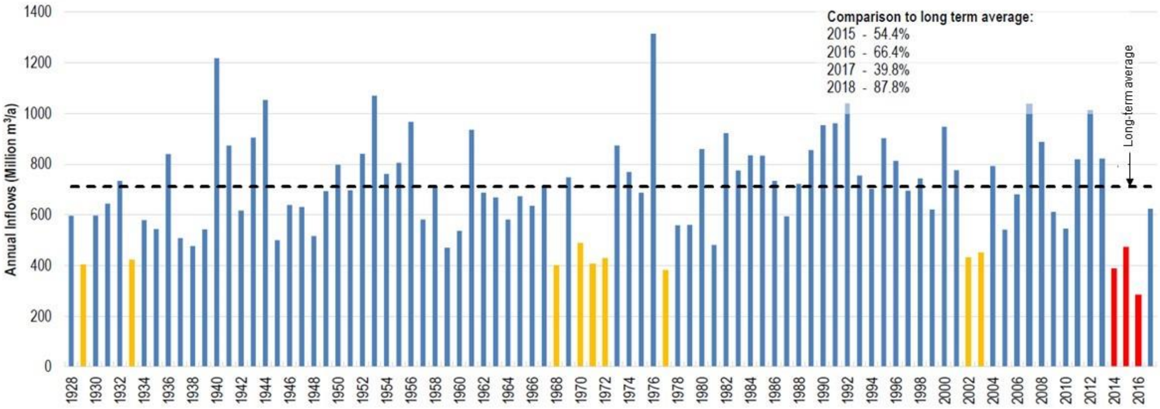


Figure 2.9: Estimated inflows into the WCWSS storages 1928 - 2017 (CCT, 2018)

Dam levels

As a result of the lower-than-average rainfall and inflows, the levels of the six major storage dams declined rapidly. At the end of the 2014 winter rainfall season, storages were full, but by the end of the winter of 2017 after a third consecutive year of low rainfall and inflows, storages only peaked at 38% and declined to 20% before the onset of winter rains in 2018 (City of Cape Town, 2018). Figure 2.10 shows a 12-year plot of the daily dam levels, illustrating the rapid decline of storages from 2015 – 2018.

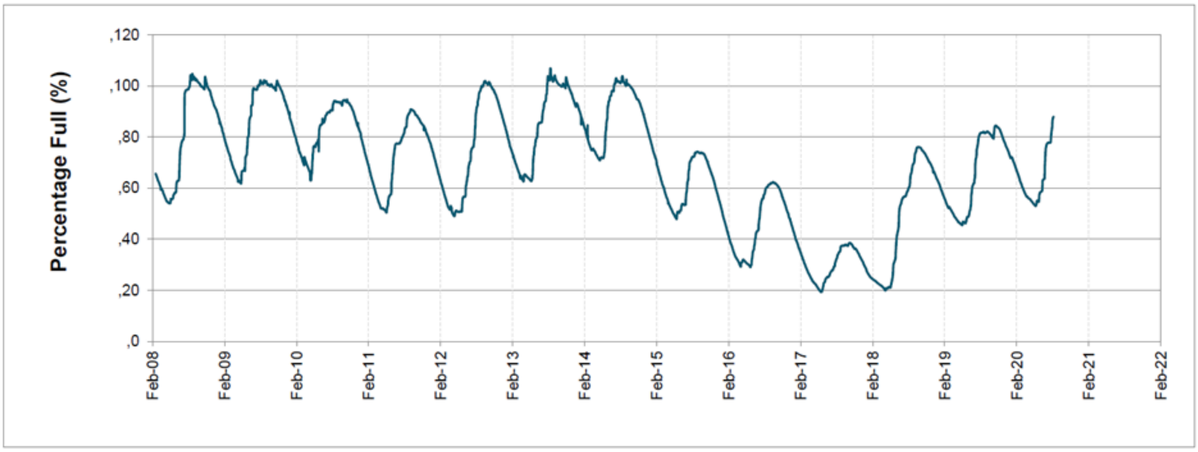


Figure 2.10: Storage levels of the WCWSS from 2008 – 2020 (from CCT, 2018)

This rapid decline in storages led to the implementation of progressively stricter water restrictions and water conservation measures over the three years.

Response to the drought

The low rainfall and inflows and declining dam levels resulted in restrictions being implemented on both urban water and agricultural users.

At the start of 2016, the City of Cape Town along with other municipalities in the WCWSS supply area implemented voluntary 20% restrictions on total usage from the system. It was only by September 2016 that the national Department of Water and Sanitation (DWS) implemented mandatory restrictions of 20% on both urban and agricultural users. In September 2017, mandatory restrictions were increased to 40% for urban users and 50% for agricultural users, and rapidly increased to 45% and 60% respectively by December 2017.

The City of Cape Town is the largest user of water from the WCWSS, using around 65% of the total annual yield of the system, and the City meeting its target was critical to ensure that water supplies did not fail. The City initially implemented restrictions limiting discretionary usage such as irrigation, but progressively had to start targeting the reduction of indoor usage by setting a target water consumption per household – by February 2018, this target was set at 50 litres per person per day, and 10.5 kilolitres per household per month. The restrictions resulted in Cape Town's average demand dropping from around 950 megalitres per day before restrictions, to around 450 megalitres per day during 2018.

By the end of winter 2018, with a combination of receiving improved rainfall and the restriction of both urban and agricultural demand, the WCWSS storages had recovered to around 75%. By December 2018, the DWS reduced restrictions to 10% on both urban and agricultural users from the WCWSS. Due to concerns around whether the drought had yet ended, the City opted to retain a 30% restriction on its demand going into the 2018/19 hydrological year.

By the end of winter 2019, the combined storages of the WCWSS had recovered to around 85%.

Discussion of the event

Numerous opinions and commentaries were published by climate and water industry professionals and researchers on the causes and impacts of the event.

Muller (2018) believed that planning for augmentation of the WCWSS had not adequately addressed underlying population growth. He argued that augmentation of the system was deferred due to the assumption that success of the City of Cape Town's WDM program had permanently reduced demand, but that good rains prior to the drought had concealed demand growth, resulting in a sudden spike in demand in the first year of the drought. Other issues were also highlighted, including the DWS failing to implement mandatory restrictions on urban and agricultural users in the first year of the drought, and that there was over-allocation from the WCWSS to certain agricultural and urban users. Further to this over-allocation of the WCWSS, the DWS (2016) also determined that the usage from the system was approaching its safe yield. All these factors together contributed to the rapid decline in the system storage before strict water restrictions took effect and curbed the demand on the storage dams.

Taing *et al.* (2019) pointed to Cape Town's reliance on surface water as a cause of the crisis, and suggested that transitioning to diversified water sources and implementing water sensitive design principles would assist in reducing the exposure to similar conditions in the future. The authors also highlighted that while Cape Town received most of the political and media attention (and criticism) due the water crisis, nearly half of the country was also experiencing similar conditions and that three provinces had been declared disaster areas due to the drought.

Ziervogel *et al.* (2019) provided a useful and comprehensive account of the response to drought, through personal observation and interviews with government officials and water industry professionals who were directly involved. The conclusions highlighted that governance of the water sector needed to be strengthened, and that management of the water supply system needed to be more adaptive to both deal with the crisis more effectively, as well as to manage the system effectively in the future.

Wolski (2018) analysed a limited set of rainfall records and estimated that the annual recurrence interval of the 3-year drought event was 311 years, concluding that regardless of the confounding issues around the management of the crisis, it was a rare and severe event and that water resource managers were always going to struggle to manage such an event.

A problem consistently experienced during the drought was the lack of readily available information on the severity of the event that was occurring. The initial discussions at the end of 2015 were informed by the failed 2015 winter filling season. Even with the sophisticated modelling of the WCWSS by the DWS using its hydrological software, the lack of information on the severity of the drought meant that decisions by the DWS, CCT and other stakeholders lacked context with the seriousness of the situation. This is evidenced in the DWS not taking a decision until September 2016 to implement formal restrictions on both urban and agricultural users, by which time agriculture had been allowed to use water unrestricted through the first year of the drought.

2.6 Defining and quantifying drought

To enable the analysis of droughts in the WCWSS, drought events must be defined, and acceptable methods need to be used to quantify droughts. This section will summarise how droughts are defined and quantified.

2.6.1 Defining droughts

The start, duration, intensity, and end of a drought is often difficult to determine. A drought can often only be determined with hindsight – the onset of a dry period does not necessarily mean that a drought is occurring, and it may only be after a low level of rainfall has occurred over a certain period or season, that the occurrence of a drought can be confirmed.

Droughts are not the same as arid conditions. Arid climates are normally dry, whereas droughts are periods of lower-than-normal precipitation. Droughts can occur in all types of climates; however, droughts in a climate that experiences typically low rainfall will be different to a region that receives seasonal rainfall.

Drought definitions are either conceptual or operational. Conceptual definitions are based on general descriptions of droughts, whereas operational definitions aim to quantify droughts in terms of start, duration, and end. The analysis of severity, duration, and frequency of droughts utilises these operational definitions. Operational definitions are often described and quantified through various drought indices. Common indices used for quantifying droughts are covered in more detail in Section 2.6.3.

There are numerous general definitions of a drought, often based on the context for which the definition is being used for. A few examples are:

- The World Meteorological Organisation (WMO) defines a drought as: 'an insidious natural hazard that results from lower levels of precipitations than what is considered normal' (WMO, 2012).
- The United Nations Food and Agriculture Organisation (FAO) defines a drought as occurring when "rains fall below a long-term average precipitation in a given place" (FAO, 2019).
- The United Nations International Strategy for Disaster Reduction (UNISDR), in association with the National Drought Mitigation Centre (NDMC), defines a drought as "a deficiency of precipitation over an extended period of time, usually a season or more, which results in a water shortage for some activity, group, or environmental sectors" (UNISDR, 2009).

Wilhite and Glantz (1985) reviewed the drought literature, and found that drought definitions are covered by four different categories:

Meteorological droughts

Meteorological droughts are defined according to the extent to which precipitation is lower than normally received. Meteorological droughts are the most common type of definitions used, in part because meteorological data is generally the most widely measured and recorded information available for drought monitoring and analysis. Because climate and precipitation patterns vary significantly between regions around the world, many different definitions have been developed and are used in different countries.

Hydrological droughts

Hydrological drought definitions are focused on the impacts of dry conditions on surface water and hydrology, rather than meteorological aspects. Hydrological drought definitions will utilise hydrological characteristics such as streamflow, catchment runoff, and snowmelt to quantify droughts. One problematic aspect of assessing hydrological droughts is that hydrology information such as streamflow is often not as widely measured and recorded as meteorological data. It is also often difficult to separate out the impacts of development and human-related activities in catchments and on streamflow, which is an issue when needing long records for analysis of severity, duration, and frequency of droughts.

Agricultural droughts

Agricultural drought definitions combine aspects of meteorological drought definitions with agricultural factors such as soil moisture, groundwater levels and evapotranspiration levels. These drought definitions are more focused on the assessment of the impacts of droughts for the planning and managing crops and are therefore more useful in applications related to the agricultural sector.

Socio-economic droughts

Socio-economic drought definitions combine features of meteorological, hydrological, and agricultural droughts, but use these to quantify the impacts of droughts on societies and economies. By considering human-related impacts, socio-economic drought definitions consider aspects of both water supply and demand. As such, the use (and over-use) of water by societies can influence the determination of a socio-economic drought. Because the aspects analysed in this type of drought definition involve various concepts and measures from different disciplines, it is a complex drought to quantify.

2.6.2 The propagation of droughts through the water cycle

Changnon (1987) described the propagation of the effects of droughts (and floods) through the water cycle.

The complex interactions of the movement of water through the atmospheric and surface water systems results in the delay of the impact of drought events through the various parts of the water cycle. This propagation of drought effects is illustrated in Figure 2.11.

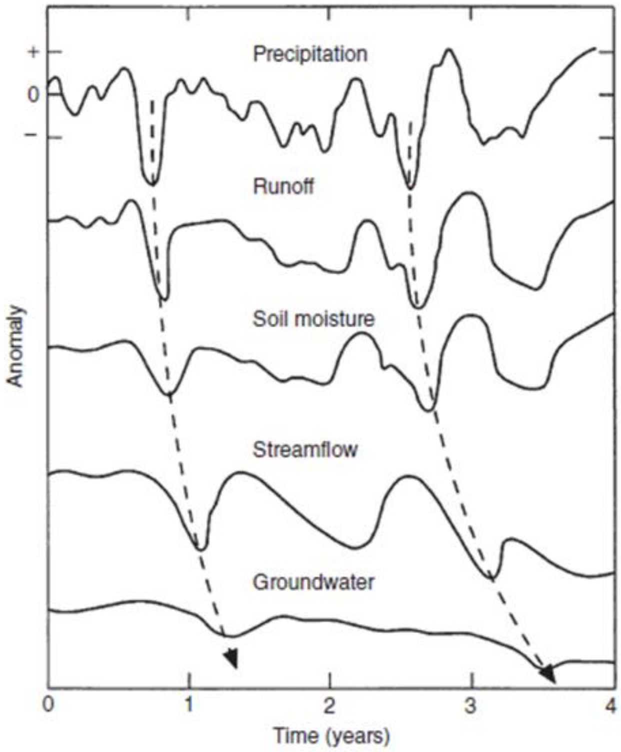


Figure 2.11: Propagation of droughts through the water cycle (Van Loon, 2015)

Droughts start with a period of deficiency in precipitation over an area or region. Drought periods can often coincide with warmer than average temperatures, which can exacerbate the impact of reduced precipitation. Over time, these conditions lead to the drying out of soils, and the lowering of the water table, which can lead to the failure of crops and vegetation dying. Lower precipitation, combined with drier surface soil layers, results in reduced catchment runoff and streamflow. The reduced soil moisture and water table causes a slower recharge of groundwater, resulting in the lowering of groundwater levels. This impact on groundwater levels is attenuated, therefore resulting in a lag between the onset of a meteorological drought and its impact on groundwater levels. In some catchments, rivers and streams are partially groundwater fed, and therefore the lowering of groundwater levels can also reduce streamflow. Consequently, this can also contribute to the lag time in the impact on catchment streamflow.

The lag in the propagation of droughts through the various parts of the water cycle will be seen when measuring the various categories of droughts outlined in the previous section, i.e., meteorological, hydrological, agricultural, and socio-economic droughts. Water resource planners and managers should be aware of this when using a drought index using one of these drought definitions, or when analysing or assessing the impact of a drought.

2.6.3 Drought indices

Drought indices are used to numerically quantify droughts, which is used to assess aspects of droughts such as severity, duration, and spatial extent. Numerous indices have been developed since the mid-twentieth century; some are applicable for assessing droughts for certain uses or sectors of the economy, while others have become more widely used in specific countries or regions.

Precipitation is the most common hydrological variable used in drought indices, either as the only input variable, or together with other meteorological or hydrological variables such as temperature and soil moisture (Mishra & Singh, 2010).

The more frequently utilised drought indices are described below.

Standardised Precipitation Index

The Standardised Precipitation Index (SPI) was developed by McKee *et al.* (1993). While developed as a method to assess droughts, the index can be used to quantify the deviation of both wet and dry periods from normal. A historical precipitation record is the sole input variable into the calculation of the index.

The SPI for a specific location is calculated by fitting the long-term precipitation record for that location to a probability distribution. A probability distribution is calculated for each month of the long-term precipitation record. As most precipitation records are not normally distributed, this probability distribution is transformed, using an appropriate function, to a normal distribution with a mean of zero and a standard deviation equal to one (McKee et al., 1993).

The SPI can quantify droughts over different time scales, normally in periods of 3, 6, 12, 24 or 48 months. The various time scales are more suited to measuring drought impacts on different types of water uses. The shorter time periods such as 3 and 6 months are more suited for assessing agricultural drought impacts, whereas the longer-term periods such as 12 to 24-months are more suited to measuring the impacts of droughts on water resources and water supply systems.

The SPI values used to quantify a drought are indicated in Table 2.1.

Table 2.1: SPI values and associated drought categories

SPI Values	Drought Category
0 to -0.99	Mild drought
-1.00 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
≤ -2.00	Extreme drought

The SPI is one of the most widely used indices in drought monitoring and research (Van Loon, 2015). Its main strengths are: (1) that it is standardised for location, which allows droughts to be spatially compared, and (2) it can be determined for different time scales appropriate for the type of drought being assessed. A further advantage is that as precipitation is the only input variable, it is a simpler index to calculate than others that require multiple meteorological and hydrological variables. However, the lack of other variables can also be a disadvantage, as no temperature or evapotranspiration component can be calculated, which can be beneficial information, especially for the agricultural sector (WMO, 2012).

Limitations identified are that the record length and the type of probability distribution can significantly impact on the SPI values calculated (Mishra & Singh, 2010).

The Standardised Precipitation Evapotranspiration Index (SPEI) is an extension of the SPI and includes an assessment of the effect of temperature on a drought through determining evapotranspiration (Vincente-Serrano *et al.*, 2010). The use of the SPEI however is more complex as it also requires temperature data, in addition to precipitation.

The SPI and SPEI have been widely used in drought research in South Africa. Naik and Abiodun (2019) used the SPI and SPEI to analyse the projected changes in drought characteristics over the Western Cape. Botai *et al.* (2017) used the SPI to assess drought characteristics over the Western Cape Province, for the period 1985 to 2016. Botai *et al*. (2016) used the SPI and SPEI to analyse the characteristics of drought in the Free State and North West Provinces. In its Monthly Drought Bulletin, the South African Weather Service publishes 12- and 24-month SPI maps (SAWS, 2021).

The WMO has recommended that the SPI be used globally by meteorological and hydrological institutions to quantify meteorological droughts, alongside other indices currently used by these institutions (WMO, 2012).

Palmer Drought Severity Index

The Palmer Drought Severity Index (PDSI) was developed by Palmer (1965). While developed as a method to assess droughts, similarly to the SPI, the index can be used to quantify both wet and dry periods. Precipitation and temperature are its input meteorological variables.

The index is essentially a water balance calculation, that considers and determines precipitation, soil moisture and evapotranspiration. The method determines a theoretical precipitation at a certain location, using historical meteorological data, by calculating a soil moisture balance which considers evapotranspiration, the ability of soils to retain or store water, and runoff. The comparison of the calculated and actual precipitation at the specific location gives an indication of the extent of wet or dry conditions being experienced (Alley, 1984).

A standardisation process allows the extent of dry or wet conditions at different locations to be compared, as well as the start and end of a drought. The extent of the deviation from normal precipitation is expressed as a dimensionless number – the PDSI value; the index values and the corresponding extent of wet or dry conditions are shown in Table 2.2. The calculation of the standardised index between different locations uses a coefficient that is determined empirically for the location being assessed (Palmer, 1965).

Table 2.2: PDSI values and associated drought classifications

PDSI Index Value	Classification of event
≥ 4.00	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.50 to -0.99	Incipient drought
-1.00 to -1.99	Mild drought
-2.00 to -2.99	Moderate drought
-3.00 to -3.99	Severe drought
≤ -4.00	Extreme drought

The index is widely used in the USA for drought monitoring and analysis. The USA government agency NOAA publishes monthly maps of the PDSI on its website.

Various limitations of the use of the PDSI for drought monitoring and analysis have been identified:

- The methodology used to produce the standardised index values is complex, uses arbitrary rules and empirically derived values, and is not statistically robust (Alley, 1984).
- The PDSI was developed and calibrated for use in the USA. While the index has been applied elsewhere, for use in other regions or countries the index must be re-calibrated (Van Loon, 2015).
- The fundamental methodology and fixed analysis period of the PDSI lends itself to monitoring and assessing agricultural droughts, rather than hydrological droughts (Mishra & Singh, 2010).

Crop Moisture Index

The Crop Moisture Index (CMI) was developed by Palmer (1968), to address limitations of the PDSI. The CMI was developed specifically for use in the agricultural sector in the US, focused on the major crop producing regions of the country. The index is used to assess short-term changes in meteorological and soil moisture conditions. Precipitation and temperature are the input variables to the calculation of the index (IDMP, 2018).

The US Department of Agriculture (USDA) and the US Department of Commerce (USDC) publish the Weekly Weather and Crop Bulletin, which includes a map of CMI values across the country.

The CMI is more suited for short-term agricultural planning and management, rather than longer-term drought monitoring (Mishra & Singh, 2010).

Surface Water Supply Index

The Surface Water Supply Index (SWSI) was developed by Shafer and Dezman (1982) as a way of including surface water supplies as a variable in a drought index. While it is useful to include surface water storage, it is not a standardised index: every water supply system is unique, and the weighting of the variables comprising the index is not fixed. The lack of standardisation makes this a less useful index.

2.6.4 Severity, duration, and frequency relationships

As discussed in Section 2.6.3, droughts are multi-faceted and need to be quantified in terms of severity, magnitude, duration, and extent. Various indices commonly used were outlined.

However, as raised by McKee *et al.* (1993) when deriving the SPI, water resource managers and decision makers find it valuable to understand the return period of a drought event being experienced.

The concept of a return period is widely used in engineering in design, operation, and asset management. In water engineering, it is widely used in applications such as stormwater and flood management, water resources management and operation, and the design of hydraulic structures. The concept is useful in quantifying events which are random and unpredictable, such as precipitation, flooding, and drought.

Return periods of floods are quantified in intensity, duration, and frequency (IDF) curves. The equivalent for drought management are severity, duration, and frequency (SDF) curves, which relate the return periods of droughts to duration and severity. SDF curves have been developed by Rahmat (2015) for the state of Victoria, Australia, and by Juliani & Okawa (2017) for the region of Minas Gerais, Brazil. This review did not find literature that showed the development of SDF curves for use in South Africa.

Droughts (and floods) are the extremes of meteorological or hydrological records. Water resource engineers are interested in understanding what the potential extreme values for rainfall or streamflow could be – these values are needed, for example, to design and operate water supply infrastructure or design hydraulic structures. As most rainfall or streamflow records are not long, it is likely that these records will not include extreme events that could possibly occur at a given location. Statistical methods, such as fitting records to probability distributions, are used to estimate possible extreme events that may be occur at a location, including the magnitude and expected return periods of these events.

The derivation of return periods for flood and drought events requires knowledge of statistical frequency analysis techniques. IDF and SDF curves allow water resource managers and decision makers information to manage extreme events, without the detailed statistical knowledge required to derive the curves.

SDF curves can provide important information for the design, planning and operation of water supply systems, and can be especially critical in decision making during drought events.

2.7 Summary of literature review

This literature review suggests that:

- Droughts are significant natural disasters that can have large scale detrimental impacts on people, communities, economies, and the environment.

- Climate change research suggests that rainfall trends over the area of the WCWSS will change in the future, with the frequency of extreme climate events such as flooding and droughts increasing.
- Cape Town has experienced periods of droughts in its history, but the droughts experienced during 2015 – 2020 had significant impacts on the city and its surrounding region. The responses to the droughts and the manner in which these were managed suggests that water resource managers could benefit from additional information on droughts that could be used to assess and index current rainfall events being experienced, which could assist with more timely and appropriate decisions being made on water supply system planning and operations.
- Drought indices are used to quantify droughts, and these are normally expressed using multiple variables, including intensity, severity, duration, and spatial extent. Various indices are used, requiring different data sets as input.
- Water resource managers, hydrologists and water engineers use the concept of return periods to understand how often an event of certain magnitude could occur in the future. This is, e.g., used in flood hydrology to design structures, used by hydrologists to understand the how often an extreme flow event could be expected to occur, and used by water resource managers to manage the risk of droughts when calculating supply system yields and allocations when designing and operating water supply systems.
- Severity-duration-frequency curves determine the relationship between the severity and duration of droughts, with the expected return periods with which these droughts are expected to occur. Information on these relationships can assist water resource managers to quantify drought conditions and make appropriate decisions on system planning and operation.

3. METHODOLOGY

This section discusses the methodology that was applied in the drought analysis and the development of the threshold values and SDF curves that were done as part of this research. As the research was focused on the supply area of the WCWSS, Section 3.1 describes the layout, components, and operation of the WCWSS; the catchments of the major dams of the system; and the location and potential sources of precipitation data that could be used for drought analysis for the WCWSS area. Section 3.2 provides a discussion of how the Standardised Precipitation Index (SPI) was selected as the drought index used in this research and how the SPI was used to index droughts. Section 3.3 covers the methodology used for developing the threshold values and SDF curves. The mapping of the threshold values and SDF curves is summarised in Section 3.4. A summary of the methodology that was applied in the research is provided in a flowchart in Section 3.5.

3.1 Focus area of the research

The focus of this research was on applying a drought index and developing SDF curves specifically for the Western Cape Water Supply System (WCWSS) area. The results of the research were used to index and quantify droughts in the WCWSS area.

The WCWSS supplies Cape Town with approximately 97% of its drinking water, through water storage in the six major dams of the system (DWAF, 2003). Almost all of Cape Town’s water is sourced from the WCWSS, which is solely reliant on surface water. An understanding and quantification of the drought impacts on the WCWSS is important in assessing the drought impacts on Cape Town’s water supply.

The WCWSS is a system of dams, weirs, abstraction works, tunnels, pipelines and pumpstations that supplies water to urban areas and irrigators in the Berg River, Eerste River and part of the Riviersonderend catchments in the Western Cape (DWAF, 2003). The infrastructure is part owned by the national Department of Water and Sanitation (DWS), and part owned by the City of Cape Town (CCT). The WCWSS supplies water to the greater Cape Town metropolitan area, South Africa’s second largest city by population. The WCWSS also supplies water to several towns and urban areas surrounding Cape Town, including Stellenbosch, Paarl, Tulbagh, Franschhoek, Saldhana Bay, Villiersdorp and Malmesbury. By 2016, approximately 65% of the unrestricted water allocation from the WCWSS was to urban and industrial consumers (DWS, 2016).

The WCWSS also supplies water to the agricultural sector and irrigators in the Berg River water management area (WMA), as well as irrigators in the Breede River WMA. The agricultural sector is an important part of the economy of the south-western region of the Western Cape and includes the farming of grapes and production of wine, fruit, winter crops such as wheat and barley, poultry, and livestock (Pegram & Baleta, 2014). By 2016, approximately 35% of the water allocation from the WCWSS was to irrigators and the agricultural sector (DWS, 2016). Figure 3.1 indicates the extent of the WCWSS area (DWS, 2016).

The south-western region of the Western Cape has a Mediterranean climate, experiencing hot, dry summers and cooler, wet winters. During winter, storms and rain are brought by cold fronts sweeping across the region from the Southern Ocean. These storms result in the wetter winter season being the primary period of the year during which the WCWSS storage dams are filled. During summer, high pressure systems over the Atlantic and Indian Oceans move south and prevent fronts from the Southern Ocean reaching the region. This results in summers being hot and generally dry.

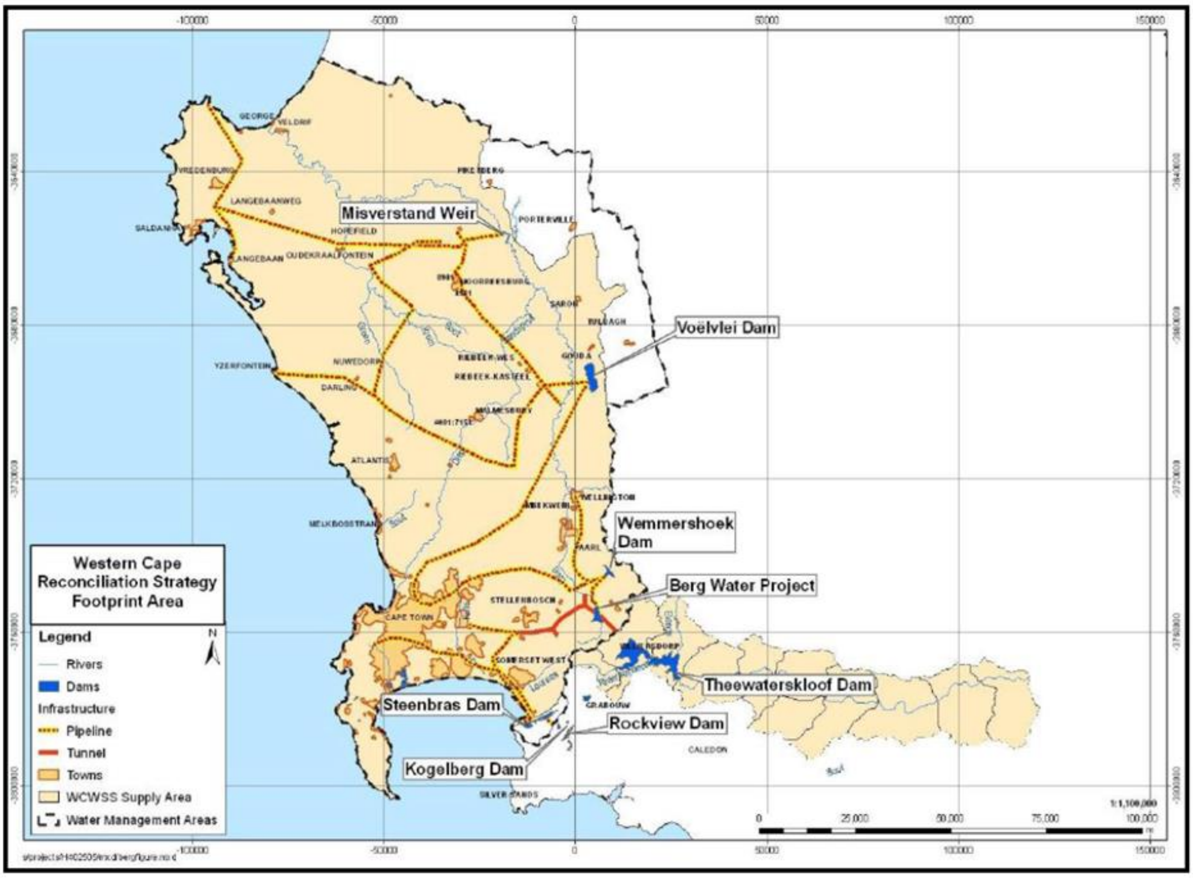


Figure 3.1: Map of the WCWSS (DWS, 2016)

Due to the variation in seasonal rainfall experienced, the region requires a system of large dams to store high runoff in the winter months, for use during the year, especially during the hotter, dry summer months when demand is normally higher.

There are six major storage dams in the WCWSS, with a total storage capacity of 898 million m^3 of water. Table 3.1 lists the individual dams and their respective storage capacities. Most of the six major dams harvest water from the catchments in which they are situated. The exception is Voëlvlei Dam, which is an off-channel storage dam. Water is transferred to Voëlvlei Dam from the Klein Berg and 24 Rivers, via abstraction works and open channels (DWAF, 2003).

Table 3.1: Major storage dams of the WCWSS (DWAF, 2003)

Dam	**Capacity (million m^3)**	**Owned by**
Berg River	130	DWS
Steenbras Lower	32	CCT
Steenbras Upper	34	CCT
Theewaterskloof	480	DWS
Voëlvlei	164	DWS
Wemmershoek	59	CCT
Total Storage	**898**	

In the Berg Water Availability Assessment Study completed in 2008, the Water Resource Planning Model (WRPM) was used to calculate the 1:50 year stochastic yield of the WCWSS to be 596 million m^3/a. This included an additional yield of 19 million m^3/a that could be realised if all the dams of the WCWSS were operated and managed in an integrated way to maximise storage and reduce spillage. A preliminary update of the WCWSS yield in 2015 using the Water Resource Yield Model (WRYM) indicated that the system yield was potentially lower, at 570 million m^3/a.

Table 3.2 lists the allocations and actual usage from the WCWSS by the various users in 2014/15, which was before the drought of 2015 – 2019, during which significant restrictions were placed on urban and agricultural water use. Actual total usage from the WCWSS in 2014/15 was 547 million m^3/a, although it should be noted that total allocation at the time was 609 million m^3/a. This indicated that the unrestricted allocation from the system had exceeded the system yield.

Table 3.2: Unrestricted allocations and water usage from the WCWSS (DWS, 2016)

User/Sector	**Unrestricted allocations (2014)**	**Water use (2014)**
CCT	358	335
Other urban	35	43
Agriculture	216	170
Total	**609**	**547**

The WCWSS is operated with the principle of maximising yield and minimising loss of water through spills (DWAF, 2003). With a variable climate, often experiencing varying levels of rainfall in the harvesting catchments, and therefore different relative storage levels in dams at the end of the winter filling season, it is the ability of the CCT's bulk water supply network to shift water demand (within certain limitations) to different storage dams during the hydrological year to meet the operating principles of the system. Due to the shared ownership and operation of the WCWSS, the planning and operation of the system has been done cooperatively between the various stakeholders in the water sector in the region. The longer-term planning and operation of the WCWSS was captured in 2007 in the WCWWS Reconciliation Strategy Study (DWS, 2007). Since its completion, the implementation of the study was overseen by a Steering Committee, comprising representatives from the DWS, CCT and other water users and stakeholders in the region (DWS, 2016).

The DWS's WRPM and WRYM are used to model the annual operation of the WCWSS, including the need to implement water restrictions. In practice, to plan and manage the operation of the WCWSS, the models are run annually in October/November, when the filling season is finished and there is certainty on what the available storages are for the coming hydrological year. While the models are sophisticated tools that use stochastically generated multiple rainfall and runoff sequences to model the range of possible short to medium term storage response of the WCWSS, it is still only a decision support system. The decision on how to operate the system, whether to implement restrictions, and what level of restrictions are to be implemented, are still decided by the DWS, stakeholders that own and operate the system, and users of water from the system. Ultimately, while planning is done collaboratively, it is the responsibility of the DWS to formally decide and implement restrictions in the WCWSS supply area (Water Act, 1998).

The scope of analysis and determining of SDF relationships for this research was limited to the supply area of the WCWSS. To aid the decision-making by water resource managers, it also focused on precipitation records in the catchments of the major storage dams of the WCWSS.

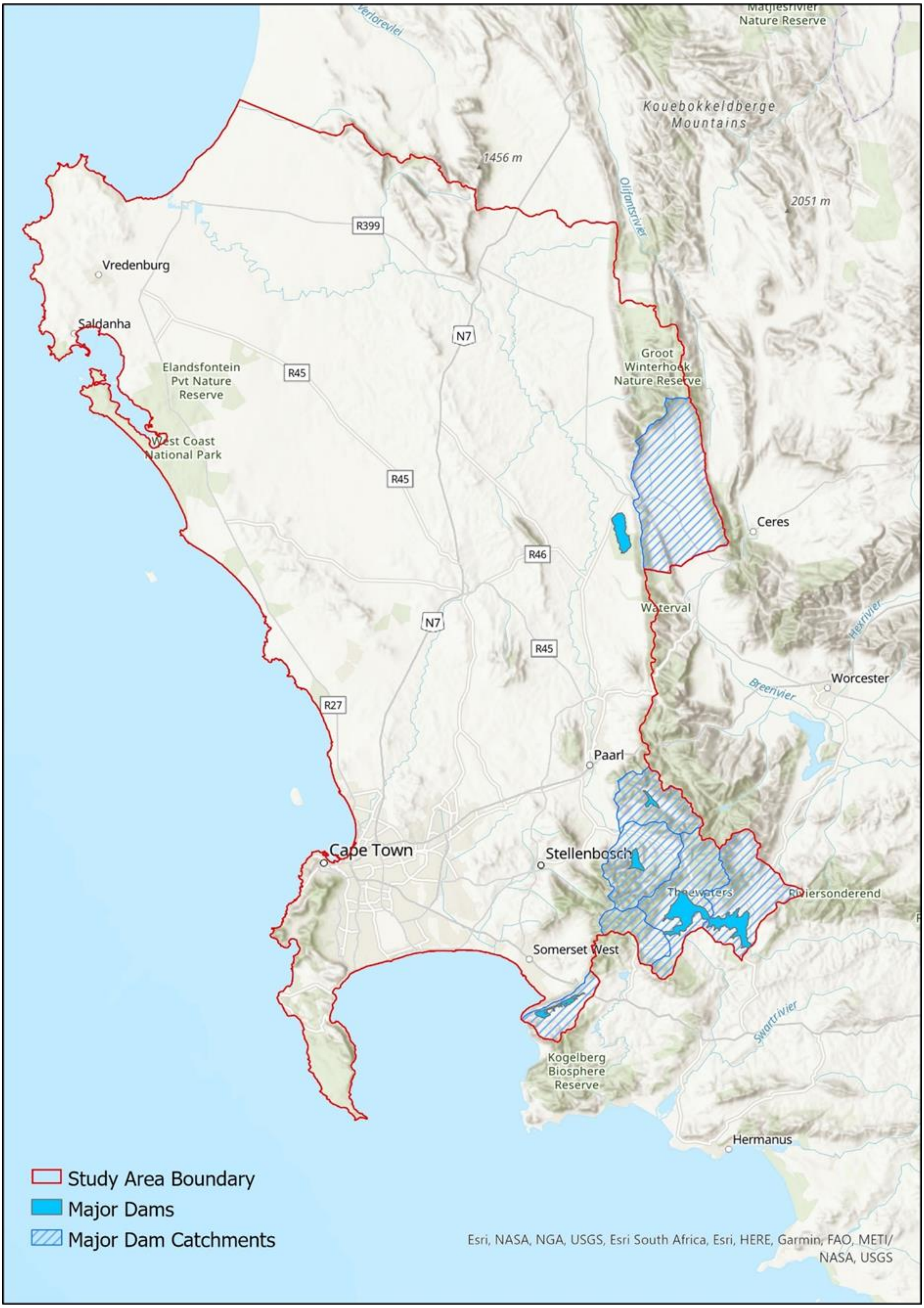
The Berg River, Steenbras Upper and Lower, Wemmershoek and Voëlvlei Dams are situated in the Berg River WMA. The quaternary catchments of the first four dams above are in the Berg River WMA. However, the Voëlvlei Dam is off-channel storage, with water being transferred into it from the Klein-Berg and 24-Rivers. The quaternary catchments for these rivers were included in the study area.

The Theewaterskloof Dam, while the largest storage in the WCWSS, is situated in the Breede River catchment, and therefore is an inter-basin transfer scheme. The quaternary catchments of the Theewaterskloof Dam were also been added to the focus area of this research. The supply area, including the additional catchments of the Voëlvlei and Theewaterskloof Dams, is shown in Figure 3.2.

While the primary focus of the research was on precipitation records within the catchments of the major dams, precipitation records across the research area were selected and analysed. This allowed for mapping of results across the research area. Records from rainfall stations just outside the boundary of the research area were also be identified and included in the analyses, to allow for better mapping of the results.

Three potential sources of precipitation data in the study area were identified:

- The South African Weather Service (SAWS): the SAWS is the national meteorological service and provides weather and climate forecasting services, including weather information for the aviation and marine sectors. It maintains a network of, amongst others, 231 automatic weather stations, 1180 rainfall stations, and 153 automatic rainfall stations.
- The Water Resources of South Africa Study, 2012 (WR2012): this study, by Bailey and Pitman (2015), was commissioned and funded by the Water Research Commission, with the objective of making hydrological information across South Africa available to practitioners and researchers. Similar studies have been conducted at various points in the past decades, and the WR2012 study has furthered these previous studies.
- The City of Cape Town maintains a network of rainfall gauges at several of its dams, water treatments plants and major bulk reservoirs. These rainfall gauges are read daily. As most of these sites are secured, staffed and operational around the clock, the CCT’s network of gauges are well maintained.



Esri, NASA, NGA, USGS, Esri South Africa, Esri, HERE, Garmin, FAO, METI/NASA, USGS

Figure 3.2: Extent of the WCWSS used in the research

The precipitation records selected had to meet the requirements of the drought index used in the research, including:

- minimum length of record in years
- resolution of data, i.e., daily, or monthly precipitation
- continuity of data, i.e., no missing data

The precipitation records had to have data up to 2020, to enable analysis of the droughts experienced between 2015 and 2020.

A basic statistical analysis was done on the selected records, including the mean, standard deviation, and minimum and maximum precipitation. The difference between the past 30-year and long term mean of each record was calculated to give an indication of any significant change in recent precipitation.

3.2 Indexing droughts using the Standardised Precipitation Index

3.2.1 Selecting the Standardised Precipitation Index for use in this research

Some of the more commonly used drought analysis indices were discussed in section 2.6. The Standardised Precipitation Index (SPI) was used in this research, for the following reasons:

- It only requires precipitation as an input value. For drought frequency calculation, sufficiently long records are needed for fitting a distribution to the data. Long-term precipitation data is available across the research area, unlike other hydrological data such as streamflow or dam levels.
- It is a standardised index, and therefore can be used to compare drought characteristics at different locations.
- The time scale to be analysed can be adjusted.
- It does not need to be calibrated for use in a specific geographical area.
- And lastly, the World Meteorological Organisation has recommended it as the standard index to be used by meteorological organisations globally (WMO, 2012).

3.2.2 Calculation of the SPI for a precipitation record

The SPI was proposed by McKee *et al.* (1993), and further expanded by Edwards (1997), as a statistical approach to determine the intensity, duration, and frequency of droughts. It was derived to address the limitations of other indices in use, particularly the Palmer Drought Severity Index (PDSI), which is an empirically based index.

Mckee *et al.* (1993) observed that water resource and supply decision makers prefer that the occurrence of droughts be expressed in terms of probability and deficit in comparison to historical precipitation. Being a statistically based method, the SPI can be used to determine these. Another benefit of the SPI is that it can be used to assess drought impacts over different time scales. Different averaging or cumulative periods of precipitation can be assessed; these can be any period, but are usually 3, 6, 12, 24 or 48 months. The shorter periods will respond more quickly to changes in monthly precipitation and will move in and out of drought periods more frequently. Alternatively, the longer periods respond more slowly to monthly changes and periods in and out of drought will be longer. The WMO (2012) recommends that shorter periods of 3 – 6 months are more suitable for operational requirements such as assessing impacts on agriculture, whereas averaging periods of 12 – 48 months are more suitable for assessing the impacts on water resource and supply systems. Long-term drought analysis also benefits from using longer averaging periods, as the data and drought periods are more stable and less erratic. For this research, an averaging period of 12 months was selected as this is generally the timing of planning and operation of water resource and supply systems, i.e., the filling and draw-down cycle of water storage dams and operation of supply systems. An averaging period of 12 months also removes the seasonal variation from the rainfall data.

McKee et al. (1993) and the WMO (2012) both advise that a record length of at least 30 years be used for SPI analysis. The record also must be continuous, i.e., no gaps in data. The WMO (2012) however advises that record lengths should ideally be 50 – 60 years in length. As this research will be using the SPI values to assess the frequency of droughts, it was decided to use a minimum record length of 50 years. The need for continuous records also meant that precipitation records had to be checked for gaps and filled if required.

The method for determining the SPI is outlined by McKee et al (1993) and Edwards (1997). The SPI is essentially a measure of the deviation of a precipitation data point in a record from the long-term mean of that record in terms of standard deviations, and then transformed into a normal cumulative distribution function (CDF) with a mean of zero and standard deviation of one. As most precipitation records are not normally distributed (they are generally positively skewed), the precipitation data is fitted to a gamma function to determine the probability distribution of the data. An inverse normal function is used to transform the gamma CDF into a normal CDF. This produces the standardised index which can then be used to assess drought severity and duration, as well as compare drought values at different locations. The SPI CDF indicates the probability of non-exceedance of precipitation – in other words, the

CDF indicates the probability that precipitation will be equal to or less than a certain precipitation depth.

The steps used in this research for calculating the 12-month SPI are outlined below.

Firstly, a continuous monthly precipitation record is prepared, with a minimum record length of 50 years. This length of record was chosen to ensure that there are sufficient drought events to conduct a meaningful frequency analysis.

The monthly data is then converted into a 12-monthly moving cumulative record. Each monthly data point is therefore the cumulative rainfall of the previous 12 months.

For the precipitation record of each rainfall station, the dataset of cumulative 12-month data points for each calendar month over the length of the record is fitted to a gamma distribution.

The gamma distribution probability density function (PDF) is defined as:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} \; x^{\alpha-1}e^{-x/\beta} \tag{3.1}$$

for: $x > 0$

where: $\alpha =$ the shape parameter

$\beta =$ the scale parameter

$x =$ the precipitation value

$\Gamma(\alpha) =$ the gamma function, where $\Gamma(\alpha) = \int_0^{\infty} y^{a-1}e^{-y}dy$

The shape and scale parameters are estimated using the method of maximum likelihood:

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{3.2}$$

where: $A = ln(\bar{x}) - \frac{\sum ln(x)}{n}$

$\hat{\alpha} =$ the estimated shape parameter

$\bar{x} =$ mean of the applicable month’s values over the record length

$n =$ number of precipitation values

and:

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \tag{3.3}$$

where: $\hat{\beta}$ = the estimated scale parameter

The gamma cumulative distribution function (CDF) is determined by calculating the integral of the PDF:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})}\int_0^x x^{\hat{\alpha}-1}e^{-x/\hat{\beta}}dx \tag{3.4}$$

Letting $t = x/\hat{\beta}$, Equation 3.4 becomes:

$$G(x) = \frac{1}{\Gamma(\hat{\alpha})}\int_0^x t^{\hat{\alpha}-1}e^{-t}dt \tag{3.5}$$

This is the incomplete gamma function. As this function is undefined for $x = 0$, and the distribution of a precipitation record may contain zeros, the cumulative probability is expressed as:

$$H(x) = q + (1 - q)G(x) \tag{3.6}$$

where: q = the probability of zero

In practice, the cumulative probability can be determined by statistical software, including statistical functions within Microsoft Excel.

The gamma CDF probability $H(x)$ is transformed, using the same probability, to the standard normal CDF (with mean = 0 and standard deviation = 1). This value of the standard normal CDF is the SPI value.

Figure 3.3 shows the above steps graphically, using the Molteno Reservoir precipitation record for the month of December, as an example.

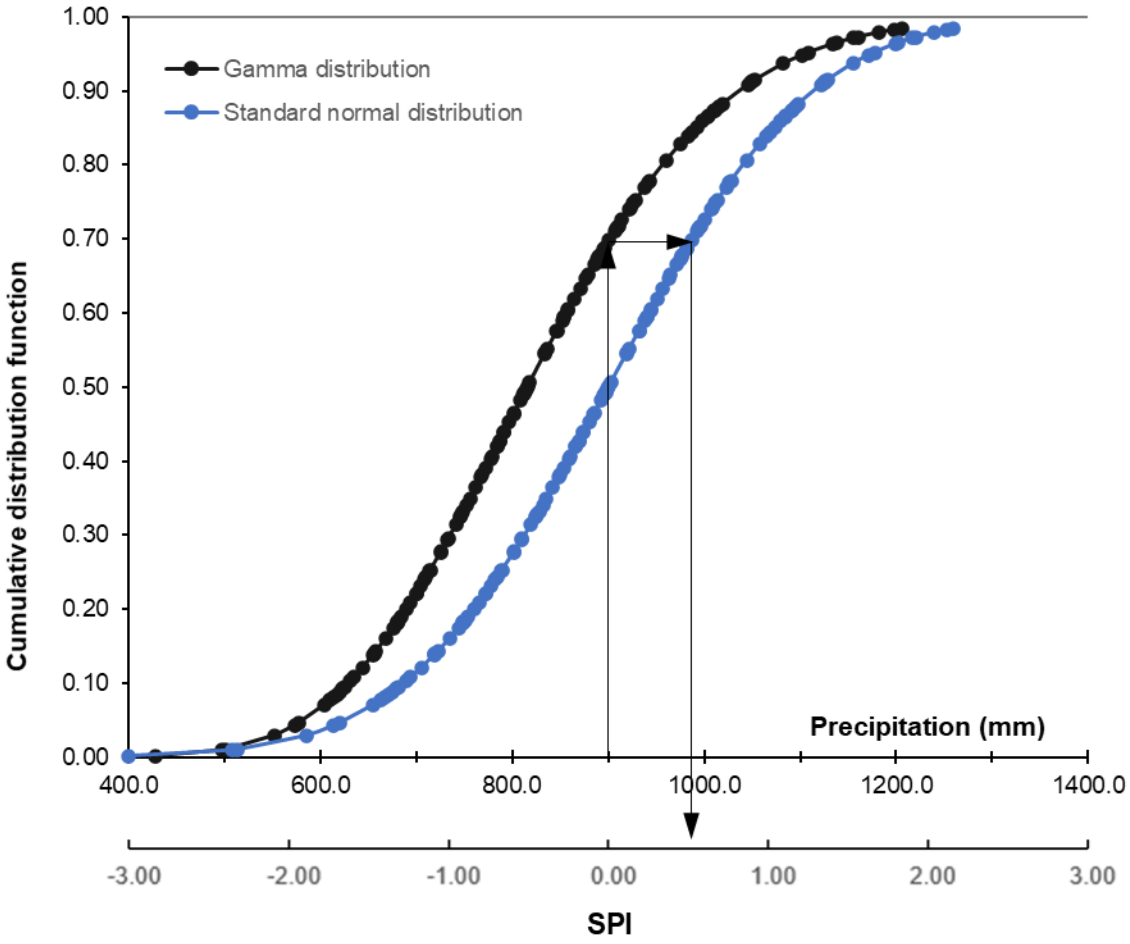


Figure 3.3: Graphical representation of the SPI calculation

The above transformation must be done for each of the 12 months in the long-term record. The SPI value of any 12-month cumulative precipitation at any point in the record can then be determined.

The objective of the SPI is to show the standardised deviation away from the mean of the record. The mean of the long-term record is an SPI value of zero. Positive SPI values indicate above average (wetter) periods, and negative values indicate below average (drier) periods.

The SPI values, drought categories and normal cumulative probability distributions are shown in Table 3.3 (adapted from McKee *et al.* (1993) and Edwards (1997)).

Table 3.3: SPI values, drought categories and cumulative probabilities

SPI values	Drought category	Cumulative probability
0.0 to -0.99	Mild drought	0.500
-1.0 to -1.49	Moderate drought	0.158
-1.5 to -1.99	Severe drought	0.066
≤ -2.0	Extreme drought	0.022

McKee *et al.* (1993) defined the following characteristics of a drought based on the SPI:

- A drought has commenced when the SPI reaches a value of -1 or lower and continues as long as the SPI remains negative. The drought ends when the SPI reaches a positive value.
- The duration of the drought is the period from when the drought starts to when it ends, as defined above.
- The peak intensity of the drought is the lowest SPI value reached during the drought period.
- The drought magnitude (DM) is the accumulated SPI values during a drought period, and is calculated by the formula:

$$DM = -\left(\sum_{j=1}^{x} SPI_{ij}\right) \tag{3.7}$$

where: $i =$ the time scale of the SPI being assessed, e.g., 12-month cumulative

$j =$ the consecutive months of the drought period, starting with 1

$x =$ the duration of the drought

Figure 3.4 illustrates these concepts.

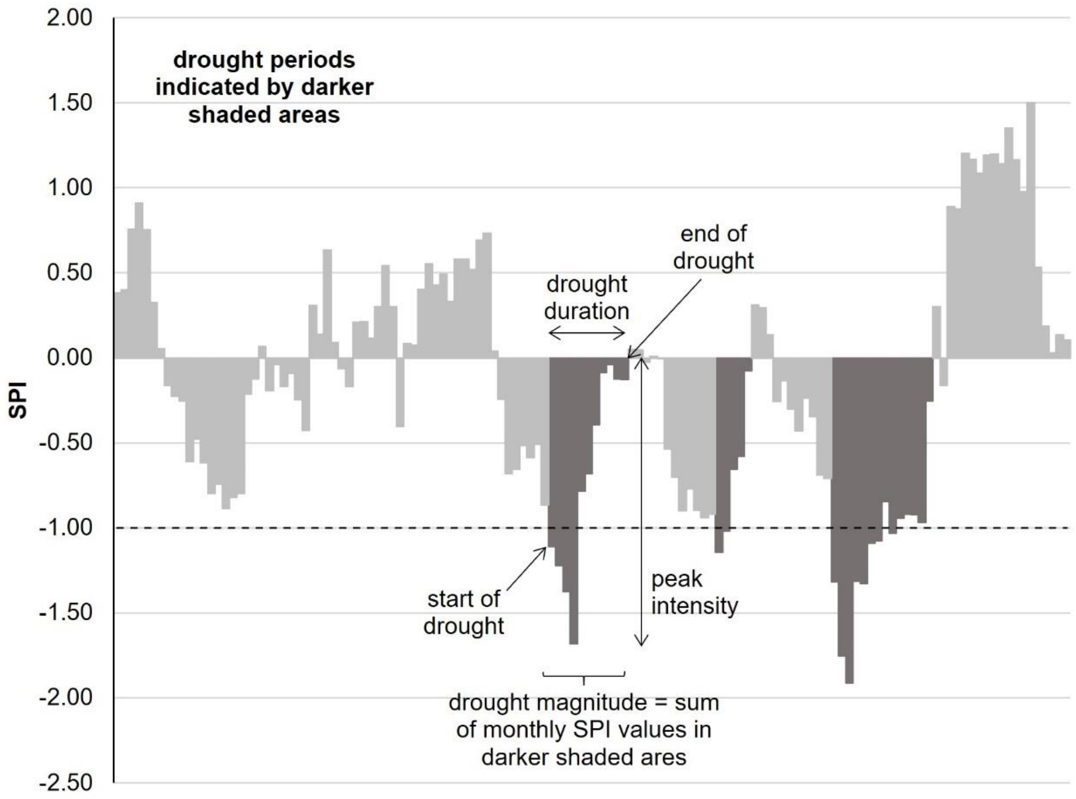


Figure 3.4: Drought start, end, duration, magnitude, and peak intensity

This research calculated the SPI values for the selected rainfall stations in the WCWSS area and identified periods of drought and peak intensities in the historical records of these rainfall stations. Models for calculating the SPI values were compiled using Microsoft Excel. The gamma distribution fitting was done using the specialist statistics software XLStat (Addinsoft, 2021), an Excel plug-in that allows preparation, calculation, and results of the distribution fitting to be used directly in the Excel models.

3.2.3 Precipitation threshold

While the SPI is a valuable tool in understanding the intensity and duration of droughts, it can be an abstract concept for water resource managers and decision-makers to use, in that it does not directly express the drought characteristics in rainfall depth. To assist with this, Rahmat (2014) proposed a method of showing the SPI values of the long-term mean of a rainfall record (SPI = 0) and the drought commencement threshold (SPI = -1) in terms of the precipitation values for a particular precipitation record.

To calculate these values, the normal cumulative probability distribution of each month is used. As per Table 3.3, the SPI = 0 for each month is calculated by determining the precipitation for a cumulative probability of 0.500. The precipitation for SPI = -1 is determined for a cumulative probability of 0.158. As these values are calculated for each month of the year, the mean precipitation of the 12 months for SPI = 0 and -1 is used for determining the precipitation thresholds for when a drought commences and ends.

As the thresholds are now expressed in precipitation (mm), water resource practitioners can more easily and intuitively determine directly from the measurements at a rainfall station whether a drought has started, is in progress, or has ended. This can be done without the need to understand the theory and calculation of the SPI.

While therefore useful, the disadvantage of not using the standardised index is that drought severities cannot be easily compared between different locations.

This research determined the precipitation thresholds for each of the selected precipitation records. The threshold calculations were done using the statistics functions in Microsoft Excel.

3.3 Severity, frequency, and duration relationships

As discussed in Section 2.6.4, water resource managers and decision makers find it valuable to understand the return period of a drought event being experienced (McKee *et al.*, 1993). The calculation of return periods, however, requires the understanding and application of statistical frequency analysis. Severity, duration, and frequency (SDF) curves allow return periods for droughts with a certain magnitude and duration to be determined without having to do detailed statistical analysis.

Rahmat (2015) produced SDF curves for rainfall stations in the state of Victoria, Australia. An example of one of these curves, for the Rainbow rainfall station, is shown in Figure 3.5. The set of curves, for a specific rainfall station, gives the precipitation depths and associated return periods for drought durations of 1 – 5 months.

A similar method to those used by Rahmat (2015) and Juliani & Okawa (2017) was adopted in this research to produce SDF curves for rainfall stations in the WCWSS area. The method is outlined below.

In this research, SDF curves were developed for each of the 29 rainfall stations being analysed for drought durations of 1 – 6 months. These shorter drought durations were chosen for this research due to the shorter record lengths available for key rainfall stations in the WCWSS area. Analysing longer drought durations reduces the number of drought events available for frequency analysis. With rainfall records with shorter lengths, a limited number of drought events can make distribution fitting problematic.

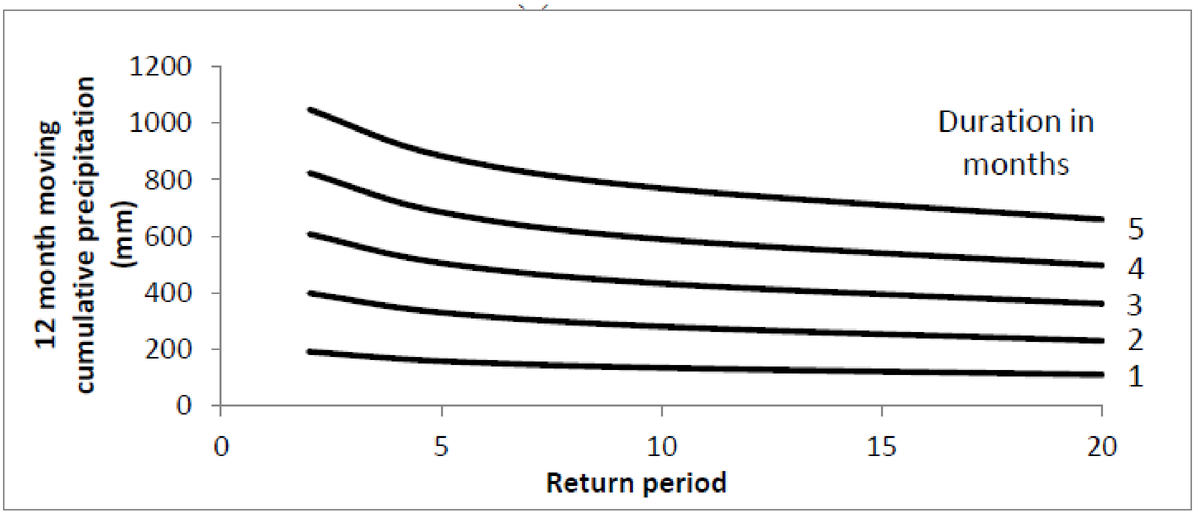


Figure 3.5: SDF curves for Rainbow in Victoria, Australia (Rahmat, 2015)

The SDF curves used precipitation depths, as these are more intuitively understood than using SPI values. However, the SPI-12 values were used to identify when droughts start, are in progress, and end.

Development of the curves starts with the monthly 12-month cumulative precipitation and associated SPI-12 values, discussed in Section 3.2.2. As outlined in the same section, the periods of droughts were identified for the precipitation record.

For each drought event in the precipitation record, the most severe 1 month, and severe consecutive 2, 3, 4, 5 and 6-month droughts were identified. For each duration, a partial duration series (PDS) was compiled of most severe droughts. Each rainfall station therefore has six separate PDS.

Each PDS was then fitted to a probability distribution. Using a suitable probability distribution is important in producing the SDF curves. Rahmat (2015) used the Log Pearson Type III distribution, which is commonly used in hydrological frequency analysis. It should be noted that the Pearson Type III distribution is the same as the generalised (3-parameter) gamma distribution (Hovey & DeFiore, 2003). Juliani & Okawa (2017) used the simpler 2-parameter gamma distribution, which is also used to derive the SPI (the method is discussed in detail in Section 3.2.2).

An initial assessment was done to fit the rainfall data using the Log Pearson Type III distribution using the Minitab statistical software, but it was found to have a poorer goodness-of-fit than the two-parameter gamma distribution. The gamma distribution was therefore used for deriving the SDF curves, as initial indications were that there was a better fit to the data in the PDS.

The XLStat statistical software was used to identify the best-fit gamma distribution using the method of maximum likelihood estimation (MLE). The method identifies the shape (α) and scale (β) parameters of the gamma distribution that best fit the drought data. An example of the MLE distribution fitting of the Wemmershoek Dam data for durations of 1 – 6 months are shown in Figure 3.6.

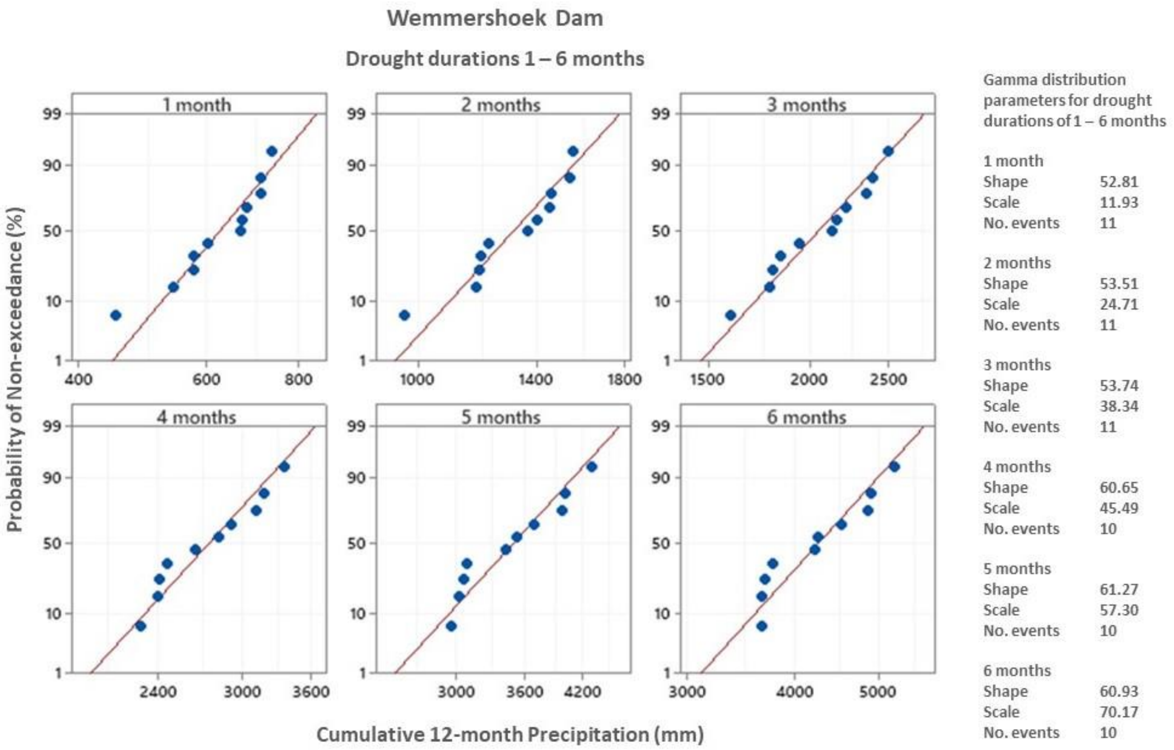


Figure 3.6: Gamma distribution fitting for Wemmershoek Dam precipitation record

The gamma CDF was then used to calculate the precipitation values for the non-exceedance probabilities of 0.2, 0.1, 0.05, 0.02 and 0.01, which corresponds to return periods of 5, 10, 20, 50 and 100 years. This information is then used to produce the SDF curves.

The goodness-of-fit of the gamma distribution to the precipitation data was assessed using the Kolmogorov-Smirnov (K-S) test. The K-S test is one of the widely used goodness-of-fit tests. The K-S test is discussed in Ang & Tang (2007), and is summarised below.

The basic methodology of the K-S test is to compare a fitted distribution to a theoretical distribution, and the maximum difference between the distributions is compared to a calculated critical value, based on the distribution sample number *n* and a significance level *α*, normally set at 0.05. If the difference between the distributions is greater than critical value, then the distribution being tested is not considered a good fit for the data.

The method is illustrated in Figure 3.7 and is outlined below.

The precipitation data PDS of size n is arranged in ascending order to form a stepwise empirical cumulative frequency function, Sn(x).

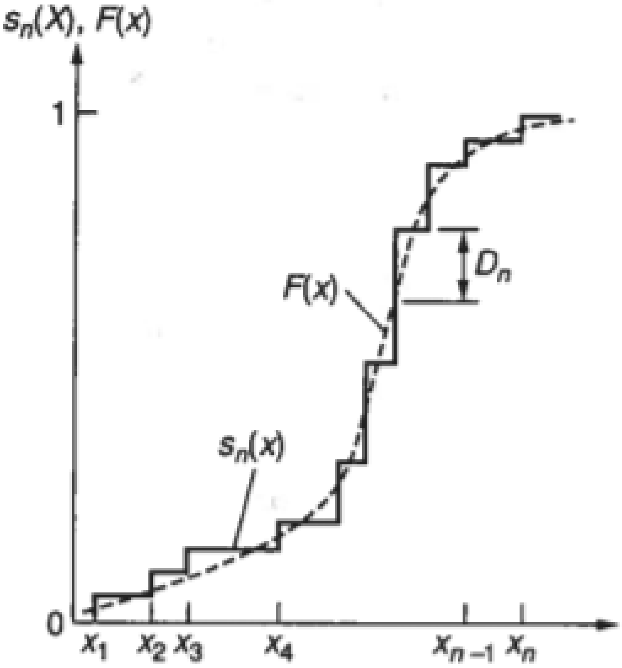


Figure 3.7: Illustration of Kolmogorov-Smirnov test (Ang & Tang, 2007)

The empirical function and the CDF being fitted, here denoted as F(x), are compared and the maximum distance calculated as:

$$D_n = max\,|F(x) - S_n(x)| \tag{3.8}$$

The difference D_n is then compared to the critical value $D_n^{\propto}$, where the critical value is determined by the sample size *n* and significance level *α*. If $D_n < D_n^{\propto}$, then the distribution being fitted is acceptable at the significance level *α,* which is normally taken as 0.05.

3.4 Regional mapping of severity, frequency, and duration relationships

SDF values were plotted on maps of the WCWSS area, as precipitation isohyets. The SDF isohyet plots give an indication of the variation of SDF values across the region.

The plots were generated using the ArcGIS mapping software, developed by Environmental Systems Research Institute (ESRI). The method used to produce isohyet plots is outlined below.

For each rainfall station, SDF precipitation depths corresponding to a duration and return period were captured into ArcGIS as point data.

The point data was then converted to a raster image using ArcGIS's Topo-to-Raster tool.

A raster image indicates z-values through pixel colour – this is normally used to indicate elevation in maps. In this research, the z-values were used to represent precipitation depths.

The ArcGIS Contour tool is then used to generate isohyets from the raster layer.

3.5 Flow diagram of methodology

The methodology above can be summarised in a flow diagram, as illustrated in Figure 3.8.

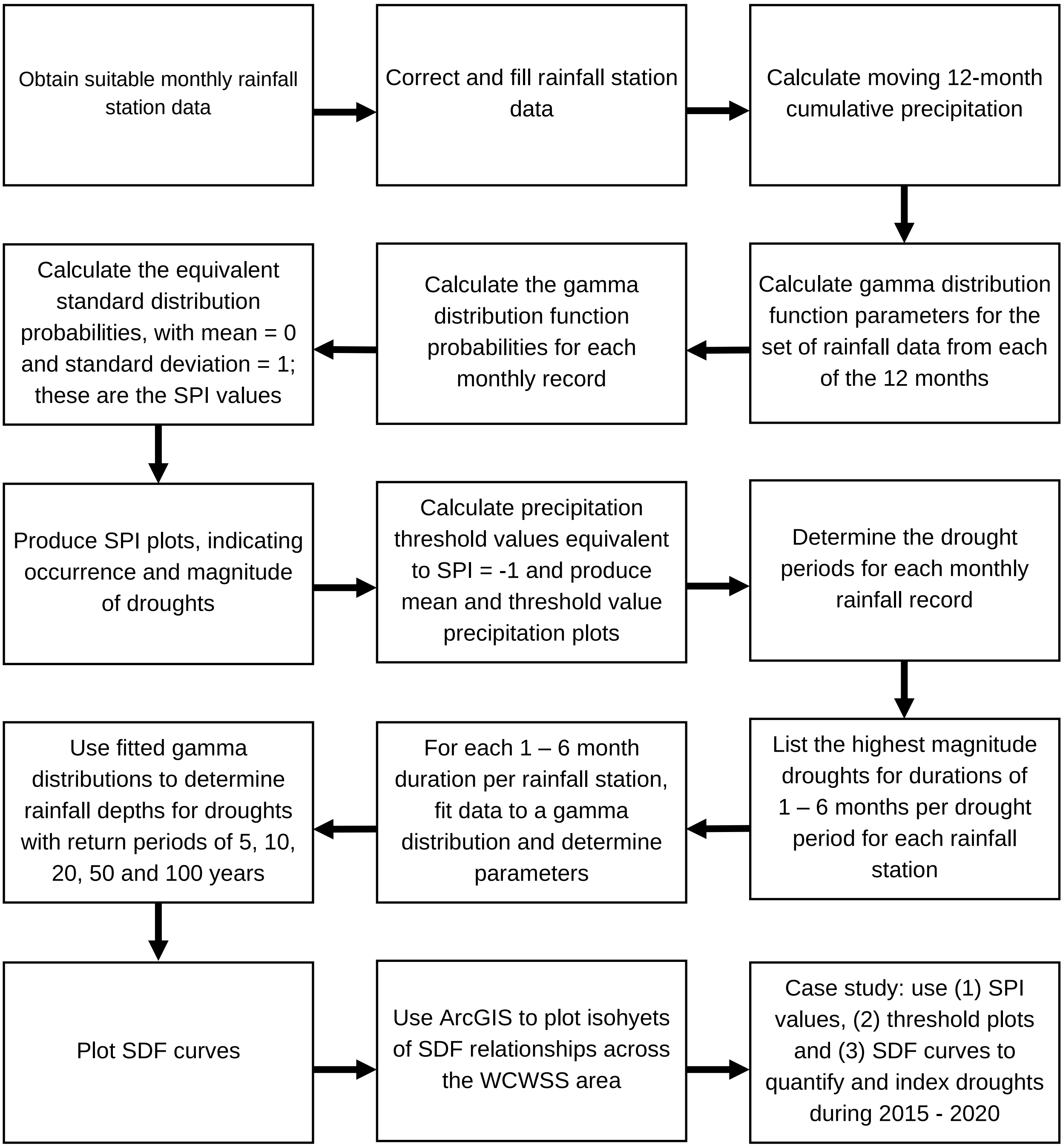


Figure 3.8: Research methodology

4. ADAPTION OF DROUGHT ANALYSIS METHODS FOR THE WCWSS AREA

This section discusses the application of the research methodology outlined in Section 3. In Section 4.1, the selection of rainfall station data and the correction and filling in of missing data is discussed. Section 4.2 covers how the SPI values were calculated for the selected rainfall station data in the WCWSS area, with a particular focus on the rainfall stations in the catchment areas of the major dams of the supply system. Section 4.3 discusses the development of threshold precipitation values, which allowed the start and end of droughts to be determined directly from precipitation values. The SPI values were also used to develop SDF curves for the selected rainfall stations, which allowed the return period of droughts at the selected rainfall stations to be determined from curves, which is discussed in Section 4.4. Lastly, Section 4.5 discusses the development of isohyet diagrams of the SDF values, which were developed to indicate SDF values spatially across the WCWSS area.

4.1 Data selection and screening

Sources of precipitation records

As this research was focused on the impacts of droughts on the planning and operation of the WCWSS, the research confined the consideration of suitable records to within the WCWSS area. Suitable stations were also identified just outside the area, to allow for more accurate mapping of data and results.

Selection of precipitation records

The CCT operates a network of 17 rainfall gauges. Of these, only 9 had precipitation records of 50 years or longer. The details of these records are shown in Table 4.1. The length of precipitation records varied from 54 years at Wemmershoek Dam to 133 years at Molteno Reservoir.

As stated previously, the CCT rainfall gauge network is well maintained and is read daily. The readings are subject to quality control when captured into the CCT's hydrological database, and therefore almost all the records are continuous and corrected. The only exception was for the Constantia Nek Reservoir precipitation record, where 8 months were missing: 4 months in 2010 and 4 months in 2020.

Table 4.1: City of Cape Town precipitation records 50 years or longer

Rainfall Gauge Location	Record Start Date	Record End Date	Calendar Years	Continuous Data	Missing Records (months)
Molteno Reservoir	Sep 1887	Jun 2020	133	Yes	-
Woodhead Dam	Feb 1893	Jun 2020	127	Yes	-
Newlands Reservoir	Jan 1907	Jun 2020	114	Yes	-
Steenbras Dam	Jan 1916	Jun 2020	105	Yes	-
Kloof Nek Reservoir	Jan 1923	Jun 2020	98	Yes	-
Constantia Nek Reservoir	Jan 1927	Jun 2020	94	No	8 (0.7%)
Wynberg Reservoir	Mar 1928	Jun 2020	92	Yes	-
Tygerberg Reservoir	Jan 1955	Jun 2020	66	Yes	-
Wemmershoek Dam	Jan 1967	Jun 2020	54	Yes	-

One distinct disadvantage of the CCT precipitation data is that six of the nine rainfall stations identified are all in close proximity in the Table Mountain area between the City Bowl and Constantia Nek areas of Cape Town. However, an advantage is that two of the nine stations are in the catchments of three of the six major dams of the WCWSS, i.e., the catchments of Steenbras Upper and Lower Dams and Wemmershoek Dam. These are considered critical in analysing the impact of drought on the WCWSS.

The WR2012 is an extensive and comprehensive hydrological database, with precipitation records in every primary catchment area in South Africa. Precipitation records have all been checked and patched. It should be noted though that some large gaps in data (where they existed in the source data) have not been filled in WR2012 records. A small number of missing data and discrepancies between patched data and original records also exist – the corrections of these are discussed in the following section. The most critical problem however with the suitability of using the WR2012 precipitation database in this research is that records are only available up to September 2010, which would not allow for analysis of the 2015 – 2020 droughts.

The SAWS operate an extensive network of weather stations and rainfall gauges across the country. Of the approximately 96 precipitation records available for the research area, a preliminary list of 22 stations was identified that satisfied the criteria outlined earlier in this section. However, on initial analysis all the precipitation records were found to have a significant number of missing records (and in some cases gaps of years in length), or unreliable monthly records due to missing daily readings.

Due to this, the approach taken in this research to generate a set of records to use was to identify precipitation records common to both the SAWS and WR2012 databases. As the WR2012 data had already been checked and patched, data from these records was used from the start of the record up to September 2010, the last month up to which WR2012 data is available. SAWS data was then used from October 2010 to July 2020.

An initial set of 33 stations common to both databases was identified. On analysis, 14 of these records were found to have significant gaps in data, or SAWS data that did not continue through to 2020, leaving 19 stations suitable for use for analysis.

The Cape Point precipitation record, which was only in the SAWS database, was added to the list of records to analyse as it was in an important geographic location to assist with mapping of values, and had a relatively low percentage of missing data.

Table 4.2 lists the precipitation records used in this research, sourced from the SAWS and WR2012 datasets. Record lengths varied from 56 to 120 years, with an average record length of 99.5 years. The number of missing or unreliable monthly data varied between 0% to 1.2% of the total number of months in the record. The correction of these records is described in the next section.

Table 4.2: SAWS and WR2012 precipitation records used in research analyses

Station Name	SAWS Station Reference Number	SAWS start date	SAWS end date	WR2012 start date	WR2012 end date	Record length (full years)	Missing or un-reliable monthly data (number)	Missing or un-reliable monthly data (%)
Altydgedacht	0021203	Feb 1940	Jul 2020	Oct 1900	Sep 2010	119	31	2.2%
Betty’s Bay	0005771	Nov 1953	Jul 2020	Oct 1926	Sep 2010	66	5	0.4%
Bokveldskloof	0042582	Jan 1963	Jul 2020	Oct 1962	Sep 2010	56	1	0.1%
Boontjieskraal	0006612	Oct 1920	Jul 2020	Oct 1918	Sep 2010	101	12	1.0%
Cape Point	0004891	Jan 1900	Aug 2020	-	-	120	17	1.2%
Ceres	0042532	Mar 1955	Aug 2020	Oct 1955	Sep 2010	64	4	0.5%
Eendekuil	0062671	Sep 1967	Aug 2020	Oct 1900	Sep 2010	119	1	0.1%
Franschhoek Robertsvlei	0022148 3	Feb 1961	Jul 2020	Oct 1919	Sep 2010	100	0	0.0%
Langebaan	0040035 8	Jul 1912	Aug 2020	Oct 1900	Sep 2010	119	0	0.0%
Langgewens	0041347 X	Nov 1930	Aug 2020	Oct 1958	Sep 2010	89	0	0.0%
Middeldeurvlei	0062768 3	Jul 1955	Feb 2020	Oct 1900	Sep 2010	119	2	0.1%
Nuweberg	0006065 1	Feb 1927	Jul 2020	Oct 1927	Sep 2010	92	2	0.2%
Picketberg	0062444 7	Jan 1900	Aug 2020	Oct 1900	Sep 2010	120	6	0.4%
Porterville	0041871 1	Jan 1959	Jul 2020	Jan 1959	Sep 2010	60	1	0.1%
Remhoogte	0042281A0	Jul 1953	Jul 2020	Oct 1952	Sep 2010	67	5	0.6%
Robben Island	0020649 3	Jan 1900	Jul 2020	Oct 1900	Sep 2010	120	5	0.3%
Rustfontein	0006332 9	Jun 1932	Jun 2020	Oct 1920	Sep 2010	99	0	0.0%
Tulbagh	0042227 3	Jan 1900	Aug 2020	Oct 1900	Sep 2010	120	5	0.3%
Vrugbaar	0022038 8	Jan 1940	Jul 2020	Oct 1900	Sep 2010	119	0	0.0%
Wolseley	0042326 X	Jan 1900	Jul 2020	Oct 1900	Sep 2010	120	6	0.4%

Checking and correction of records

A few different types of errors were found in the CCT, WR2012 and SAWS records, and these were corrected to produce continuous records for use in the SPI and SDF analyses. The types of errors found, and correction methods used, are summarised below.

Missing monthly data

The missing monthly data listed in Tables 4.1 and 4.2 was filled using a linear regression method (De Silva, Dayawansa & Ratnasiri, 2007). Linear regression using least squares was used to find the relationship between the rainfall station with the missing data, and rainfall stations in closest proximity. The linear regression data fitting was done for the year in which the data point was missing, as climatic conditions can vary over time, influencing the regression analysis. The physically closest station with the highest coefficient of correlation was used to calculate the missing monthly precipitation value. The coefficients were generally high – around 0.8 to 0.9. Microsoft Excel was used for the analysis.

Significant differences between SAWS data and patched WR2012 data

The difference in the monthly data between the overlapping SAWS and WR2012 data was calculated, and differences were flagged. Differences were mainly due to unreliable SAWS data being patched. However, in a small number of cases, the patched data was interpreted as zero precipitation for the month, whereas the SAWS data, although incorrect, showed that there had been rainfall at that station. In these instances, the linear regression method was used to estimate the monthly rainfall, and the estimates were used to replace the zero values in the patched WR2012 data. Microsoft Excel was used for the analysis.

Missing year in record

The Cape Point rainfall gauge was specifically identified as an important record to include in the analysis, as its geographic position at the south-western point of the WCWSS supply area would assist with mapping of SPI and SDF results across the WCWSS area.

This station is in the SAWS dataset, but not part of the WR2012 dataset.

Of the 17 missing monthly precipitation values, 12 are in a full missing calendar year of 1962.

The four missing monthly values at various months in the record were corrected using linear regression.

The missing 12 months for 1962 however were filled using the Normal Ratio Method (NRM) (De Silva *et al.*, 2007). The NRM estimates the missing rainfall data values using the weighted averages of known neighbouring stations. The weighting of the average is based on the normal rainfall of the record, which is the annual average of the previous 30 years. The missing precipitation value is calculated as follows:

$$p_x = \frac{1}{m} \sum_{i=1}^{m} \left(\frac{N_x}{N_i}\right) p_i$$

Where:
p_x = missing precipitation value
m = number of neighbouring stations
N_x = normal precipitation of the station with the missing value(s)
N_i = normal precipitation of the neighbouring stations
p_i = known precipitation values of the neighbouring stations

To estimate the missing 12 months at the Cape Point rainfall station, neighbouring stations were identified that are not affected by the Cape Peninsula mountain chain, such as Woodhead Dam, Newlands, or Constantia Nek rainfall stations, as the mountains can have a significant impact on rainfall at that location. The Molteno Reservoir, Robben Island and Maitland rainfall stations were used (note: Maitland was not used for the SPI analysis, as SAWS records did not continue to 2020, but 30 years of records prior to 1962 were available).

Shift in double mass curve

As part of the basic statistical analysis of the rainfall records (including the CCT sources), the mean precipitation of the last 30 years (1990 – 2019) of the record was compared to the mean precipitation of the full record (refer to Table 4.3). Besides the Langebaan rainfall station, this difference for all other stations was between -9.8% and 7.5%, which was considered reasonable. The Langebaan rainfall station however had a difference of 30.8%, which indicated that it warranted further analysis.

A double mass curve plot was generated using the cumulative precipitation of the Langebaan rainfall station, plotted against the sum of the cumulative precipitation of the Langgewens, Picketberg, and Porterville rainfall stations. Figure 4.1 shows the original mass curve plot, which shows a distinct change in gradient in the year 2001. This change may have been caused by the rainfall gauge being moved, or a shift in the rainfall record being taken from a gauge at a different location.

To correct the record, the annual precipitation values from 2001 to 2020 were adjusted to fit the gradient of the mass curve plot prior to 2001. The monthly values were then adjusted to the ratio of the corrected annual value over the original annual value. The corrected plot for 2001 to 2020 is also indicated in Figure 4.1.

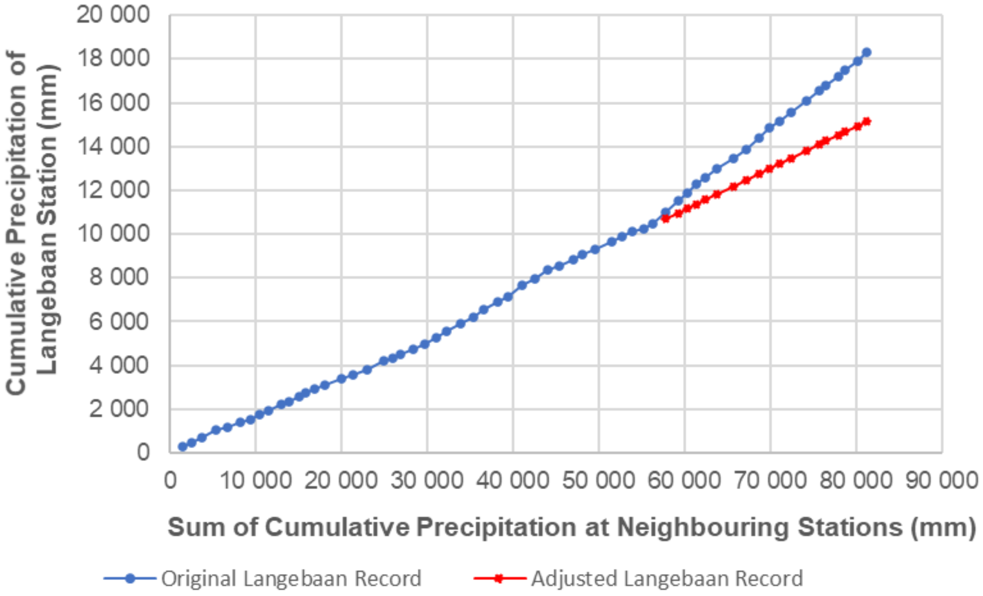


Figure 4.1: Double mass plot of the Langebaan rainfall station

Rainfall stations selected for SPI and SDF analysis

The 29 rainfall stations selected from CCT, SAWS and WR2012 sources are listed in Table 4.3. All these precipitation records were filled and corrected. Table 4.3 also shows the results of the basic statistical analyses of the records, including:

- Mean annual precipitation for the record length
- Standard deviation of the annual precipitation record
- Maximum annual precipitation in the record
- Minimum annual precipitation in the record
- Mean annual precipitation for the last 30-year period, from 1990 - 2019
- Percentage difference of the mean precipitation of the last 30 years of the record compared to the mean precipitation of the full record

The locations of the rainfall stations are shown in Figure 4.2.

The rainfall data in Table 4.3 is visualised in Figures 4.3 and 4.4. Figure 4.3 shows that 76% of the rainfall records are longer than 80 years, which will provide sufficient data for drought frequency analysis. Figure 4.4 shows the significant variation in rainfall across the WCWSS area, ranging from around 250 mm/year – 500 mm/year in the drier northern areas, to up to 1881 mm/year in the wetter eastern mountainous catchments.

Table 4.3: Rainfall stations used for drought analyses

No	Name	Record length (years)	Mean annual precip. (mm)	Std Dev	Max annual precip. (mm)	Min annual precip. (mm)	Mean precip. 1990 - 2019 (mm)	Diff 30-yr to LT mean (%)
1	Altydgedacht	119	586	118	872	257	572	-2.5%
2	Betty’s Bay	66	1078	240	2162	681	1060	-1.6%
3	Bokveldskloof	56	692	189	1135	346	703	1.6%
4	Boontjieskraal	101	390	86	609	227	413	6.0%
5	Cape Point	120	364	100	747	139	374	2.8%
6	Ceres	64	1039	264	1822	559	1036	-0.3%
7	Constantia Nek Reservoir	94	1194	239	1867	751	1119	-6.3%
8	Eendekuil	119	305	79	523	122	298	-2.1%
9	Franschhoek Robertsvlei	100	1881	420	3247	1059	1770	-5.9%
10	Kloof Nek Reservoir	98	767	168	1156	369	825	7.5%
11	Langebaan	119	247	67	508	109	256	3.7%
12	Langgewens	89	404	127	1040	111	388	-4.0%
13	Middeldeurvlei	119	301	76	522	134	299	-0.5%
14	Molteno Reservoir	133	826	160	1206	428	832	0.7%
15	Newlands Reservoir	114	1652	330	2771	1030	1597	-3.3%
16	Nuweberg	92	1551	399	3009	647	1399	-9.8%
17	Picketberg	120	464	104	727	224	452	-2.7%
18	Porterville	60	498	106	813	268	498	-0.1%
19	Remhoogte	67	960	261	1619	351	911	-5.1%
20	Robben Island	120	410	91	659	239	402	-2.1%
21	Rustfontein	99	781	201	1407	441	804	3.0%
22	Steenbras Dam	105	941	199	1330	495	960	2.0%
23	Tulbagh	120	479	114	765	240	475	-0.8%
24	Tygerberg Reservoir	66	527	117	880	317	522	-0.9%
25	Vrugbaar	119	753	146	1142	401	745	-1.0%
26	Wemmershoek Dam	54	985	242	1688	598	965	-2.1%
27	Wolseley	120	639	145	1077	315	618	-3.3%
28	Woodhead Dam	127	1584	296	2537	949	1538	-2.8%
29	Wynberg Reservoir	92	1162	285	1987	627	1074	-7.6%

Figure 4.2: Location of rainfall stations used for drought analyses

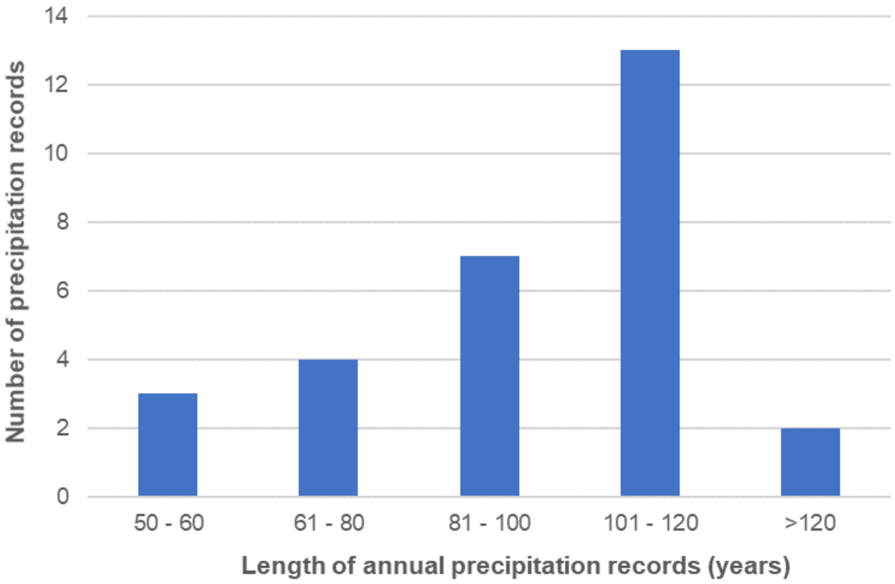


Figure 4.3: Length of precipitation records

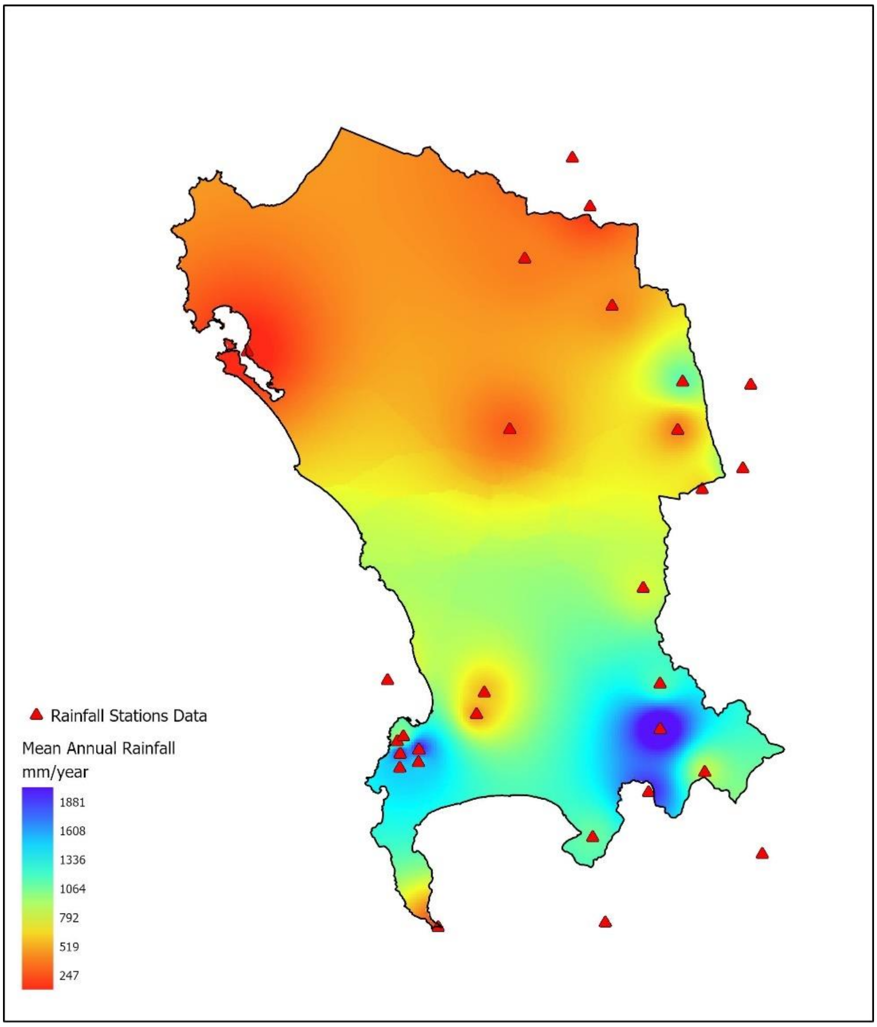


Figure 4.4: Mean annual rainfall in the WCWSS area

4.2 Quantifying droughts using the Standardised Precipitation Index

For each of the precipitation records used for analysis in this research, a model was built in Microsoft Excel to calculate the 12-month Standardised Precipitation Index (SPI-12) value for each month of the record. The SPI-12 is considered an appropriate cumulative time scale to use for analysing the intensity and duration of droughts impacting on water resource and supply system, that have an annual filling and drawdown cycle.

The following steps were used in each precipitation record model:

- The continuous filled precipitation record for a rainfall station was used.
- For each precipitation record, for each month from the start to the end of the record, the sum of the precipitation of that month and the previous 11 months was calculated. This creates a moving 12-month cumulative precipitation record. There are, of course, no 12-month cumulative totals for the first 11 months of the precipitation record. For example, for the Wemmershoek Dam precipitation record, there are monthly values recorded from January 1967 to June 2020. The 12-month cumulative precipitation record starts with December 1967, which is the sum of monthly precipitation values from January to December 1967. Likewise, for January 1968 it is the sum of monthly precipitation values from February 1967 to January 1968, and this continues up to June 2020, which is the sum of monthly precipitation from July 2019 to June 2020.
- The above moving 12-month cumulative precipitation record was then divided into 12 groups of data, one for each calendar month. Using the Microsoft Excel plugin XLStat, the set of 12-month cumulative precipitations for a given month, say January, was fitted to a two variable gamma distribution. For example, for the Wemmershoek Dam precipitation record, there are 53 years of 12-month cumulative totals for the month of January in the record, from January 1968 to January 2020. These 53 values were fitted to a two variable gamma distribution, and a shape and scale parameter were determined. This was similarly done for each month from February to December.
- For each of the 12 gamma distributions determined in the previous step, the cumulative probability was calculated using the gamma distribution functions in Microsoft Excel.
- The cumulative probability was then transformed into a standardised normal distribution, with a mean = zero and a standard deviation = 1. These are the SPI-12 values for each month in the record.

To illustrate the above, the example of calculating the SPI-12 values for the Wemmershoek Dam precipitation record is outlined below.

The Wemmershoek Dam rainfall record has monthly precipitation values from January 1967 to June 2020. It therefore has 12-month cumulative running totals from December 1967 to June 2020. The 12-month cumulative totals are indicated in Table 4.4. A two-variable gamma distribution was fitted to the 12-month totals for each calendar month of the year, and a shape and scale parameter was determined for each month of the year. These parameters for each month are indicated in the last two rows of Table 4.4.

The monthly rainfall and moving 12-month cumulative rainfall for Wemmershoek Dam is also listed in Appendix A, Tables A1 and A2.

Table 4.4: Wemmershoek Dam moving 12-month cumulative precipitation

(Precipitation in mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967												951
1968	954	966	971	959	1 071	968	1 113	1 136	1 060	1 163	1 117	1 152
1969	1 160	1 162	1 178	1 120	913	877	713	770	905	842	831	784
1970	756	751	732	673	851	971	1 045	1 037	971	915	934	971
1971	971	962	994	992	893	781	812	852	780	759	737	749
1972	776	790	771	852	929	894	767	689	739	738	731	724
1973	695	680	698	627	512	452	775	743	771	802	813	859
1974	863	863	850	839	927	1 161	886	1 351	1 343	1 401	1 415	1 334
1975	1 354	1 376	1 360	1 449	1 572	1 438	1 540	1 107	1 037	1 010	1 019	1 011
1976	984	962	979	916	771	1 045	1 151	1 101	1 150	1 082	1 251	1 396
1977	1 430	1 479	1 478	1 584	1 756	1 713	1 665	1 898	1 891	1 912	1 742	1 618
1978	1 601	1 561	1 615	1 530	1 315	977	728	687	718	720	700	706
1979	721	769	704	667	815	961	1 009	882	898	962	952	922
1980	933	884	880	928	911	893	870	865	786	712	843	942
1981	985	974	1 025	1 015	828	736	983	1 004	1 182	1 175	1 072	1 001
1982	967	968	924	957	1 048	1 168	981	920	736	804	808	838
1983	795	879	916	849	1 029	1 111	1 172	1 176	1 315	1 234	1 226	1 198
1984	1 203	1 126	1 147	1 185	1 204	1 069	1 056	1 065	1 071	1 185	1 163	1 218
1985	1 242	1 275	1 329	1 364	1 143	1 182	1 205	1 291	1 211	1 099	1 107	1 036
1986	1 021	1 001	944	923	914	1 028	1 006	1 065	1 051	1 049	1 063	1 048
1987	1 051	1 052	996	981	1 109	1 018	1 021	956	994	988	967	1 032
1988	1 011	990	993	1 056	955	806	778	802	794	805	815	783
1989	793	846	944	876	899	962	981	948	969	1 009	1 021	994
1990	994	982	874	1 088	1 073	1 158	1 271	1 183	1 103	1 050	1 053	1 102
1991	1 093	1 061	1 066	850	968	1 174	1 197	1 190	1 358	1 391	1 382	1 335
1992	1 331	1 392	1 421	1 460	1 321	1 396	1 295	1 310	1 163	1 292	1 295	1 291
1993	1 299	1 264	1 234	1 396	1 450	1 113	1 352	1 364	1 327	1 167	1 158	1 183
1994	1 188	1 158	1 157	968	873	1 162	831	762	822	840	835	821

(Precipitation in mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	823	827	831	784	830	540	640	760	707	786	791	839
1996	833	876	889	917	931	1 199	1 129	1 158	1 298	1 286	1 352	1 342
1997	1 346	1 297	1 279	1 269	1 224	1 117	1 061	996	830	742	739	711
1998	722	721	718	738	893	676	771	719	754	764	748	749
1999	727	728	719	748	619	707	687	843	952	938	910	884
2000	907	908	926	854	828	770	761	637	618	624	611	620
2001	612	621	603	644	770	750	989	1 149	1 159	1 214	1 209	1 209
2002	1 334	1 347	1 360	1 392	1 346	1 352	1 171	1 071	977	964	981	1 030
2003	904	888	934	900	787	711	578	631	670	677	648	631
2004	627	619	582	614	583	685	714	629	592	637	638	598
2005	634	640	631	648	799	852	857	962	959	883	925	923
2006	877	880	876	860	895	819	825	795	776	787	817	831
2007	830	849	879	889	934	1 072	1 167	1 097	1 094	1 091	1 082	1 102
2008	1 116	1 095	1 059	980	820	712	752	748	907	886	890	878
2009	865	861	857	893	955	1 060	923	908	840	893	1 004	990
2010	990	992	1 003	984	1 097	1 058	1 010	1 008	922	941	878	902
2011	930	927	929	964	878	904	888	883	924	884	831	843
2012	818	819	833	851	760	680	774	936	963	957	913	871
2013	883	904	903	981	1 025	1 181	1 187	1 406	1 525	1 533	1 689	1 688
2014	1 720	1 696	1 735	1 634	1 705	1 708	1 795	1 524	1 365	1 325	1 193	1 198
2015	1 174	1 179	1 117	1 069	936	788	781	682	675	679	658	675
2016	680	687	748	844	829	917	890	892	929	937	923	923
2017	900	887	825	746	718	691	601	618	577	615	682	676
2018	678	697	731	849	1 056	1 130	1 127	1 122	1 225	1 184	1 124	1 140
2019	1 164	1 156	1 154	1 050	924	858	1 016	958	839	936	928	957
2020	947	936	903	919	892	896						
Gamma distribution parameters												
Shape (α)	17.00	17.88	17.08	17.01	17.29	15.26	16.45	16.32	15.74	16.53	17.08	17.74
Scale (β)	57.94	55.09	57.68	57.81	56.85	64.33	59.96	60.41	62.56	59.65	57.65	55.54

The gamma distribution function and the distribution parameters were used to calculate the cumulative probability for the associated 12-month cumulative monthly precipitation. The gamma distribution function probabilities were then transformed into a standard normal distribution with a mean = 0 and standard deviation = 1; this generated the SPI values for the record.

This transformation for the month of July for the 53 years of the Wemmershoek record is illustrated in the graph in Figure 4.5. Separate transformations were similarly done for each month of the calendar year.

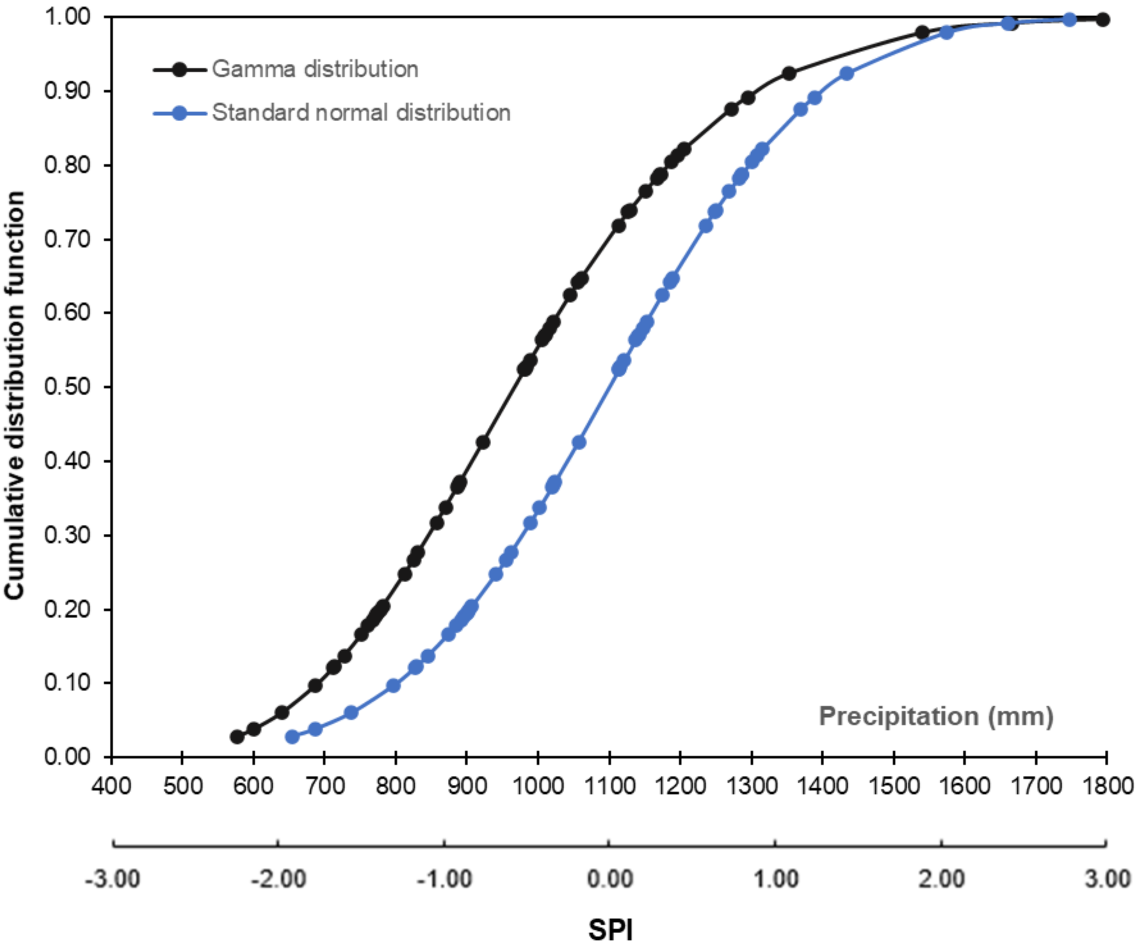


Figure 4.5: Calculation of SPI-12 values for July at Wemmershoek Dam

Table 4.5 shows, for brevity, 10 years of monthly data of the 53-year record for Wemmershoek Dam, from January 2011 to July 2020, indicating for each month of the record the gamma distribution function probabilities and the transformed standard normal distribution function probabilities – the SPI values. These are referred to as SPI-12, as the SPI values are based on 12-month cumulative precipitation. The full dataset is shown in Appendix A, Tables A3 and A4.

Table 4.5: Wemmershoek Dam monthly gamma function and SPI values

Drought periods shaded in grey

Month	Gamma function	SPI-12	Month	Gamma function	SPI-12	Month	Gamma function	SPI-12	Month	Gamma function	SPI-12	Month	Gamma function	SPI-12
Jan-2011	0.44	-0.15	Jan-2013	0.36	-0.36	Jan-2015	0.80	0.82	Jan-2017	0.39	-0.29	Jan-2019	0.78	0.79
Feb-2011	0.43	-0.17	Feb-2013	0.39	-0.28	Feb-2015	0.80	0.86	Feb-2017	0.36	-0.36	Feb-2019	0.78	0.77
Mar-2011	0.44	-0.16	Mar-2013	0.39	-0.27	Mar-2015	0.73	0.61	Mar-2017	0.26	-0.63	Mar-2019	0.77	0.75
Apr-2011	0.50	0.00	Apr-2013	0.53	0.07	Apr-2015	0.67	0.43	Apr-2017	0.16	-1.01	Apr-2019	0.64	0.35
May-2011	0.35	-0.38	May-2013	0.60	0.26	May-2015	0.45	-0.12	May-2017	0.12	-1.16	May-2019	0.43	-0.17
Jun-2011	0.41	-0.23	Jun-2013	0.80	0.83	Jun-2015	0.23	-0.74	Jun-2017	0.11	-1.21	Jun-2019	0.33	-0.43
Jul-2011	0.37	-0.33	Jul-2013	0.80	0.86	Jul-2015	0.20	-0.83	Jul-2017	0.04	-1.77	Jul-2019	0.58	0.20
Aug-2011	0.36	-0.35	Aug-2013	0.95	1.60	Aug-2015	0.09	-1.32	Aug-2017	0.05	-1.67	Aug-2019	0.49	-0.03
Sep-2011	0.43	-0.17	Sep-2013	0.97	1.95	Sep-2015	0.09	-1.32	Sep-2017	0.03	-1.86	Sep-2019	0.30	-0.54
Oct-2011	0.36	-0.35	Oct-2013	0.98	2.02	Oct-2015	0.09	-1.35	Oct-2017	0.05	-1.69	Oct-2019	0.45	-0.13
Nov-2011	0.27	-0.60	Nov-2013	0.99	2.53	Nov-2015	0.07	-1.48	Nov-2017	0.09	-1.35	Nov-2019	0.44	-0.16
Dec-2011	0.29	-0.56	Dec-2013	0.99	2.57	Dec-2015	0.08	-1.42	Dec-2017	0.08	-1.41	Dec-2019	0.48	-0.04
Jan-2012	0.25	-0.66	Jan-2014	1.00	2.61	Jan-2016	0.09	-1.36	Jan-2018	0.09	-1.36	Jan-2020	0.47	-0.08
Feb-2012	0.25	-0.68	Feb-2014	1.00	2.60	Feb-2016	0.09	-1.36	Feb-2018	0.10	-1.30	Feb-2020	0.45	-0.13
Mar-2012	0.28	-0.59	Mar-2014	1.00	2.66	Mar-2016	0.16	-1.01	Mar-2018	0.14	-1.09	Mar-2020	0.39	-0.27
Apr-2012	0.31	-0.50	Apr-2014	0.99	2.36	Apr-2016	0.30	-0.53	Apr-2018	0.30	-0.51	Apr-2020	0.42	-0.20
May-2012	0.17	-0.94	May-2014	1.00	2.60	May-2016	0.27	-0.61	May-2018	0.65	0.38	May-2020	0.38	-0.32
Jun-2012	0.10	-1.27	Jun-2014	0.99	2.46	Jun-2016	0.43	-0.18	Jun-2018	0.74	0.65	Jun-2020	0.39	-0.27
Jul-2012	0.19	-0.86	Jul-2014	1.00	2.77	Jul-2016	0.37	-0.33	Jul-2018	0.74	0.63			
Aug-2012	0.45	-0.13	Aug-2014	0.98	1.98	Aug-2016	0.38	-0.32	Aug-2018	0.73	0.61			
Sep-2012	0.50	0.00	Sep-2014	0.93	1.45	Sep-2016	0.44	-0.15	Sep-2018	0.84	0.98			
Oct-2012	0.48	-0.04	Oct-2014	0.91	1.34	Oct-2016	0.45	-0.12	Oct-2018	0.80	0.85			
Nov-2012	0.41	-0.23	Nov-2014	0.82	0.90	Nov-2016	0.43	-0.18	Nov-2018	0.74	0.64			
Dec-2012	0.33	-0.43	Dec-2014	0.82	0.93	Dec-2016	0.42	-0.19	Dec-2018	0.76	0.71			

As defined by McKee *et al.* (1993), a drought begins when the SPI value falls to or below -1, and ends when the SPI value moves from negative to zero or positive. The drought periods in Table 4.5 have been shaded grey.

The SPI values over the time periods of the precipitation records being analysed (53 – 127 years) can be more easily visualised in graphs. Figure 4.6 shows the monthly SPI-12 values for the full 53 years of the Wemmershoek Dam precipitation record, from December 1967 to June 2020. Figure 4.7 shows the same monthly SPI-12 values but indicates the drought and non-drought periods.

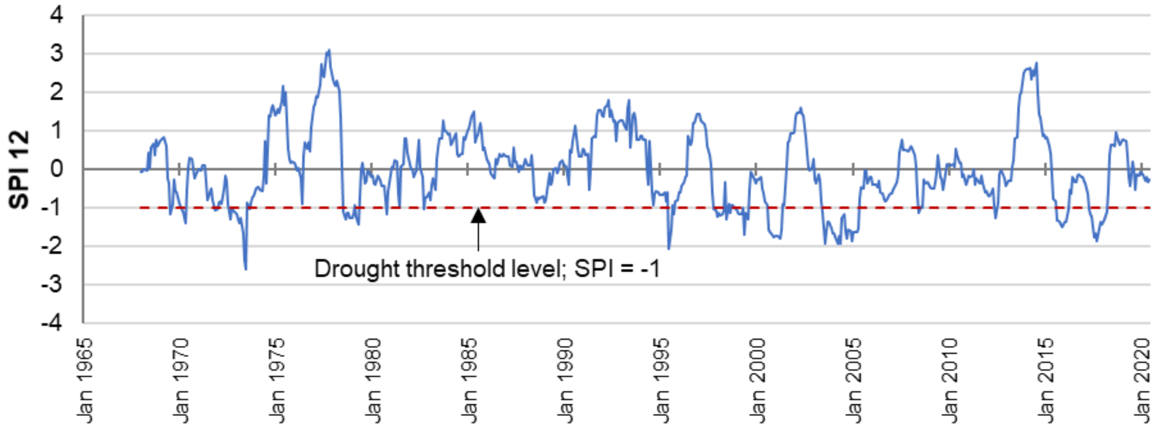


Figure 4.6: Wemmershoek Dam SPI-12 values, 1967 - 2020

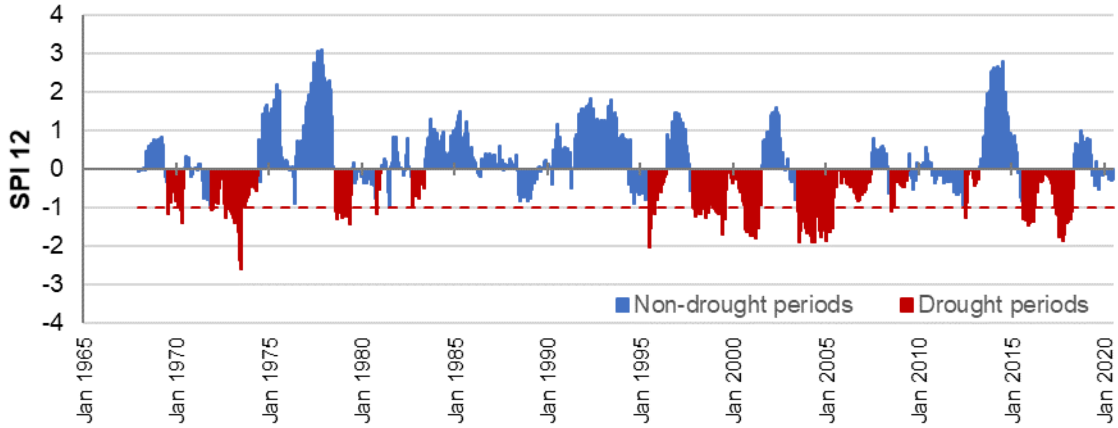


Figure 4.7: Wemmershoek Dam SPI-12 values, with drought periods indicated

An analysis of the SPI-12 values for the Wemmershoek Dam precipitation record showed that over the 53-year long record, there have been 11 droughts events, with durations ranging from 3 to 48 months. Table 4.6 summarises the characteristics of these 11 drought events, including duration, peak intensity, and magnitude.

Table 4.6: Historical drought events in the Wemmershoek Dam precipitation record

Drought event number	Start month	End month	Duration (months)	Peak severity (SPI)	Magnitude (ΣSPI)
1	Jul 1969	May 1970	11	-1.39	-9.24
2	Nov 1971	May 1974	31	-2.60	-29.34
3	Jul 1978	May 1979	11	-1.42	-12.51
4	Oct 1980	Dec 1980	3	-1.17	-1.82
5	Sep 1982	Apr 1983	8	-1.02	-4.91
6	Jun 1995	May 1996	12	-2.04	-9.53
7	Oct 1997	Jun 2001	45	-1.79	-45.57
8	Jun 2003	May 2007	48	-1.92	-47.87
9	Jun 2008	May 2009	12	-1.11	-6.12
10	Jun 2012	Mar 2013	10	-1.27	-3.87
11	Aug 2015	Apr 2018	33	-1.86	-31.88

The Wemmershoek Dam rainfall station is indicative of the precipitation in the Wemmershoek Dam catchment.

Figures 4.8 to 4.15 show the SPI values and drought periods for the rainfall stations indicative of precipitation in the catchment areas of the other five major dams of the WCWSS:

- Franschhoek-Robertsvlei rainfall station (Berg River Dam catchment)
- Rustfontein rainfall station (Theewaterskloof Dam catchment)
- Steenbras Dam rainfall station (Steenbras Upper and Lower Dam catchment)
- Tulbagh rainfall station (Voëlvlei Dam catchment)

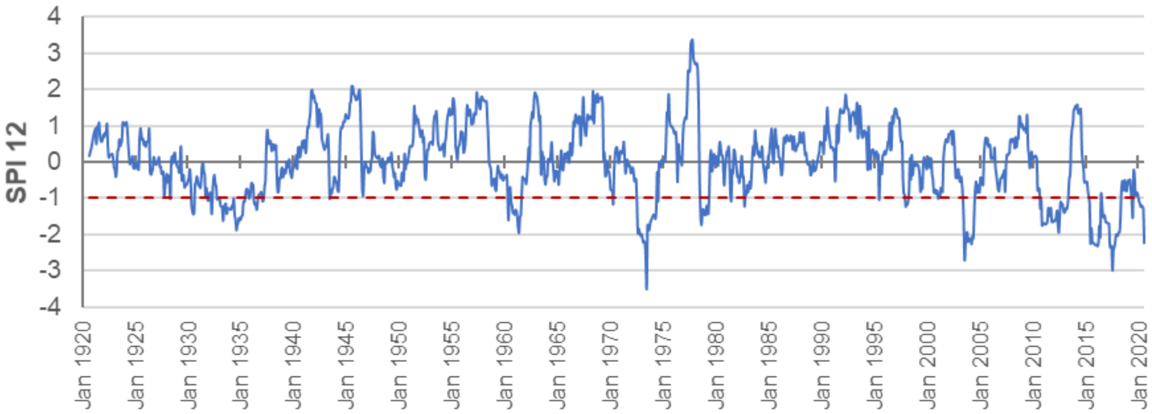


Figure 4.8: Franschhoek-Robertsvlei SPI-12 values, 1920 to 2020

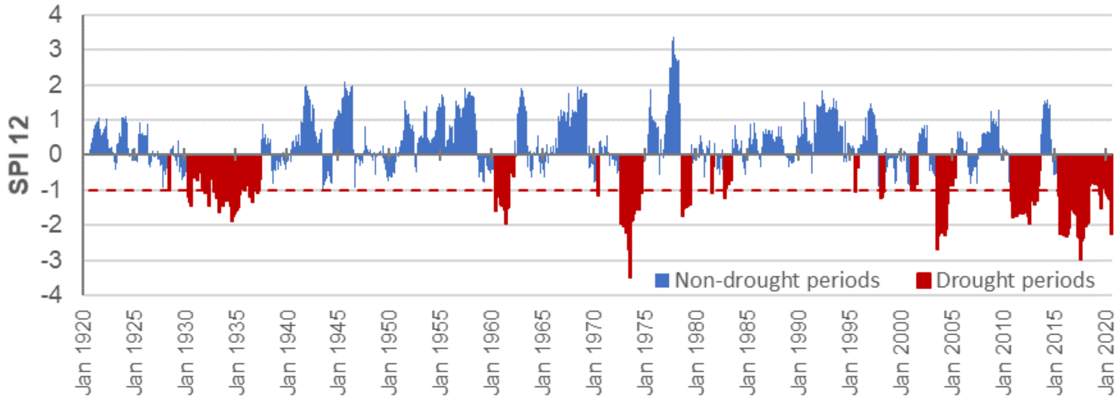


Figure 4.9: Franschhoek-Robertsvlei SPI-12 values, with drought periods indicated

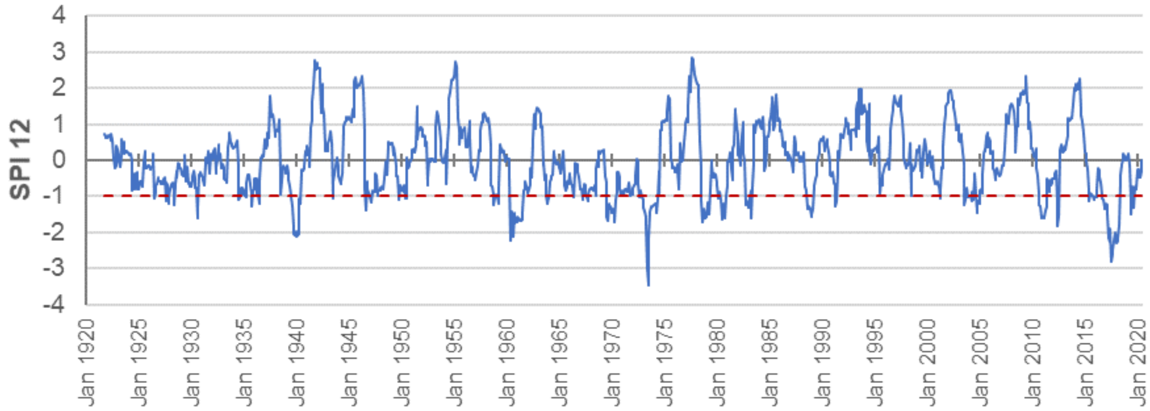


Figure 4.10: Rustfontein SPI-12 values, 1921 to 2020

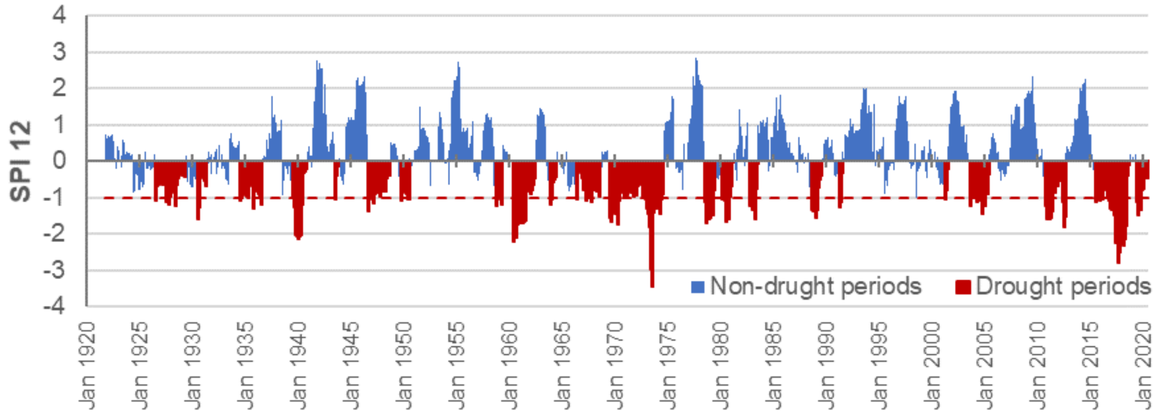


Figure 4.11: Rustfontein SPI-12 values, with drought periods indicated

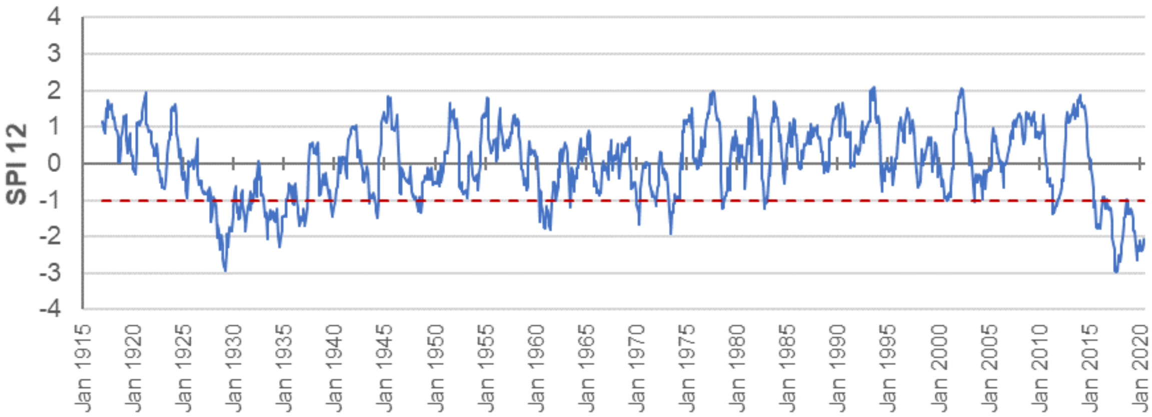


Figure 4.12: Steenbras Dam SPI-12 values, 1916 to 2020

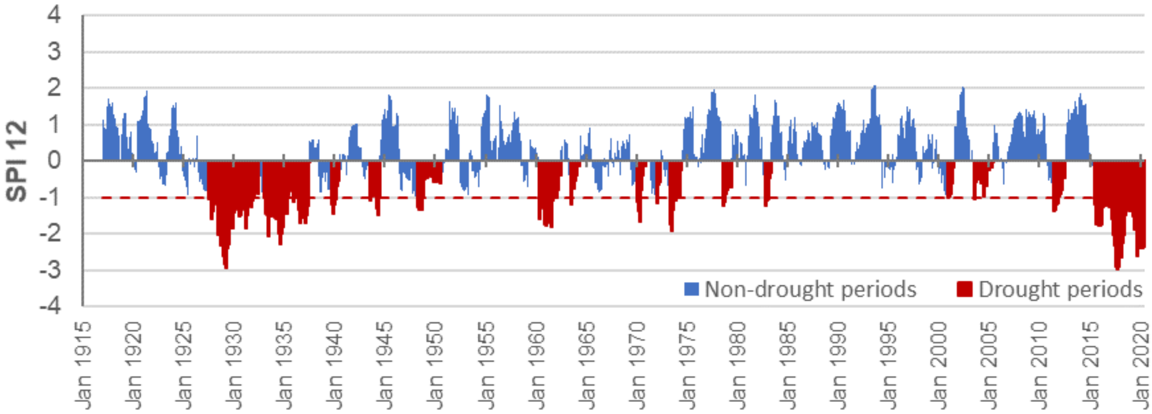


Figure 4.13: Steenbras Dam SPI-12 values, with drought periods indicated

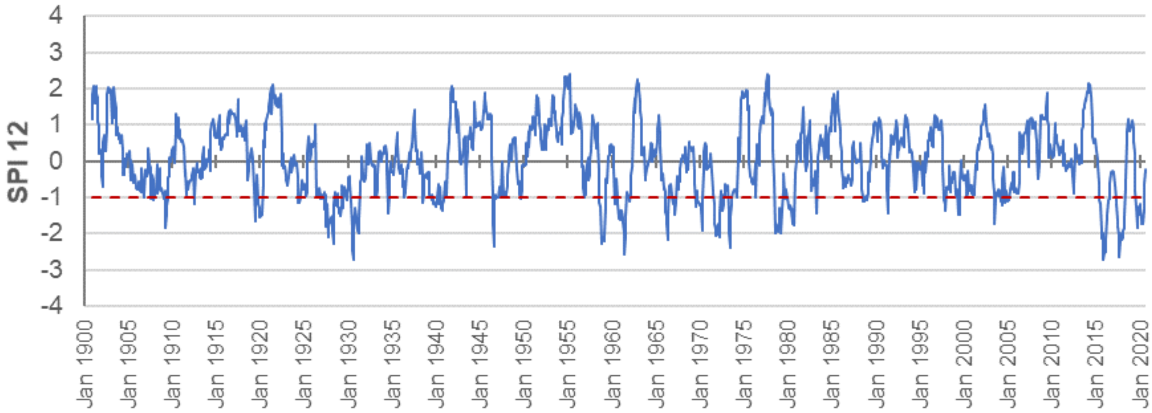


Figure 4.14: Tulbagh SPI-12 values, 1900 to 2020

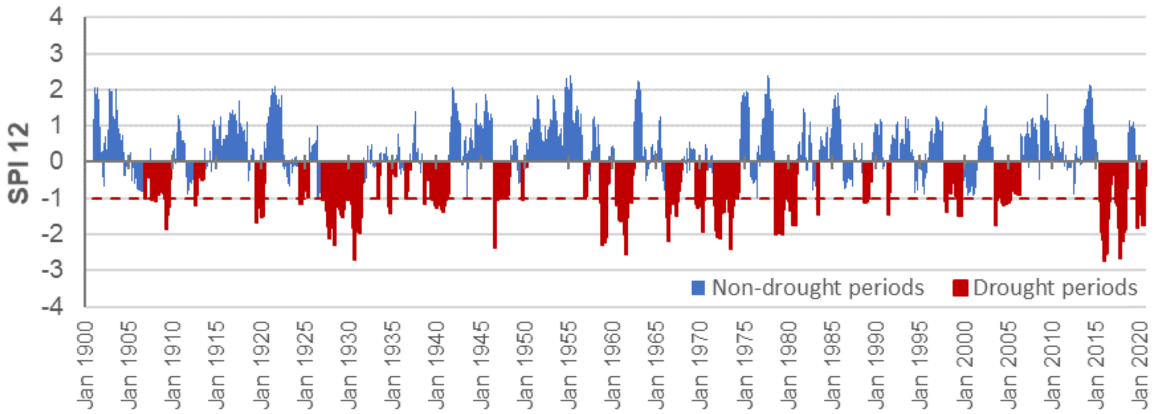


Figure 4.15: Tulbagh SPI-12 values, with drought periods indicated

The SPI values for the full records shown in Figures 4.8 – 4.15 are listed in Appendix B.

A few observations can be made from the above graphs:

- Significant droughts have repeatedly occurred during the 53 to 120-year records of the five rainfall stations in the catchment areas of the WCWSS dams.
- Severe droughts were experienced from 2015 – 2018 in the catchment areas. Of the five rainfall stations in the catchment areas of the six major dams of the WCWSS, four are still experiencing drought conditions in June 2020.

The SPI values for all 29 rainfall records were calculated.

The 29 precipitation records were analysed for the largest magnitude drought over the length of each individual record. Table 4.7 lists the total number of droughts, as well as the largest magnitude drought for each station, including the duration, and start and end date of this drought.

Table 4.7: Number of droughts and largest magnitude drought

No	Rainfall Station	Length of record (years)	Number of droughts	Largest magnitude drought			
				Magnitude (ΣSPI)	Duration (months)	Start date	End date
1	Altydgedacht	119	19	-114.61	62	Jun 2015	Jul 2020
2	Betty's Bay	93	18	-75.22	66	Jan 1970	Jun 1975
3	Bokveldskloof	58	11	-44.53	38	Jun 1971	Jul 1974
4	Boontjieskraal	101	25	-85.39	83	Sep 1967	Jan 1972
5	Cape Point	120	20	-58.66	49	Dec 1969	Jul 1974
6	Ceres	65	11	-61.23	57	Nov 1965	Jul 1970
7	Constantia Nek Reservoir	93	16	-83.99	60	Jul 2015	Jun 2020
8	Eendekuil	119	21	-109.03	64	May 2015	Aug 2020
9	Franschhoek Robertsvlei	100	14	-92.15	63	May 2015	Jul 2020
10	Kloof Nek Reservoir	96	19	-58.31	35	Jul 1948	May 1951
11	Langebaan	119	19	-69.15	61	Jul 1969	Jul 1974
12	Langgewens	89	17	-55.21	37	Nov 1939	Nov 1942
13	Middeldeurvlei	119	20	-81.66	55	Aug 2015	Feb 2020
14	Molteno Reservoir	131	32	-68.54	61	May 1927	May 1932
15	Newlands Reservoir	113	24	-66.93	61	Jun 2015	Jun 2020
16	Nuweberg	92	14	-93.73	62	Jun 2015	Jul 2020
17	Picketberg	120	21	-96.44	60	Jun 1969	May 1974
18	Porterville	60	13	-53.94	57	Aug 1969	Apr 1974
19	Remhoogte	67	12	-74.92	39	Jun 2015	Aug 2018
20	Robben Island	120	26	-67.42	55	Oct 1927	Apr 1932
21	Rustfontein	99	23	-51.23	38	Jun 2015	Jul 2018
22	Steenbras Dam	104	16	-109.21	61	Jun 2015	Jun 2020
23	Tulbagh	120	26	-71.71	56	Jan 1926	Jul 1931
24	Tygerberg Reservoir	65	20	-34.74	33	Sep 2010	May 2013
25	Vrugbaar	119	24	-94.64	63	May 2015	Jul 2020
26	Wemmershoek Dam	53	11	-47.87	48	Jun 2003	May 2007
27	Wolseley	120	27	-102.59	63	May 2015	Jul 2020
28	Woodhead Dam	127	29	-80.09	62	May 2015	Jun 2020
29	Wynberg Reservoir	91	17	-85.75	61	Jun 2015	Jun 2020

A few observations from the results of the above analysis:

- The largest magnitude droughts are mostly clustered around drought events during the periods 1969 – 1975 and 2015 – 2020. Of the 29 precipitation records, 20 have the largest magnitude droughts clustered around these dates:
    - 1970 – 1975: 6 (21%) of the precipitation records.
    - 2015 – 2020: 14 (48%) of the precipitation records.

  The remaining 9 (31%) were spread across other periods.

- Of the five rainfall stations representing precipitation in the five catchment areas, three experienced the largest magnitude droughts during the 2015 – 2020 period:
    - 2015 – 2020:
        - Franschhoek-Robertsvlei (Berg River Dam catchment)
        - Rustfontein (Theewaterskloof Dam catchment)
        - Steenbras Dam (Steenbras Dam catchment)
    - Tulbagh (Voelvlei Dam catchment) experienced its largest magnitude drought from 1926 – 1931.
    - Wemmershoek Dam (Wemmershoek Dam catchment) experienced its largest magnitude drought from 2003 – 2007.

The analysis of the SPI values indicated that the drought experienced from 2015 to 2020 was the highest magnitude for just under half of the rainfall stations in the WCWSS area. More specifically, these included rainfall stations in three of the five catchments of the main dams in the WCWSS.

4.3 Using the threshold approach to indicate SPI values

The SPI is important to index drought, and for the severity of dry conditions to be compared between different locations. However, as noted by Rahmat (2015), the index can be difficult for practitioners and decision makers to understand and therefore use to manage critical drought situations. This is also supported by experiences during the drought in Cape Town when key decisions were not made to respond to the drought due, in part, to clear information on the severity of the climatic situation not being readily available.

Rahmat (2015) proposed using a threshold approach, which relates the SPI values of zero and -1 to the precipitation values at a specific station. It therefore becomes easier and more intuitive to relate rainfall measurements to whether a drought has begun, is in progress, or has ended.

The mean (equivalent to SPI = 0) and the threshold (equivalent to SPI = -1) 12-month cumulative precipitations were calculated for each rainfall station. For each record, the 12-month moving average can therefore be used to determine when a drought has commenced (the 12-month moving cumulative precipitation falls below the threshold) or a drought has ended (the 12-month moving cumulative precipitation moves from below to above the SPI mean). The calculations were done using the statistical functions in Microsoft Excel.

To illustrate the above, the example of calculating the SPI mean and threshold values for the Wemmershoek Dam precipitation record is outlined below.

As described in Section 4.2, the SPI values for the 12-month cumulative record were calculated, using a gamma distribution fitted for all the values for each calendar month across the period of the record. For example, for the Wemmershoek Dam precipitation, a gamma distribution was fitted to a set of 12-month cumulative precipitation depths for the month of January for each year from 1968 to 2020. This is illustrated in Table 4.4. The cumulative probabilities for SPI values of 0 and -1 were determined by McKee, *et al* (1993) as 0.50 and 0.16 respectively, and subsequently by Edwards (1997) as 0.500 and 0.158 respectively.

Using the gamma distribution shape (α) and scale (β) parameters for each calendar month record, a precipitation value for the cumulative distribution values of 0.500 and 0.158 were used to calculate the mean and threshold precipitation values for each calendar month. The average of the mean and threshold precipitation values for the 12 calendar months were used for the overall record. The calculation method and values for the Wemmershoek Dam precipitation record is shown in Table 4.8. The SPI mean and threshold precipitation values were similarly calculated for all 29 precipitation records analysed in this research.

Table 4.8: Wemmershoek Dam mean and threshold 12-month cumulative precipitation

Month	**Gamma distribution parameters**		**SPI = 0 & cumulative probability = 0.5: Mean precipitation (mm)**	**SPI = -1 & cumulative probability = 0.158 Threshold precipitation (mm)**
	Shape (α)	**Scale (β)**		
January	17.00	57.94	966	748
February	17.88	55.09	967	754
March	17.08	57.68	966	748
April	17.01	57.81	964	747
May	17.29	56.85	964	748
June	15.26	64.33	961	733
July	16.45	59.96	967	745
August	16.32	60.41	966	744
September	15.74	62.56	964	739
October	16.53	59.65	966	745
November	17.08	57.65	966	748
December	17.74	55.54	967	753
Average			**965**	**746**
Standard Deviation			**1.78**	**5.70**

The 12-month moving cumulative precipitation for the Franschhoek-Robertsvlei, Rustfontein, Steenbras Dam, Tulbagh and Wemmershoek Dam rainfall stations, with mean (SPI = 0) and threshold (SPI = -1) precipitations, are shown in Figures 4.16 to 4.20 respectively.

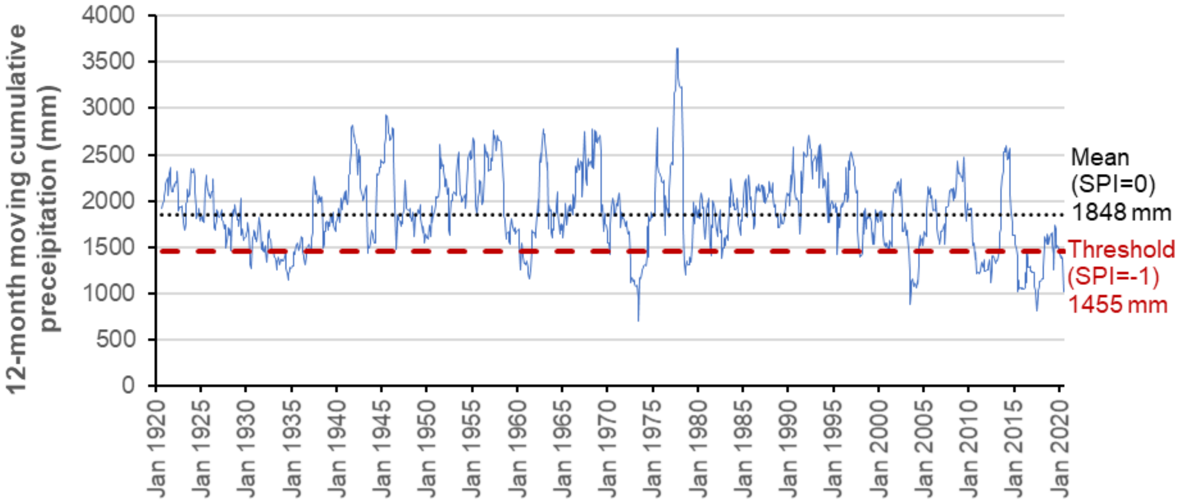


Figure 4.16: Franschhoek-Robertsvlei mean and threshold precipitation

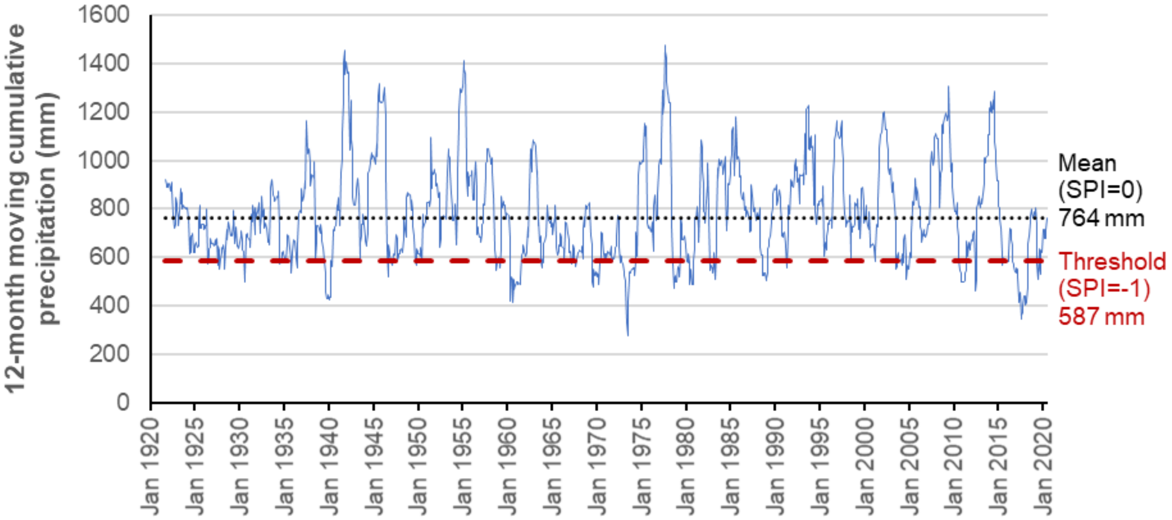


Figure 4.17: Rustfontein mean and threshold precipitation

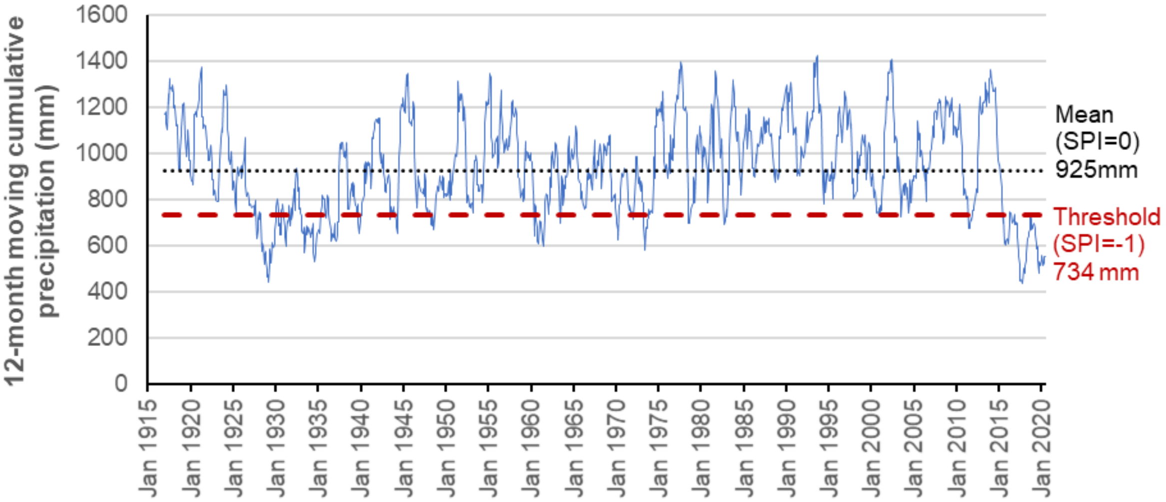


Figure 4.18: Steenbras Dam mean and threshold precipitation

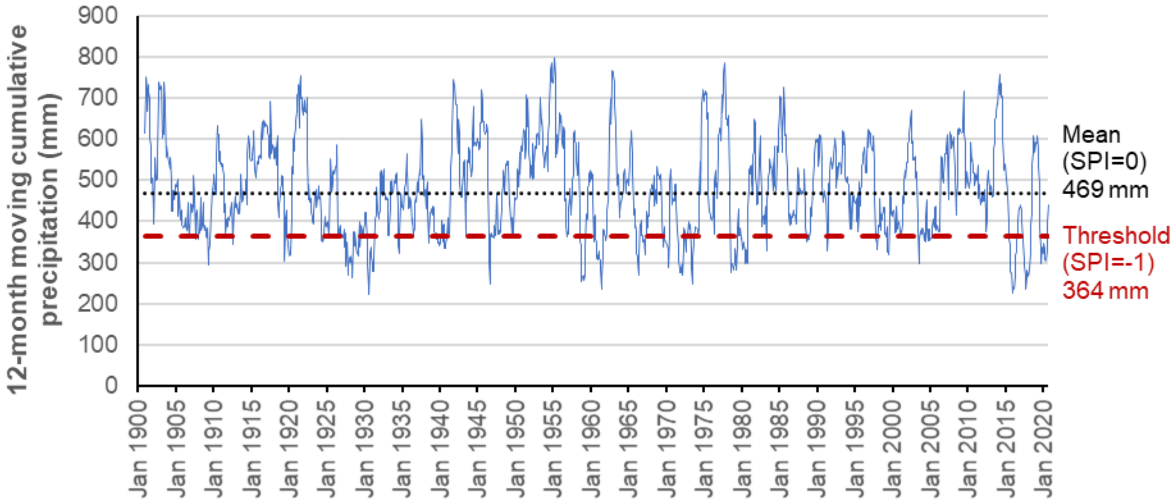


Figure 4.19: Tulbagh mean and threshold precipitation

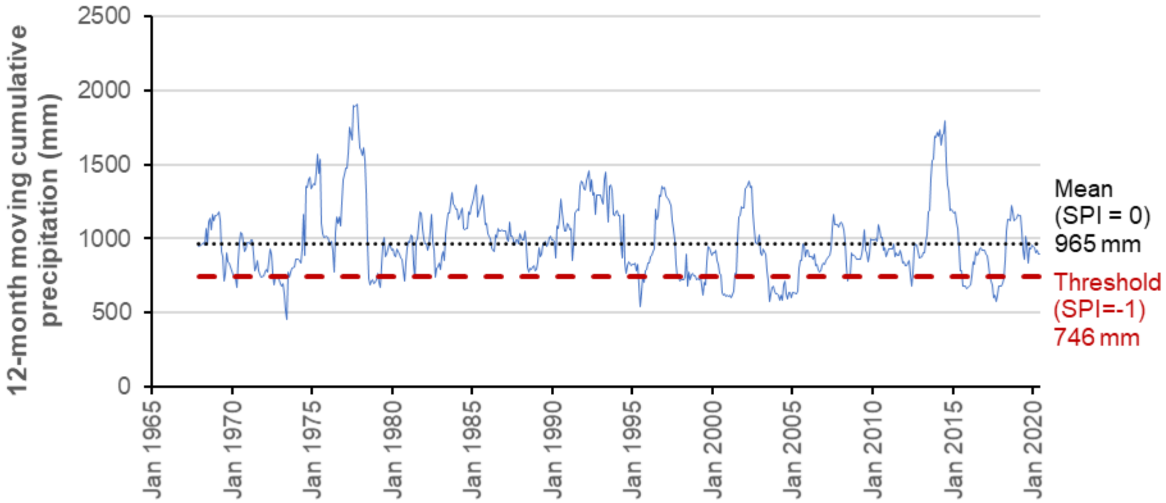


Figure 4.20: Wemmershoek Dam mean and threshold precipitation

The data shown in Figures 4.16 – 4.20 is also listed in Appendix B.

Table 4.9 lists the mean (SPI = 0) and threshold (SPI = -1) 12-month cumulative totals for each of the 29 precipitation records.

The mean and threshold precipitation values, related to the SPI values of 0 and -1, can be used to assess for a precipitation record whether a drought has begun, is in progress, or has ended. The more intuitive use of precipitation depths could make it easier for decision makers and water resource managers to relate drought conditions to actual rainfall measurements.

Table 4.9: Mean and threshold 12-month cumulative precipitation values

No	Station	12-month cumulative precipitation mean (SPI12 = 0) (mm)	12-month cumulative precipitation drought threshold (SPI12 = -1) (mm)
1	Altydgedacht	577	462
2	Betty's Bay	1 063	857
3	Bokveldskloof	674	502
4	Boontjieskraal	383	302
5	Cape Point	356	269
6	Ceres	1020	780
7	Constantia Nek Reservoir	1178	952
8	Eendekuil	297	224
9	Franschhoek Robertsvlei	1 848	1 455
10	Kloof Nek Reservoir	754	600
11	Langebaan	240	179
12	Langgewens	393	292
13	Middeldeurvlei	294	224
14	Molteno Reservoir	815	666
15	Newlands Reservoir	1 630	1 325
16	Nuweberg	1 518	1 161
17	Picketberg	455	355
18	Porterville	490	390
19	Remhoogte	935	697
20	Robben Island	404	317
21	Rustfontein	764	587
22	Steenbras Dam	925	734
23	Tulbagh	469	364
24	Tygerberg Reservoir	518	411
25	Vrugbaar	742	601
26	Wemmershoek Dam	965	746
27	Wolseley	628	491
28	Woodhead Dam	1 565	1 298
29	Wynberg Reservoir	1 138	877

The SPI-12 threshold values are plotted across the WCWSS area in Figure 4.21. The plot is generated using ESRI's ArcGIS software.

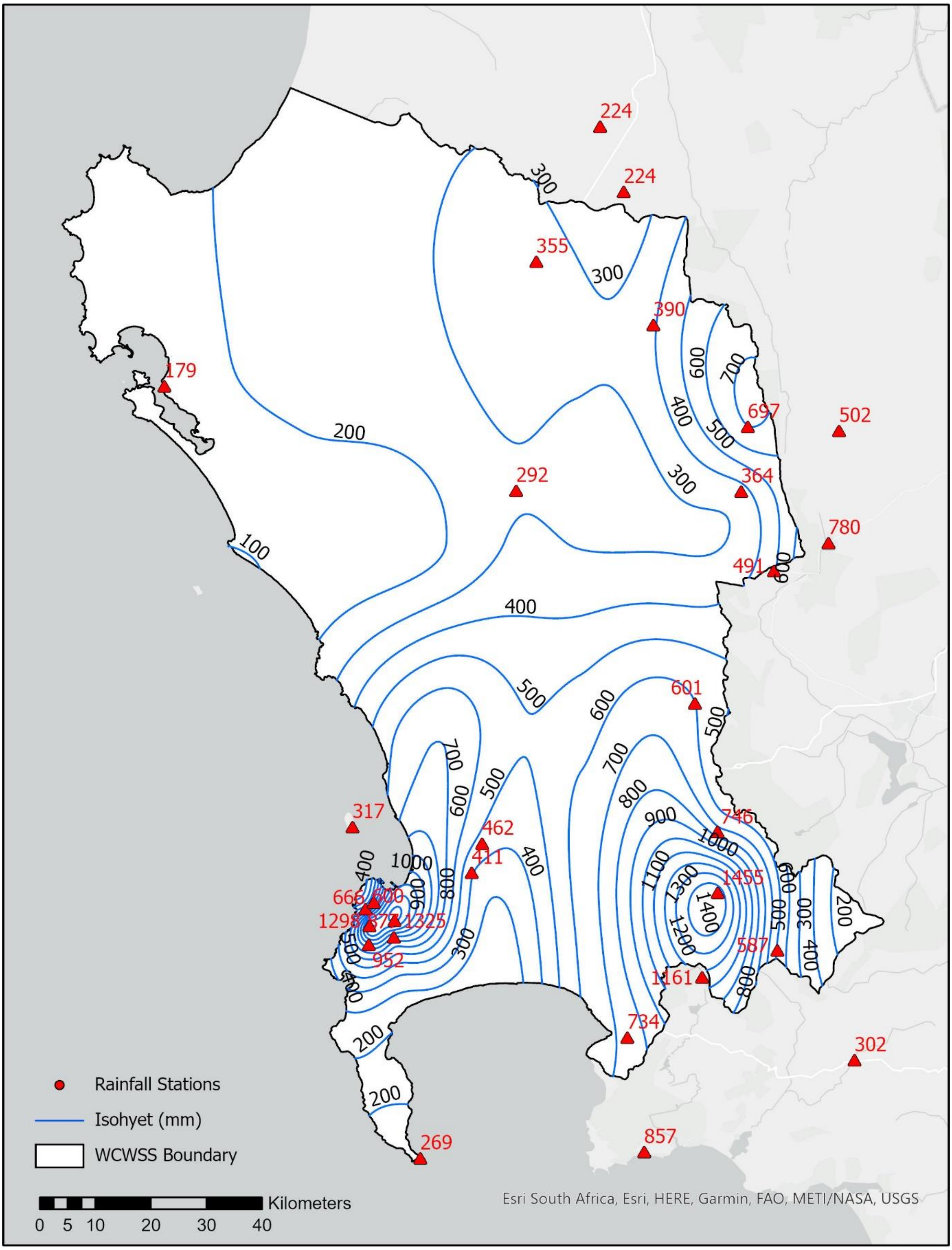


Figure 4.21: SPI-12 drought threshold precipitation isohyets over the WCWSS area

The isohyet plot of SPI-12 threshold precipitation values over the WCWSS area can be used to assess the onset of a drought at any location in the region by measuring at least 12 months of rainfall at that location.

4.4 SDF relationships of rainfall data in the supply area of the WCWSS

Drought severity, duration, and frequency relationships for all 29 precipitation records were determined. These relationships have been shown as severity-frequency-duration (SDF) curves.

SDF curves aim to combine the severity, duration and return periods of droughts, at a specific location, in one diagram. The severity and duration of droughts for the precipitation records in this research were determined using the SPI results discussed in previous sections. Return periods of droughts were determined using frequency analysis. The frequency analysis involved fitting historical drought events from a precipitation record to a probability distribution function, and then this function was used to estimate the magnitude of droughts for non-exceedance probabilities of 0.2, 0.1, 0.05, 0.02 and 0.01, which equates to return periods of 5, 10, 20, 50 and 100 years, respectively.

The example of deriving the SDF curves for the Wemmershoek Dam precipitation record is outlined below.

The derivation of the SDF curves uses the severity and duration of droughts identified by the SPI analysis. As shown in Table 4.6, for the Wemmershoek Dam precipitation record, over the 52-year record of 12-month cumulative SPI values, 11 drought events have occurred, with durations varying from 3 to 48 months.

Frequency analysis to produce the SDF curves were done for droughts of durations of 1 – 6 months. The number of droughts which had a minimum duration of 1 – 6 months were identified. For drought events that were longer than the SDF duration being analysed, the highest magnitude drought for the durations of 1 and consecutive 2 – 6-month periods were identified in each drought event. As an example, in the Wemmershoek Dam record, for the 2-month duration analysis, for the drought event from August 2015 to April 2018 that lasted 33 months, the 2 months with largest magnitude drought were September and October 2017, with a combined magnitude of -3.55 (see Tables 4.5 and A4).

Table 4.10 shows the cumulative SPI-12 values with the highest magnitude for durations of 1 - 6 months for each drought event in the Wemmershoek Dam precipitation record. The events are arranged in order of decreasing magnitude for each drought duration.

Table 4.10: Wemmershoek Dam highest drought magnitudes per drought event

Drought event number	Highest drought magnitudes for 1 – 6 months duration per drought event (ΣSPI)					
	1 month	2 months	3 months	4 months	5 months	6 months
1	-2.60	-4.96	-6.60	-7.87	-9.26	-10.60
2	-2.04	-3.66	-5.55	-7.28	-8.93	-10.54
3	-1.92	-3.59	-5.30	-6.99	-8.73	-10.38
4	-1.86	-3.55	-5.26	-6.99	-8.34	-9.76
5	-1.79	-3.52	-4.52	-5.68	-6.48	-7.28
6	-1.42	-2.65	-3.64	-4.78	-6.03	-7.22
7	-1.39	-2.48	-3.49	-4.46	-5.30	-5.90
8	-1.27	-2.13	-3.06	-3.30	-3.80	-4.19
9	-1.17	-2.07	-2.44	-3.02	-3.64	-3.97
10	-1.11	-1.73	-2.26	-2.26	-2.30	-2.53
11	-1.02	-1.72	-1.82			

For the SDF curves, the actual precipitation depths were used to generate the SDF curves. This allows the SDF curves to be used to assess the return period of a drought if the appropriate precipitation data is available for the rainfall stations that were analysed. Table 4.11 shows the associated precipitation depths for the drought magnitudes listed in Table 4.10. The precipitation depths are cumulative – for example, the precipitation depths for the 2-month duration are the total for the highest magnitude 2-month drought per event.

Table 4.11: Wemmershoek Dam precipitation depths of highest magnitude droughts

Drought event number	Total precipitation depths for highest drought magnitudes for 1 – 6 months duration per drought event (mm)					
	1 month	2 months	3 months	4 months	5 months	6 months
1	451.9	963.7	1590.3	2288.0	2967.9	3656.7
2	539.5	1179.5	1779.2	2398.6	3025.5	3662.7
3	577.1	1192.5	1795.7	2411.1	3065.8	3690.2
4	577.7	1196.0	1835.3	2455.3	3092.6	3768.3
5	602.8	1223.3	1939.0	2646.0	3431.9	4222.9
6	666.5	1370.9	2125.1	2824.6	3530.9	4251.4
7	672.6	1404.6	2155.5	2911.3	3695.5	4526.7
8	679.8	1453.7	2211.4	3117.9	3981.7	4860.2
9	711.7	1463.8	2348.6	3187.0	4004.2	4894.5
10	712.3	1540.5	2389.4	3352.6	4309.7	5222.8
11	736.1	1555.2	2497.2			

The precipitation depths for each of the above periods analysed is then fitted to an appropriate probability distribution, which is used to calculate the theoretical drought precipitation depths for commonly used return periods of 5, 10, 20, 50 and 100 years.

In two similar recent studies, Rahmat (2014) produced SDF curves for the state of Victoria, Australia, and Juliani and Okawa (2017) derived curves for the Minas Gerais region of Brazil.

To produce SDF curves, Rahmat (2014) used a Log Pearson Type III (LP3) distribution and found an acceptable goodness of fit. Juliani and Okawa (2017) used a gamma two parameter distribution, and also found an acceptable goodness-of-fit.

For this research, the Minitab software was used to assess the goodness-of-fit of the LP3 and gamma distributions on a sub-set of the precipitation records. The gamma two parameter distribution was consistently found to have a better goodness-of-fit than the LP3 distribution, and therefore it was used to calculate the SDF relationships in this research.

Table 4.12 shows the results of the calculation of the precipitation depths for the SDF design return periods of 1 - 6 months, using the gamma distribution fitted to each of the drought duration periods, for the Wemmershoek Dam precipitation record. The SDF relationships were similarly calculated for all 29 precipitation records used in this research.

These SDF relationships are then used to generate SDF curves. The SDF curves for the Franschhoek-Robertslei (Berg River Dam), Rustfontein (Theewaterskloof Dam), Steenbras Dam, Tulbagh (Voelvlei Dam) and Wemmershoek Dam rainfall stations are shown in Figures 4.22 – 4.26 respectively. The SDF curves were plotted using return periods of 1 in 5, 10, 20, 50 and 100 years.

Table 4.12: Wemmershoek Dam drought SDF relationships

Exceedance probability	Return period (years)	Cumulative 12-month precipitation (mm)					
		1-month duration	2-month duration	3-month duration	4-month duration	5-month duration	6-month duration
1%	100.0	444.4	938.3	1 463.6	1 999.4	2 552.2	3 105.2
2%	50.0	463.5	977.9	1 525.3	2 078.4	2 652.2	3 227.1
3%	33.3	475.9	1 003.7	1 565.3	2 129.6	2 716.9	3 306.2
4%	25.0	485.4	1 023.4	1 596.0	2 168.7	2 766.3	3 366.5
5%	20.0	493.2	1 039.5	1 621.1	2 200.9	2 807.0	3 416.1
6%	16.7	499.9	1 053.5	1 642.8	2 228.5	2 841.9	3 458.8
7%	14.3	505.8	1 065.8	1 662.0	2 252.9	2 872.8	3 496.4
8%	12.5	511.2	1 076.9	1 679.2	2 275.0	2 900.6	3 530.4
9%	11.1	516.1	1 087.0	1 695.0	2 295.1	2 926.0	3 561.5
10%	10.0	520.7	1 096.5	1 709.7	2 313.8	2 949.6	3 590.3
20%	5.0	555.3	1 168.1	1 821.2	2 455.6	3 128.8	3 809.0
30%	3.3	581.2	1 221.7	1 904.6	2 561.5	3 262.4	3 972.2
40%	2.5	604.0	1 268.8	1 977.9	2 654.3	3 379.6	4 115.3
50%	2.0	625.8	1 313.9	2 048.0	2 743.1	3 491.6	4 252.1
60%	1.7	648.1	1 360.1	2 119.8	2 833.8	3 606.1	4 391.9
70%	1.4	672.6	1 410.7	2 198.4	2 933.0	3 731.4	4 544.9
80%	1.3	702.0	1 471.4	2 292.9	3 052.1	3 881.5	4 728.3
90%	1.1	744.2	1 558.5	2 428.3	3 222.4	4 096.3	4 990.7
99%	1.0	851.0	1 778.6	2 770.6	3 651.7	4 637.4	5 651.9
Gamma distribution parameters							
Shape (α)		51.8	53.5	53.7	60.2	61.3	60.9
Scale (β)		12.1	24.7	38.4	45.8	57.3	70.2

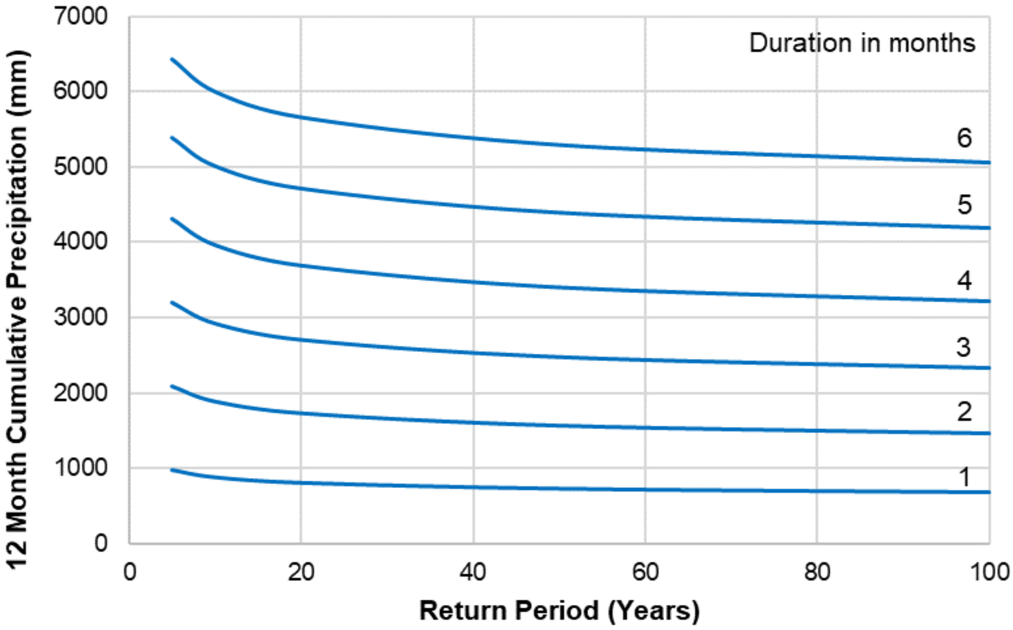


Figure 4.22: SDF curves for Franschhoek-Robertsvlei

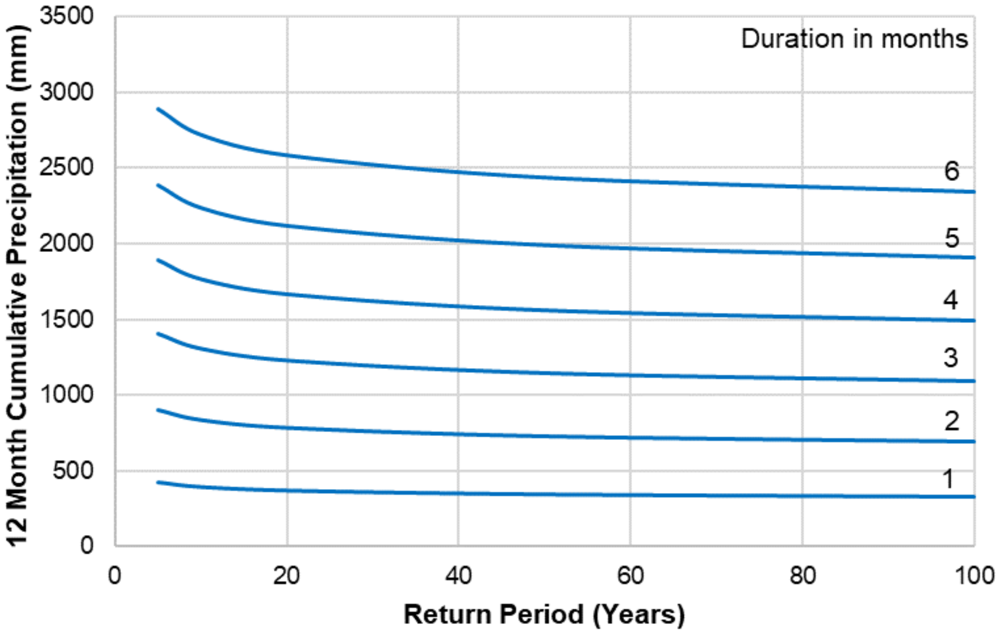


Figure 4.23: SDF curves for Rustfontein

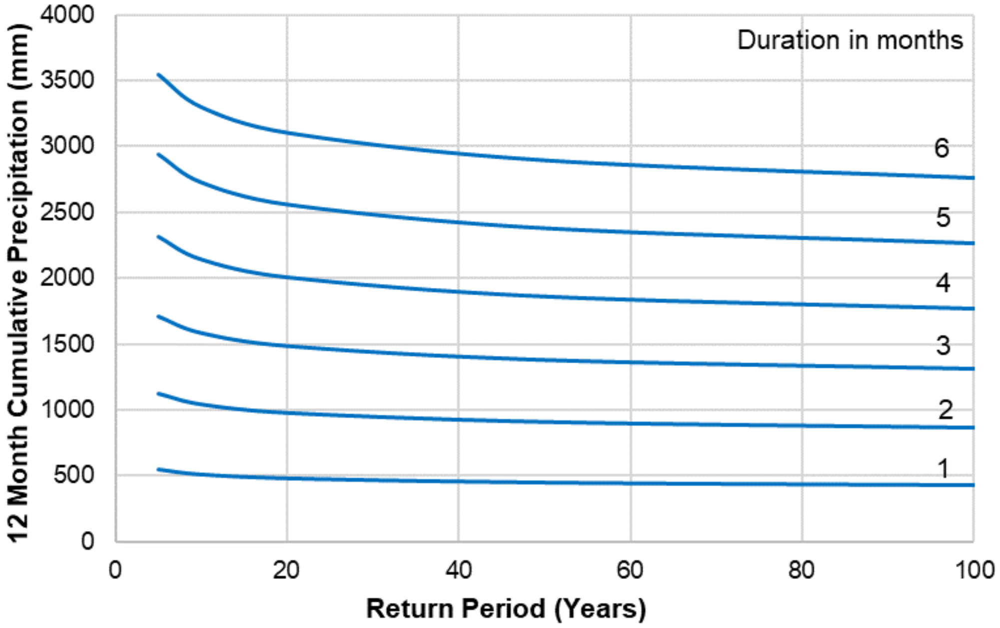


Figure 4.24: SDF curves for Steenbras Dam

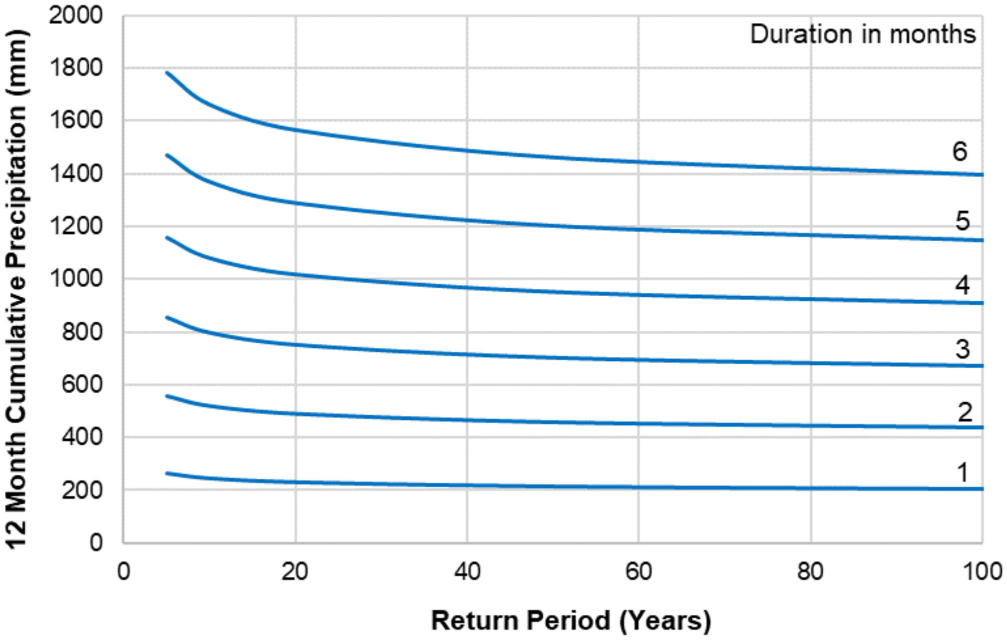


Figure 4.25: SDF curves for Tulbagh

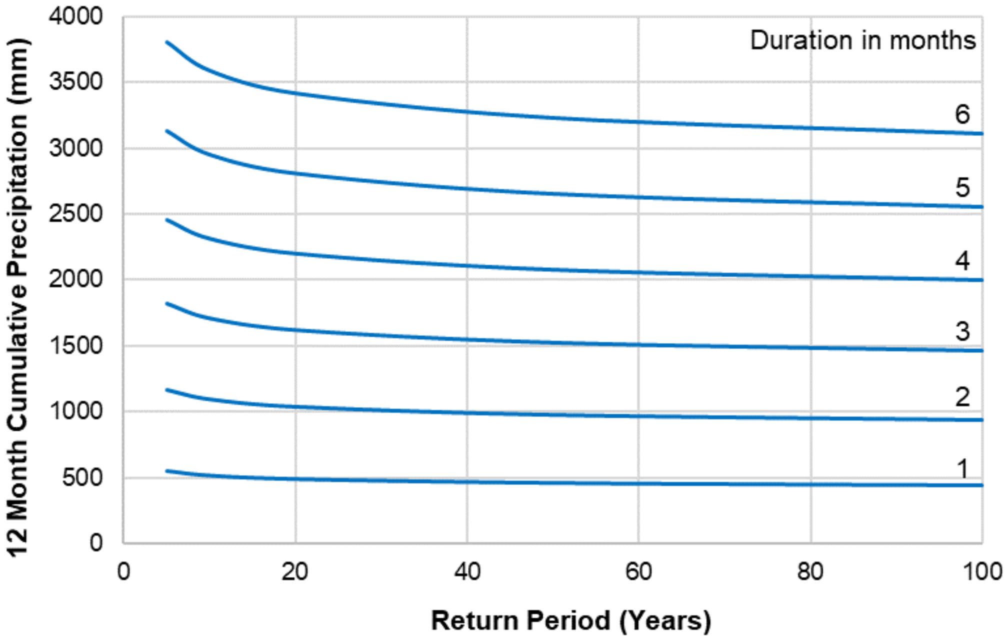


Figure 4.26: SDF curves for Wemmershoek Dam

The goodness-of-fit of the gamma distributions to the drought occurrences for each of the durations used for the SDF plots were tested using the Kolmogorov-Smirnov (K-S) test. The test procedure is outlined in Ang & Tang (2007) and detailed in Section 3.3. The analysis below was done using the XLStat software.

The K-S test assumes the following null (H0) and alternative (Ha) hypotheses:

H0: The sample being tested follows a gamma distribution.
Ha: The sample being tested does not follow a gamma distribution.

The K-S test determines a D-value, which is the maximum difference between a theoretical and the actual cumulative distribution function (CDF) for which the goodness-of-fit (GOF) is being tested. An associated observed p-value is calculated for the D-value, and this is compared to the significance level being considered in the GOF test, which is usually 0.05.

If the observed p-value is equal to or larger than the significance level, then the null hypothesis cannot be rejected – in the case of this analysis that the distribution being tested follows a gamma distribution. If not, then the null hypothesis is rejected and the alternative hypothesis is accepted – here, that the observed distribution does not follow a gamma distribution.

The observed p-values for the 29 precipitation records, for each of the distributions for 1 – 6 months duration, are shown in Table 4.13.

Table 4.13: Kolmogorov-Smirnov goodness-of-fit test observed p-values

No	Rainfall Station	Kolmogorov-Smirnov Test Observed P-Values					
		1 month	2 months	3 months	4 months	5 months	6 months
1	Altydgedacht	0.124	0.269	0.213	0.456	0.392	0.377
2	Betty's Bay	0.626	0.219	0.220	0.167	0.183	0.259
3	Bokveldskloof	0.722	0.957	0.626	0.461	0.429	0.516
4	Boontjieskraal	0.396	0.170	0.487	0.384	0.626	0.726
5	Cape Point	0.146	0.066	0.061	0.097	0.079	0.091
6	Ceres	0.795	0.981	0.975	0.991	0.957	0.828
7	Constantia Nek	0.788	0.919	0.925	0.904	0.994	0.897
8	Eendekuil	0.085	0.321	0.407	0.641	0.501	0.409
9	Franschhoek	0.261	0.825	0.953	0.974	0.881	0.891
10	Kloof Nek	0.645	0.335	0.319	0.311	0.362	0.412
11	Langebaan	0.798	0.935	0.992	0.985	0.996	0.997
12	Langgewens	0.206	0.343	0.338	0.367	0.349	0.370
13	Middeldeurvlei	0.405	0.432	0.359	0.542	0.745	0.837
14	Molteno	0.068	0.225	0.408	0.110	0.191	0.355
15	Newlands	0.165	0.392	0.559	0.622	0.714	0.840
16	Nuweberg	0.555	0.913	0.308	0.504	0.540	0.573
17	Picketberg	0.321	0.834	0.812	0.930	0.893	0.960
18	Porterville	0.358	0.330	0.656	0.476	0.594	0.535
19	Remhoogte	0.338	0.611	0.742	0.419	0.437	0.471
20	Robben Island	0.702	0.640	0.639	0.495	0.580	0.588
21	Rustfontein	0.372	0.330	0.307	0.741	0.686	0.577
22	Steenbras	0.314	0.492	0.394	0.305	0.233	0.305
23	Tulbagh	0.707	0.514	0.994	0.998	0.965	0.901
24	Tygerberg	0.592	0.831	0.992	0.983	0.991	0.972
25	Vrugbaar	0.311	0.659	0.593	0.378	0.365	0.252
26	Wemmershoek	0.578	0.866	0.927	0.747	0.623	0.633
27	Wolseley	0.615	0.555	0.385	0.593	0.563	0.973
28	Woodhead	**0.041**	0.274	0.220	0.194	0.271	0.180
29	Wynberg	0.578	0.539	0.422	0.509	0.506	0.535

Almost all observed p-values for all stations and durations were greater than the significance level of 0.05. This indicates that the hypotheses for the distributions tested – that the distributions follow a gamma distribution - cannot be rejected and can be accepted. The only exception is for the 1-month duration Woodhead distribution (shown in bold red in Table 4.13).

However, the p-value is only just below the significance value of 0.05, and therefore the gamma distribution will be used for this distribution.

The SDF plots can now be used to read off the return periods of droughts of durations from 1 – 6 months, using 12-month cumulative precipitation values taken from the associated rainfall record.

4.5 Regional mapping of SDF relationships

As discussed in section 4.4, SDF relationships were determined for all 29 precipitation records considered in this research. SDF curves were developed for key precipitation records in the catchment areas of the WCWSS, to allow for droughts in these catchment areas to be directly read off from the curves.

However, to show the regional distribution of SDF relationships across the WCWSS, the SDF relationships derived in Section 4.4 were drawn as isohyet plots across the WCWSS region.

The regional mapping was done using the ESRI ArcGIS Pro software, which is widely used to analyse and map data spatially, including for hydrological applications.

To generate the regional SDF maps, the Raster Interpolation and Contour functions were used to convert SDF point data of the 29 precipitation records into SDF isohyets.

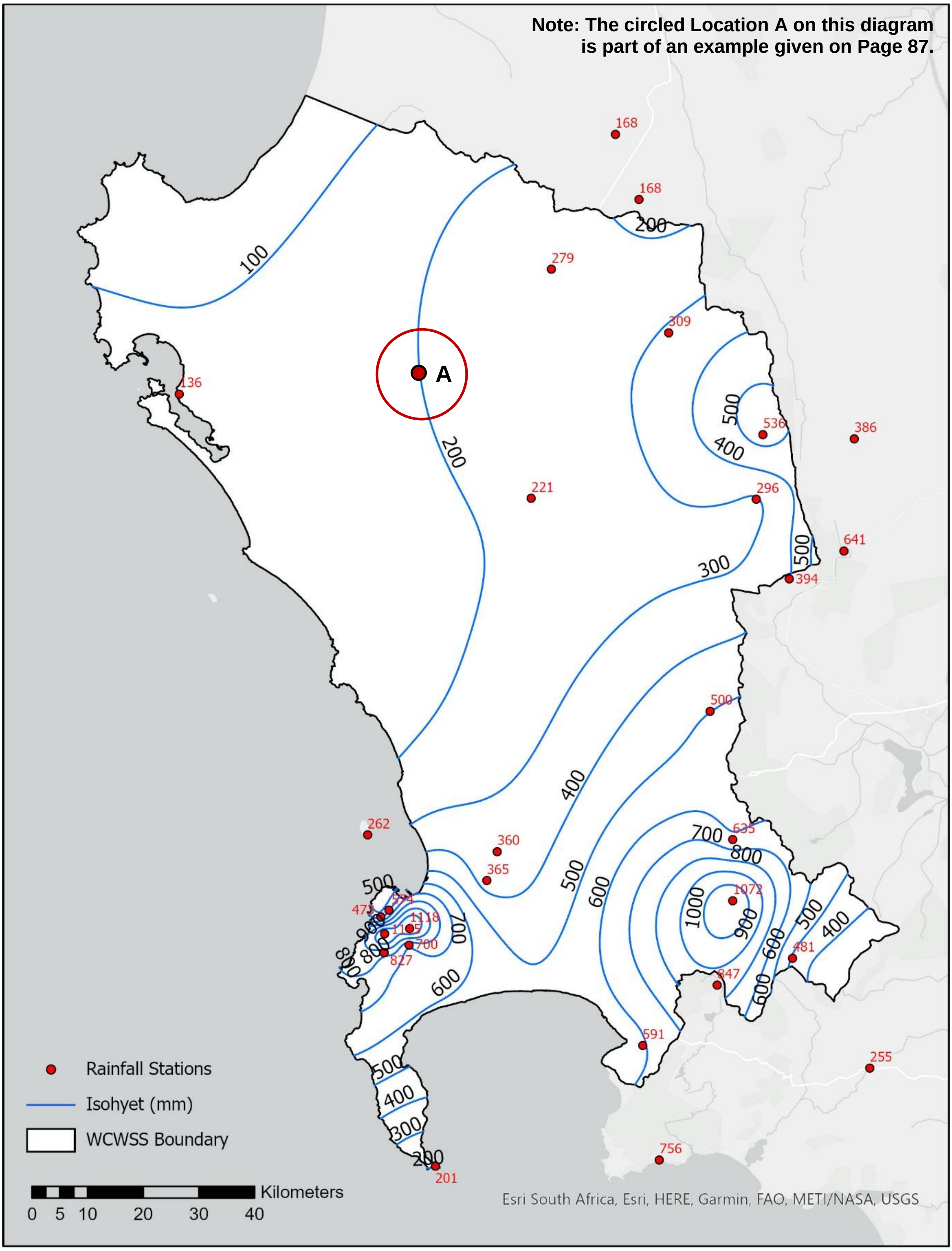
The SDF isohyet maps show the precipitation depths in mm, for durations of droughts of 1 – 6 months, for drought return periods of 5, 10, 20, 50 and 100 years.

For brevity, only the maps of the SDF isohyets for 6-month drought durations for return periods of 5, 10, 20, 50 and 100 years are included in Figures 4.27 – 4.31. The drought severities are expressed in the precipitation depths related to the cumulative 12-month SPI data. For ease of display and reference, the cumulative 12-month precipitation depths for the 6-month drought durations are shown as a monthly average.

The regional maps provide a complementary way to the SDF curves to show the distribution of SDF relationships regionally.

Using the plots, SDF relationships can be assessed at any location in the WCWSS area by collecting between 12 to 18 (continuous) months of rainfall measurements.

As an example, say, in Figure 4.27 at the circled location A, if monthly rainfall data is collected for 18 months, then a series of moving 12-month cumulative precipitation can be calculated for a period of 6 months. If the average of these 6 months at location A is 200 mm, then a 6-month 1:5 year drought is reported.



Note: The circled Location A on this diagram is part of an example given on Page 87.

Figure 4.27: Isohyets of the cumulative 12-month precipitation, measured as an average over a 6-month period for a 1:5 year drought event

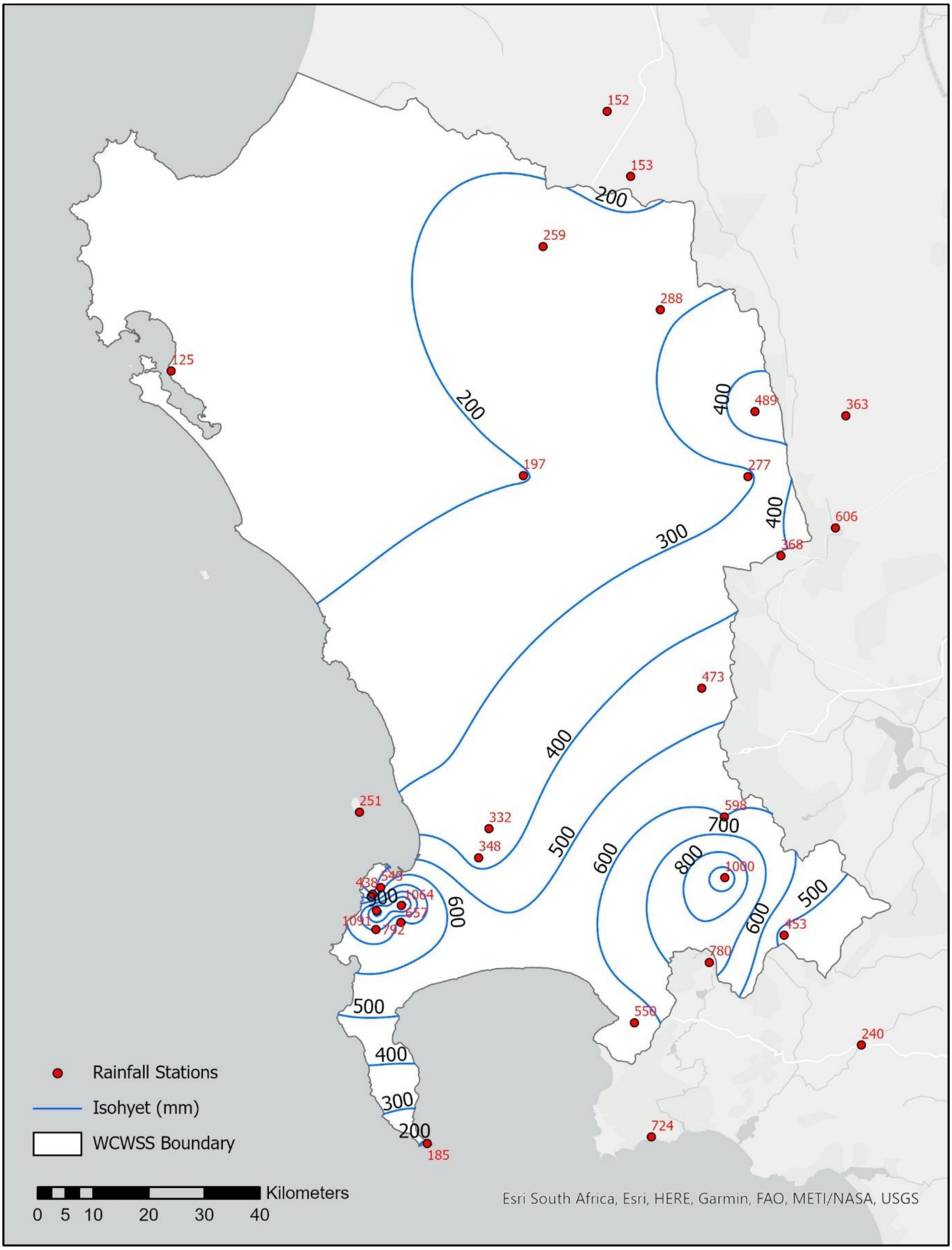


Figure 4.28: Isohyets of the cumulative 12-month precipitation, measured as an average over a 6-month period for a 1:10 year drought event

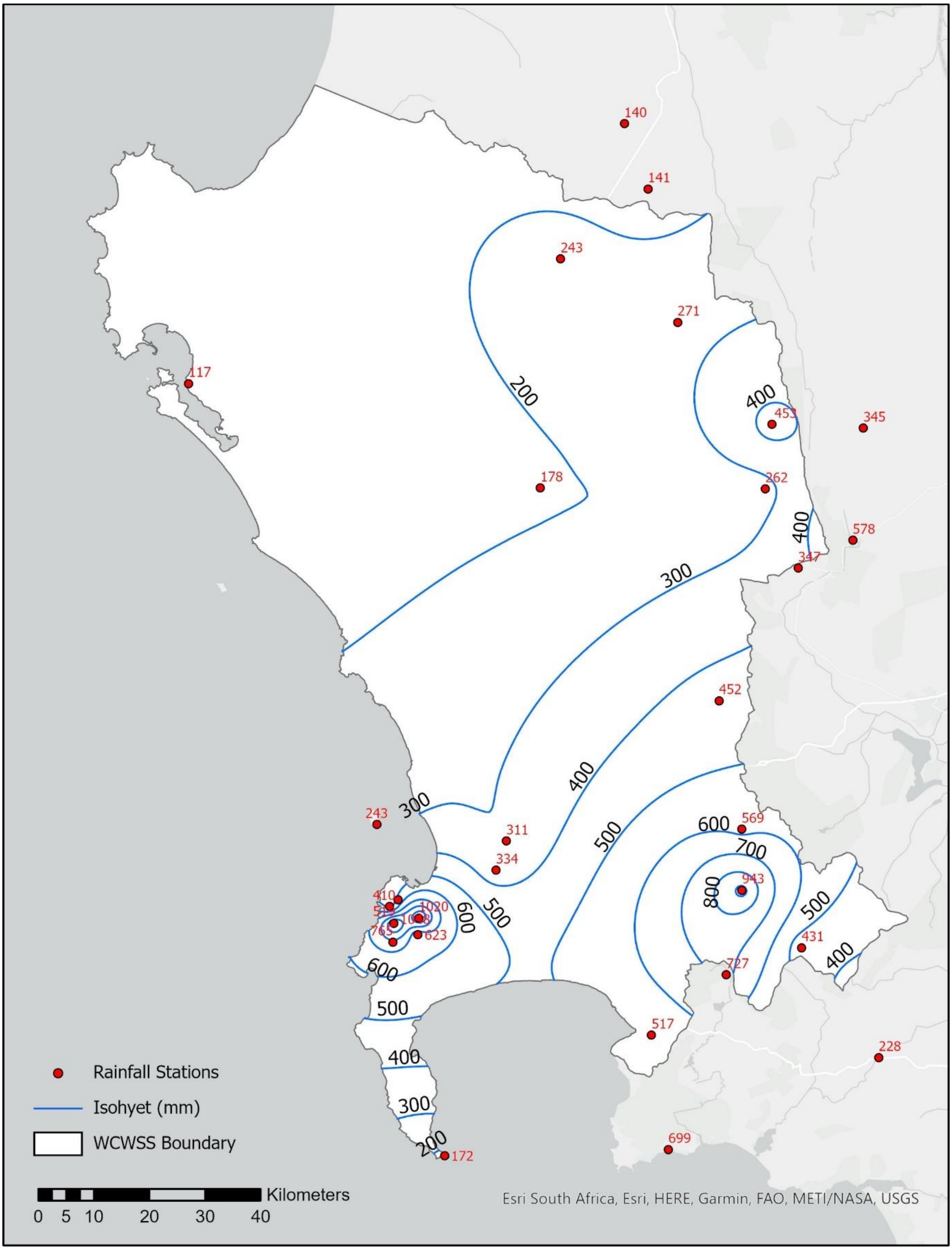


Figure 4.29: Isohyets of the cumulative 12-month precipitation, measured as an average over a 6-month period for a 1:20 year drought event

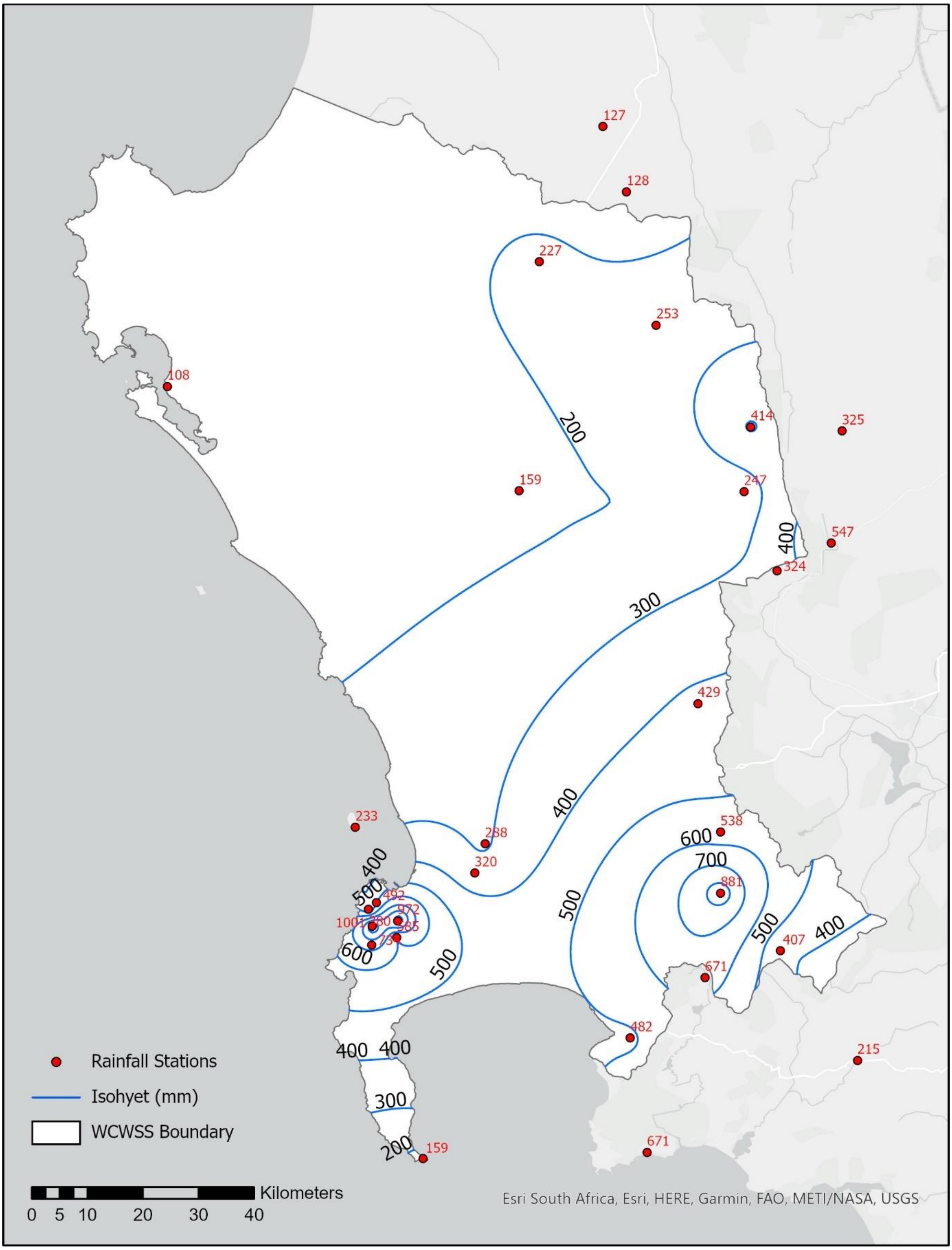


Figure 4.30: Isohyets of the cumulative 12-month precipitation, measured as an average over a 6-month period for a 1:50 year drought event

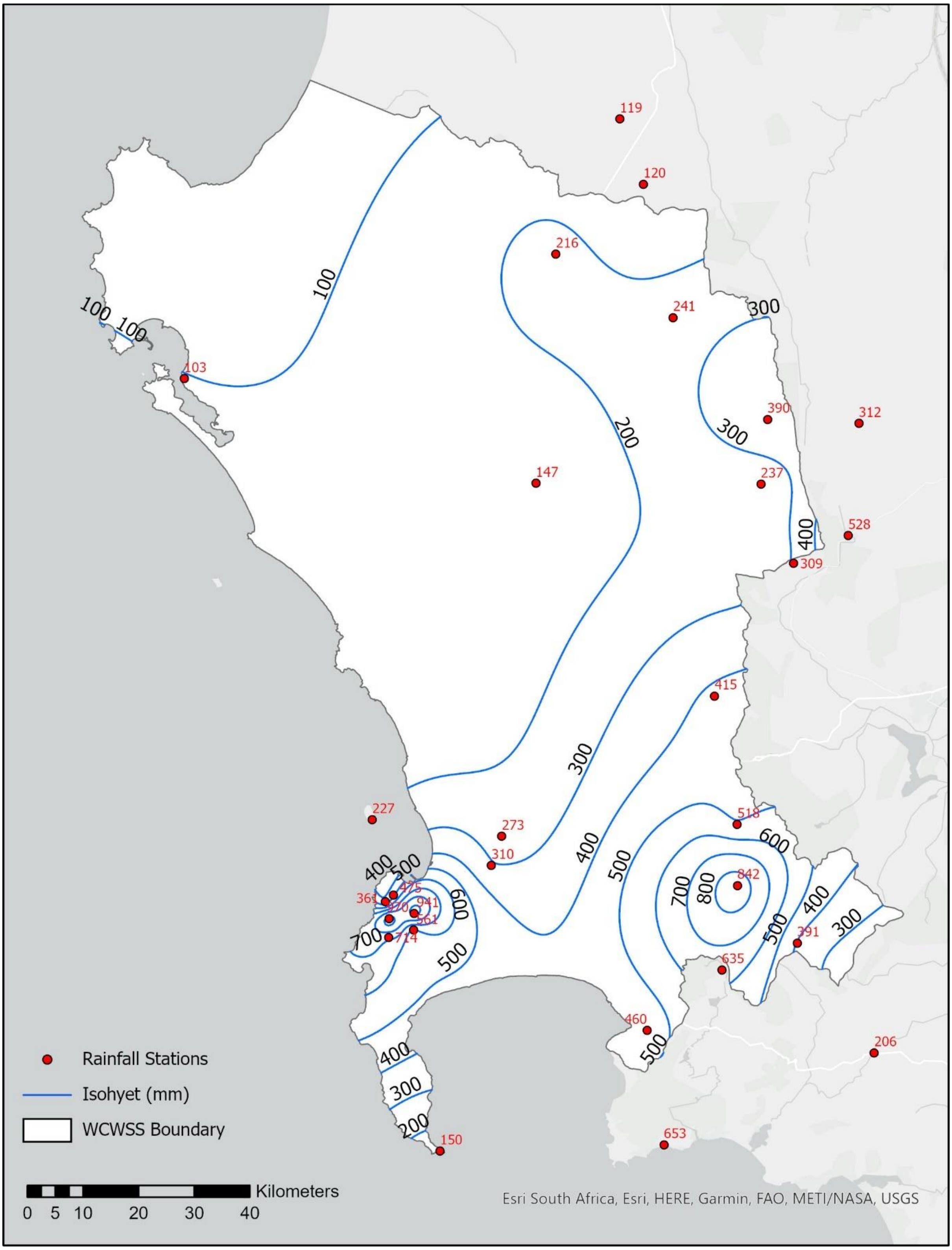


Figure 4.31: Isohyets of the cumulative 12-month precipitation, measured as an average over a 6-month period for a 1:100 year drought event

5. CASE STUDY OF DROUGHTS IN THE WCWSS AREA DURING 2015 - 2020

A case study was conducted to quantify and understand the severity and duration of the droughts experienced in the WCWSS area during the period from 2015 – 2020, using the SPI-12 values calculated and the threshold values and SDF curves developed in Section 4.2 – Section 4.4. The case study illustrated the application of the information developed to detect and quantify droughts in the WCWSS area. As this research focused on providing information to assist water resource managers, the case study focused on rainfall stations in the catchments of the major dams of this supply system. Section 5.1 describes the use of threshold values to determine the start and end of droughts. The SPI-12 values were also used to quantify droughts that had occurred, which is covered in Section 5.2. Lastly, Section 5.3 discusses how the SDF curves were used to determine the return periods of droughts experienced in the catchment areas of the WCWSS.

5.1 Determining the onset of drought using the threshold values

The SPI precipitation mean (SPI = 0) and threshold (SPI = -1) values developed in Section 4.3 were used to determine the onset and end of the droughts in the catchment of the main storage dams of the WCWSS during 2015 – 2020.

The advantage of this method is that it only requires the SPI mean and threshold precipitation values, together with the 12-month moving cumulative precipitation. Determining the start and end of droughts can therefore be done without needing to understand or do the SPI calculation itself. However, the disadvantage of this method is that is does not quantify the intensity or magnitude of the identified drought.

To illustrate the use of the threshold values for detecting future droughts, the SPI precipitation mean (SPI = 0) and threshold (SPI = -1) values were also calculated for the catchment area rainfall stations using rainfall data up to December 2014. This was done to assess how well the threshold value up to 2014 could detect droughts over the following 5-year period. This was compared to the mean and threshold values calculated using the full record up to 2020.

Franschhoek-Robertsvlei threshold value drought determination

The moving 12-month cumulative precipitation for the Franschhoek-Robertsvlei rainfall station for the period of January 2015 to June 2020 is shown in Figures 5.1 and 5.2. The rainfall station is indicative of the precipitation in the Berg River Dam catchment.

Figure 5.1 shows the SPI-12 mean and threshold precipitation values, calculated over the length of the complete record. The full record is listed in Appendix B, Table B2.

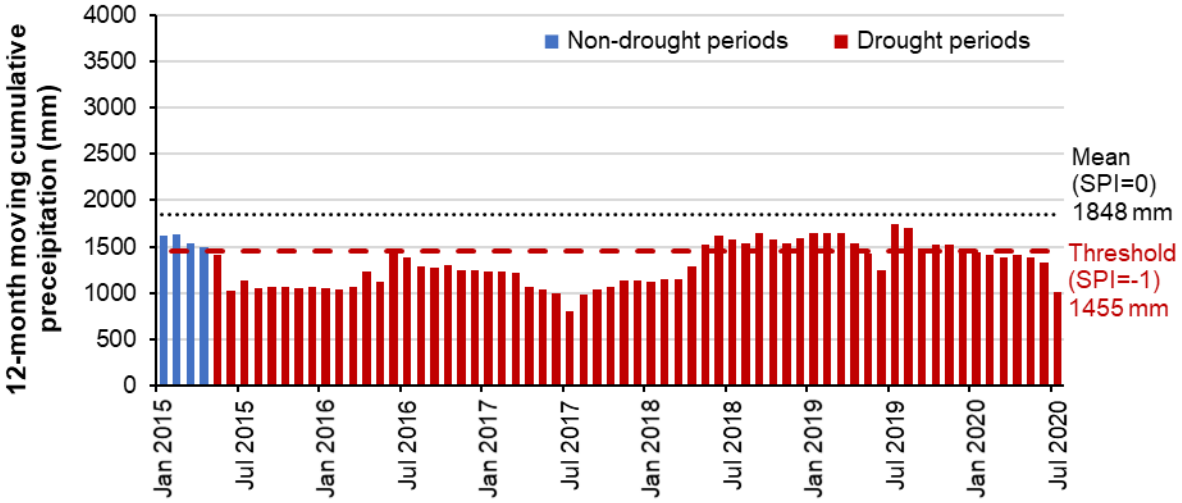


Figure 5.1: Franschhoek-Robertsvlei moving 12-month cumulative precipitation, using SPI mean and threshold values from the full precipitation record

Figure 5.2 shows the SPI-12 mean and threshold precipitation values calculated over the record up to December 2014.

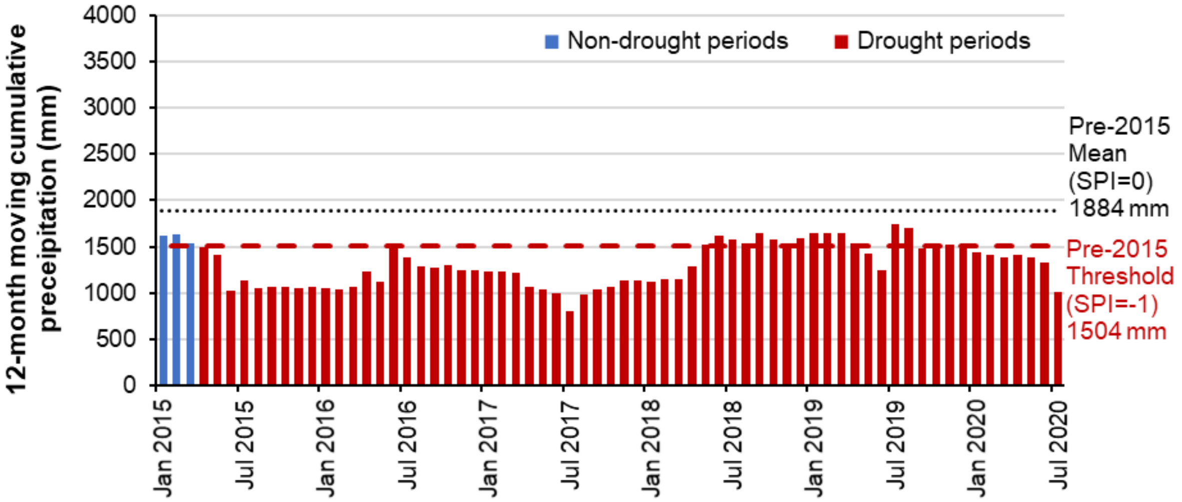


Figure 5.2: Franschhoek-Robertsvlei moving 12-month cumulative precipitation, using SPI mean and threshold values calculated up to December 2014

The following observations are made from Figures 5.1 and 5.2:

- For the mean and threshold values calculated over the full record, the cumulative 12-month precipitation first drops below the threshold precipitation in May 2015, indicating the start of a drought.
- For the mean and threshold values calculated up to 2014, the cumulative 12-month precipitation first drops below the threshold a month earlier, in April 2015.
- The moving 12-month cumulative precipitation does not move above the mean precipitation value from April/May 2015 to the end of the record in July 2020, indicating that a drought has occurred during this entire period.
- Both sets of mean and threshold precipitation values detect the onset of a drought, within a month of each other.

Rustfontein threshold value drought determination

The moving 12-month cumulative precipitation for the Rustfontein rainfall station for the period of January 2015 to June 2020 is shown in Figures 5.3 and 5.4. The rainfall station is indicative of the precipitation in the Theewaterskloof Dam catchment.

Figure 5.3 shows the SPI-12 mean and threshold precipitation values, calculated over the length of the complete record. The full record is listed in Appendix B, Table B4.

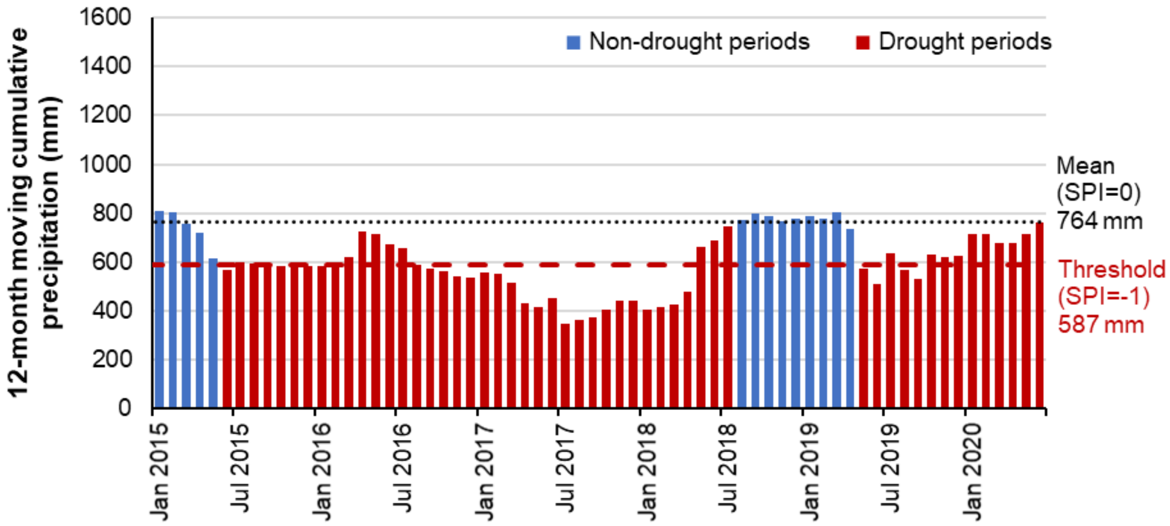


Figure 5.3: Rustfontein moving 12-month cumulative precipitation, using SPI mean and threshold values from the full precipitation record

Figure 5.4 shows the SPI-12 mean and threshold precipitation values calculated over the record up to December 2014.

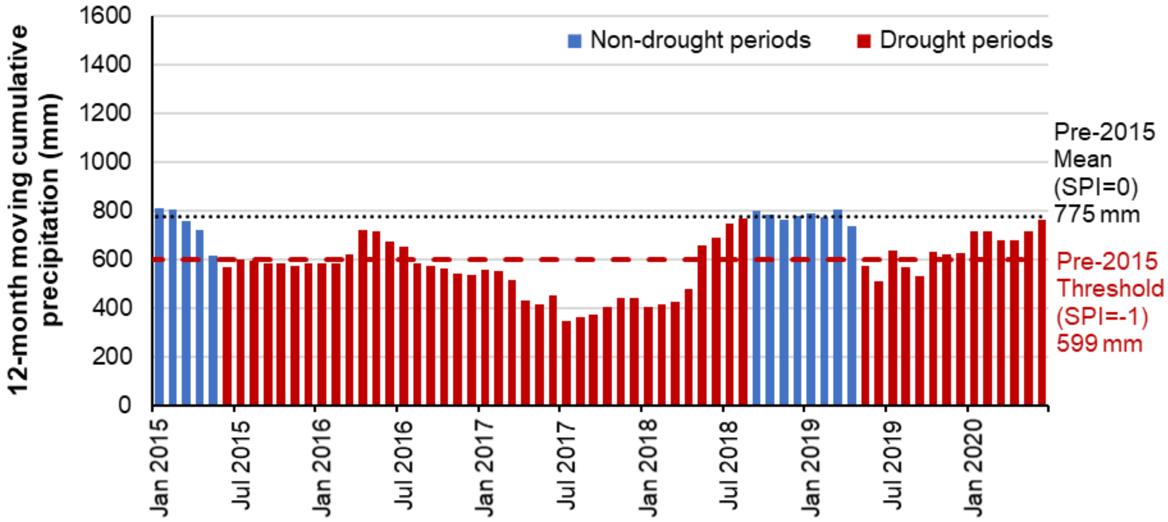


Figure 5.4: Rustfontein moving 12-month cumulative precipitation, using SPI mean and threshold values calculated up to December 2014

The following observations are made from Figures 5.3 and 5.4:

- For the mean and threshold values calculated over the full record, a first drought period occurred from June 2015 to July 2018. For the mean and threshold values calculated up to December 2014, the drought lasted one month longer until August 2018.
- A second drought period, which occurred from May 2019 to the end of the record in June 2020, was detected by both sets of mean and threshold values.

Steenbras Dam threshold value drought determination

The moving 12-month cumulative precipitation for the Steenbras Dam rainfall station for the period of January 2015 to June 2020 is shown in Figures 5.5 and 5.6. The rainfall station is indicative of the precipitation in the catchment of the Steenbras Upper and Lower Dams.

Figure 5.5 shows the SPI-12 mean and threshold precipitation values, calculated over the length of the complete record. The full record is listed in Appendix B, Table B6.

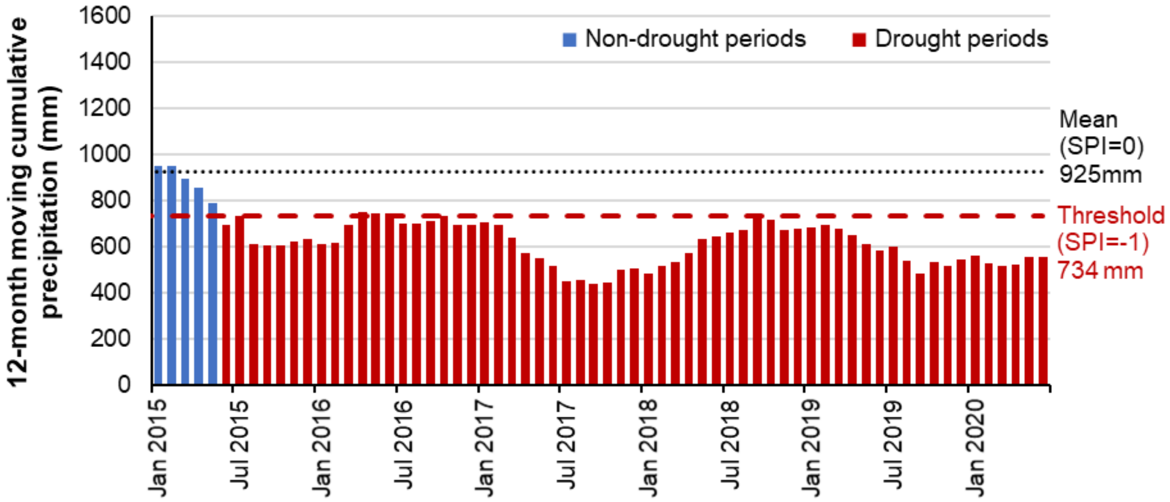


Figure 5.5: Steenbras Dam moving 12-month cumulative precipitation, using SPI mean and threshold values from the full precipitation record

Figure 5.6 shows the SPI-12 mean and threshold precipitation values calculated over the record up to December 2014.

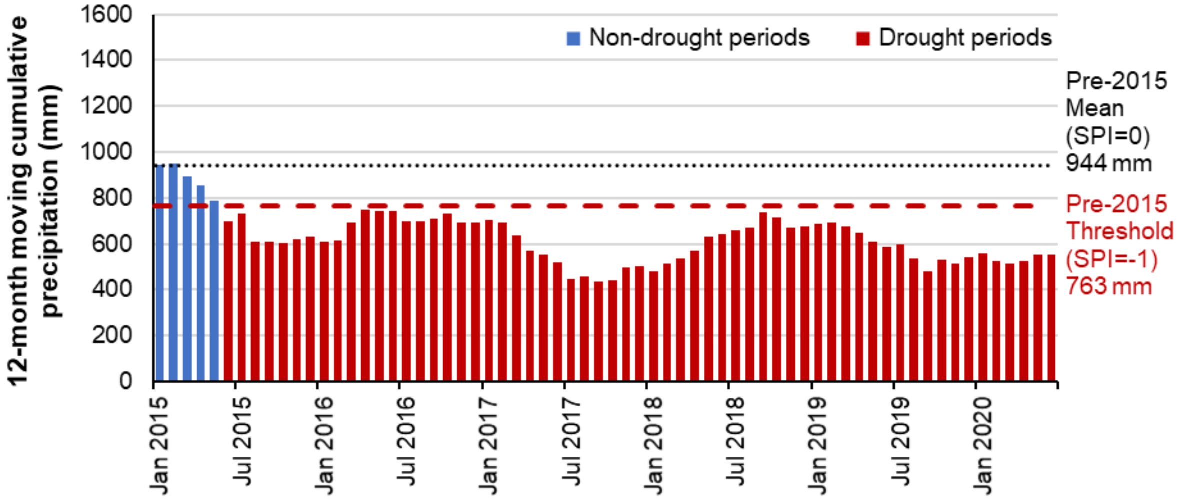


Figure 5.6: Steenbras Dam moving 12-month cumulative precipitation, using SPI mean and threshold values calculated up to December 2014

The following observations are made from Figures 5.5 and 5.6:

- The drought periods detected were the same for the mean and threshold values calculated over the full record, as those calculated up to December 2014.
- For the period being analysed, a first drought period occurred from May 2015, and continued to the end of the record in June 2020.

Tulbagh threshold value drought determination

The moving 12-month cumulative precipitation for the Tulbagh rainfall station for the period of January 2015 to June 2020 is shown in Figures 5.7 and 5.8. The rainfall station is indicative of the precipitation in the catchment from which water is transferred to the off-channel Voëlvlei Dam.

Figure 5.7 shows the SPI-12 mean and threshold precipitation values, calculated over the length of the complete record. The full record is listed in Appendix B, Table B8.

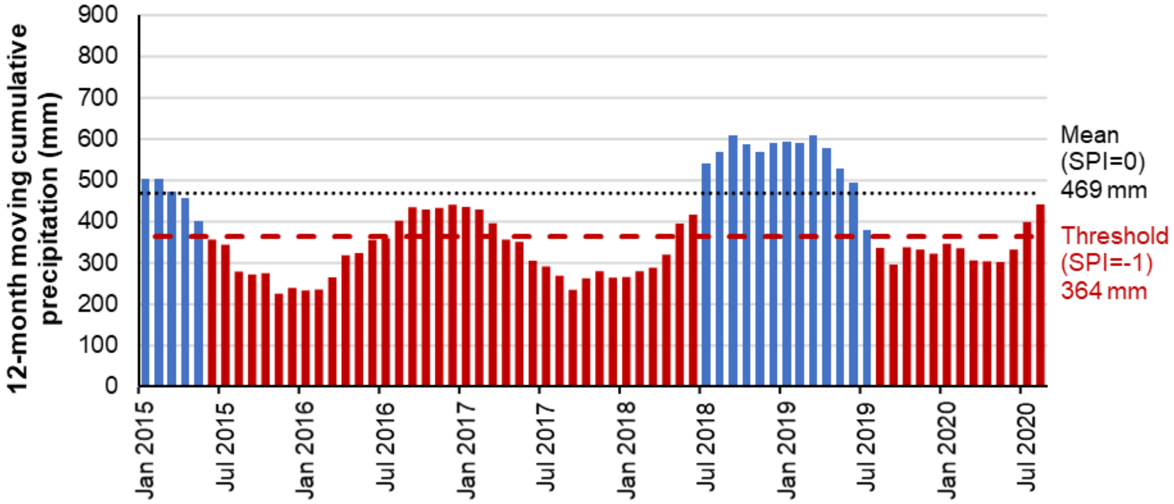


Figure 5.7: **Tulbagh moving 12-month cumulative precipitation, using SPI mean and threshold values from the full precipitation record**

Figure 5.8 shows the SPI-12 mean and threshold precipitation values calculated over the record up to December 2014.

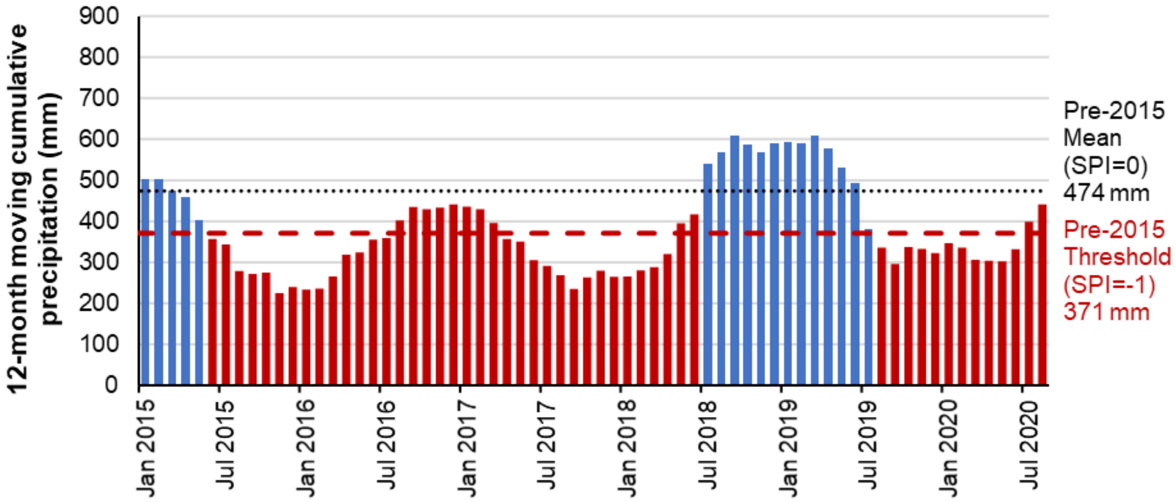


Figure 5.8: Tulbagh moving 12-month cumulative, using SPI mean and threshold values calculated up to December 2014

The following observations are made from Figures 5.7 and 5.8:

- The drought periods detected were the same for the mean and threshold values calculated over the full record, as those calculated up to December 2014.
- For the period being analysed, a first drought period occurred from May 2015 to June 2018.
- A second drought period occurred from August 2019 to the end of the record in August 2020.

Wemmershoek Dam threshold value drought determination

The moving 12-month cumulative precipitation for the Wemmershoek Dam rainfall station for the period of January 2015 to June 2020 is shown in Figures 5.9 and 5.10. The rainfall station is indicative of the precipitation in the Wemmershoek Dam.

Figure 5.9 shows the SPI-12 mean and threshold precipitation values, calculated over the length of the complete record. The full record is listed in Appendix A, Table A2. The mean and threshold values are indicated in Table 4.6.

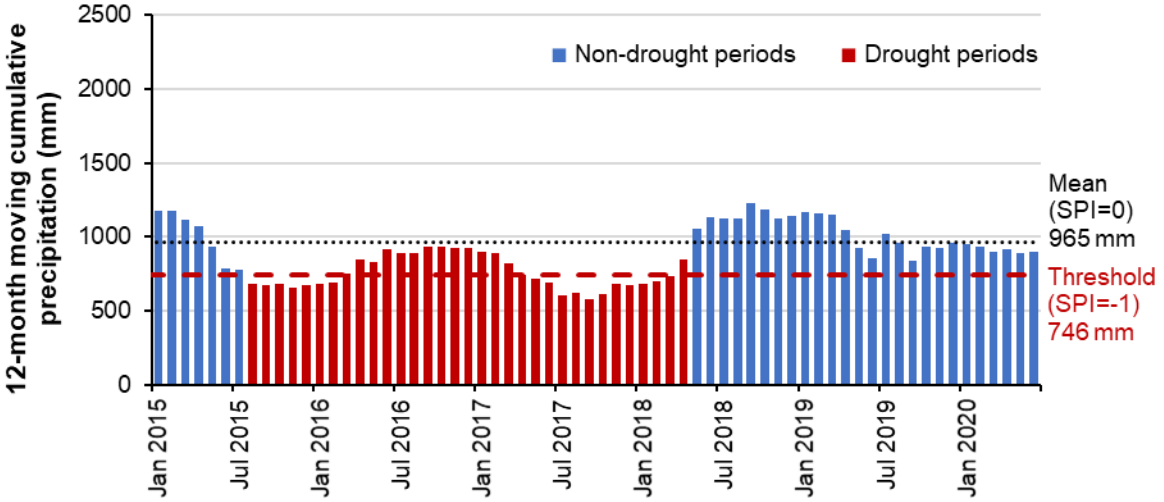


Figure 5.9: Wemmershoek Dam moving 12-month cumulative precipitation, using SPI mean and threshold values from the full precipitation record

Figure 5.10 shows the SPI-12 mean and threshold precipitation values calculated over the record up to December 2014.

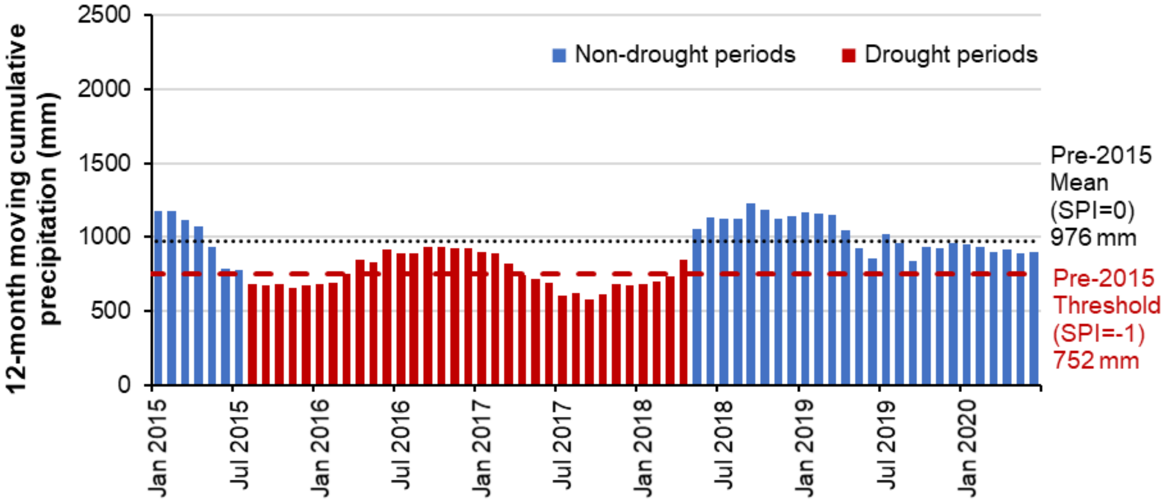


Figure 5.10: Wemmershoek Dam moving 12-month cumulative precipitation, using SPI mean and threshold values calculated up to December 2014

The following observations are made from Figures 5.9 and 5.10:

- The drought periods detected were the same for the mean and threshold values calculated over the full record, as those calculated up to December 2014.
- For the period being analysed, a drought occurred from August 2015 to April 2018.

5.2 Severity and duration of droughts using the SPI-12 index

The SPI relationships developed in Section 4.2 can be used to quantify the severity and duration of the droughts experienced in the WCWSS area during the period 2015 – 2020. The analysis in this section will focus on the precipitation records in the catchment areas of the main storage dams of the WCWSS.

Franschhoek-Robertsvlei SPI-12 indexing of drought

The SPI-12 values for the Franschhoek-Robertsvlei rainfall station for the period of January 2015 to July 2020 are shown in Figure 5.11.

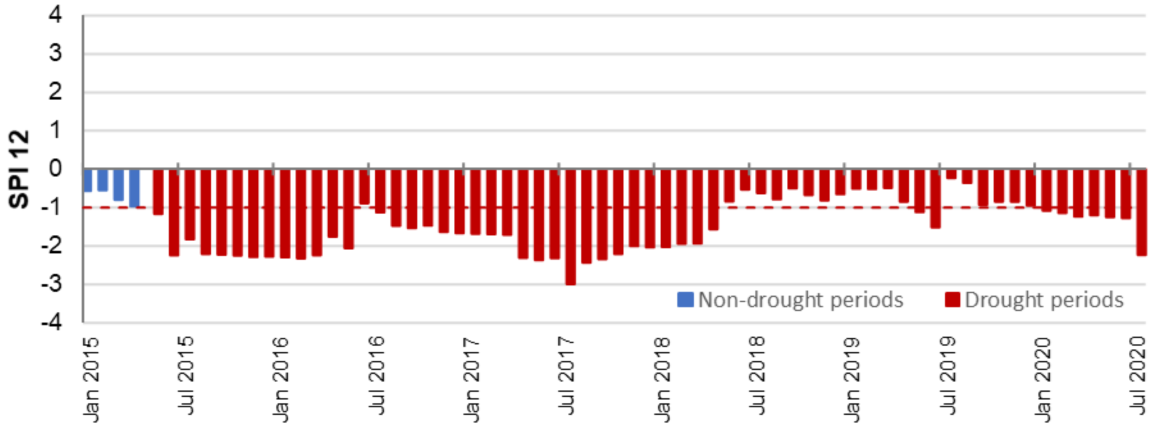


Figure 5.11: SPI-12 values for Franschhoek-Robertsvlei, January 2015 to July 2020

The following observations are made on the Franschhoek-Robertsvlei precipitation record based on the above graph, as well as the historical SPI record shown in Figure 4.8 and listed in Appendix B, Table B1:

- A drought was experienced for the entire period from May 2015 to July 2020.
- The SPI-12 index detected the onset of the drought in May 2015.
- The SPI-12 index showed the continuation of the drought to July 2020, with a duration of 63 months. The drought was therefore still ongoing by the end of the analysis period used in this research.
- Of the 14 drought periods in the 99-year precipitation record from September 1920 to July 2020, the 2015 - 2020 period had:
    - The largest magnitude drought, with a ΣSPI = -94.3.
    - The second longest drought duration of 63 months.
    - The second highest SPI-12 monthly intensity of -2.99 (indicating extreme drought conditions).

- The last month analysed in this research, July 2020, had an SPI-12 value of -2.23. This indicates an extreme drought condition and indicates a possible start of another very dry period.

Rustfontein SPI-12 indexing of drought

The SPI-12 values for the Rustfontein rainfall station for the period of January 2015 to June 2020 are shown in Figure 5.12. The SPI-12 values for this rainfall station are indicative of the precipitation in the Theewaterskloof Dam catchment.

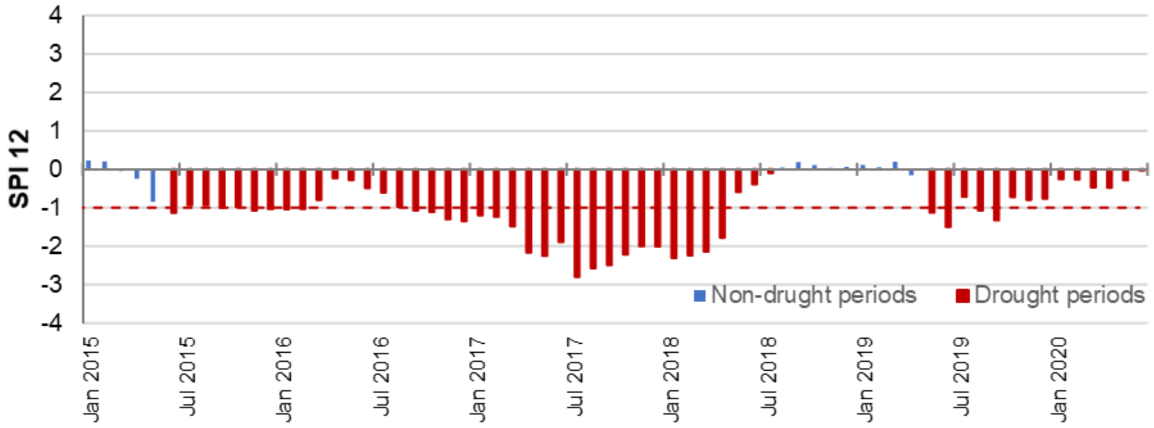


Figure 5.12: SPI-12 values for Rustfontein, January 2015 to June 2020

The following observations are made on the Rustfontein precipitation record based on the above graph, as well as the historical SPI record shown in Figure 4.10 and listed in Appendix B, Table B3:

- Two droughts periods were experienced during January 2015 to July 2020:
  - The first from June 2015 to July 2018.
  - The second from May 2019 to June 2020.
- Of the 23 drought periods in the 98-year precipitation record from September 1921 to June 2020, the SPI-12 index indicated during the 2015 – 2020 period:
  - The drought from June 2015 to July 2018 was:
    - The highest magnitude drought, with a ΣSPI = -51.2.
    - The longest magnitude drought of 38 months.
    - The second highest SPI-12 monthly intensity of -2.80 (indicating extreme drought conditions).
  - The second drought which began in May 2019 was still ongoing in June 2020.

Steenbras Dam SPI-12 indexing of drought

The SPI-12 values for the Steenbras Dam rainfall station for the period January 2015 to June 2020 are shown in Figure 5.13. The SPI-12 values for this rainfall station are indicative of the precipitation in the catchment area of the Steenbras Upper and Lower Dams.

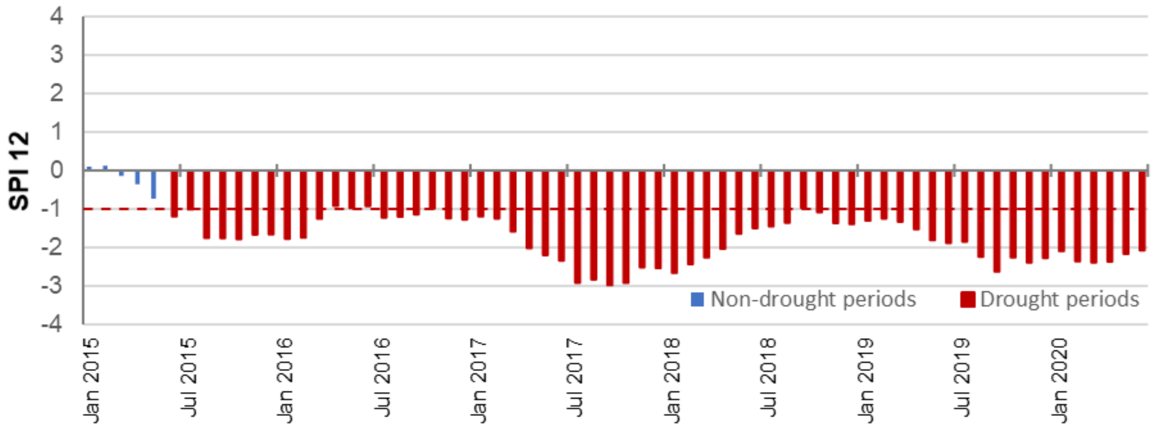


Figure 5.13: SPI-12 values for Steenbras Dam, January 2015 to June 2020

The following observations are made on the Steenbras Dam precipitation record based on the above graph, as well as the historical SPI record shown in Figure 4.12 and listed in Appendix B, Table B5:

- A drought was experienced for the entire period from June 2015 to June 2020.
- The SPI-12 index detected the onset of the drought in June 2015.
- The SPI-12 index showed that this drought continued to June 2020, with a duration of 61 months. The drought was still ongoing by the end of the period of analysis in this research.
- Of the 16 drought periods in the 103-year precipitation record from December 1916 to June 2020, the 2015 – 2020 period had:
  - The largest magnitude drought, with a ΣSPI = -109.2.
  - The longest drought duration of 61 months.
  - The highest single SPI-12 monthly intensity of -2.98 (indicating extreme drought conditions).
- From August 2019 – June 2020, all the monthly SPI-12 values were < -2.00, indicating extreme drought conditions were being experienced. The drought was also ongoing at the end of the research analysis period in June 2020.

Tulbagh SPI-12 indexing of drought

The SPI-12 values for the Tulbagh rainfall station for the period January 2015 to August 2020 are shown in Figure 5.14. The SPI-12 values for this rainfall station are indicative of the precipitation which falls in the catchment from which water to Voëlvlei Dam is transferred. Voëlvlei Dam is an off-channel storage dam.

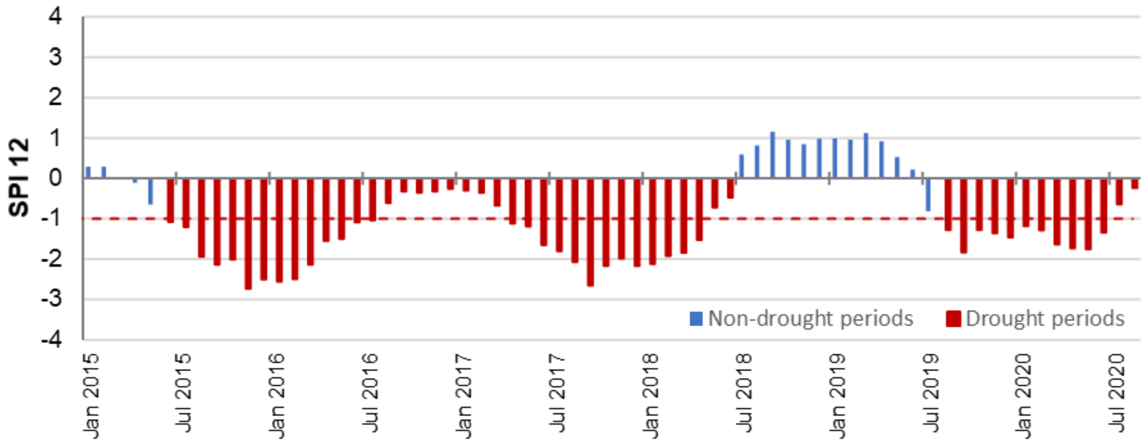


Figure 5.14: SPI-12 values for Tulbagh, January 2015 to August 2020

The following observations are made on the Tulbagh precipitation record based on the above graph, as well as the historical SPI record shown in Figure 4.14 and listed in Appendix B, Table B7:

- Two drought periods were experienced during June 2015 to August 2020:
  - The first drought period was from June 2015 to June 2018.
  - The second drought period was from August 2019 to June 2020.
- Of the 63 months from June 2015 to June 2020, the SPI-12 index indicated that 50 months (79%) were in drought.
- Of the 26 drought periods in 119-year precipitation record from December 1900 to June 2020, the SPI-12 index indicated during the 2015 – 2020 period:
  - The drought from June 2015 to June 2018 was:
    - Detected by the SPI-12 index to have started in June 2015.
    - The second largest magnitude drought, with a ΣSPI = -54.7.
    - The second longest magnitude drought of 37 months.
    - The highest SPI-12 monthly intensity of -2.79 (indicating extreme drought conditions).
  - The second drought that began in August 2019 was still ongoing at the end of the analysis period in August 2020.

Wemmershoek Dam SPI-12 indexing of drought

The SPI-12 values for the Wemmershoek Dam rainfall station for the period January 2015 to June 2020 are shown in Figure 5.15. The SPI-12 values for this rainfall station are indicative of the precipitation which falls in the Wemmershoek Dam catchment.

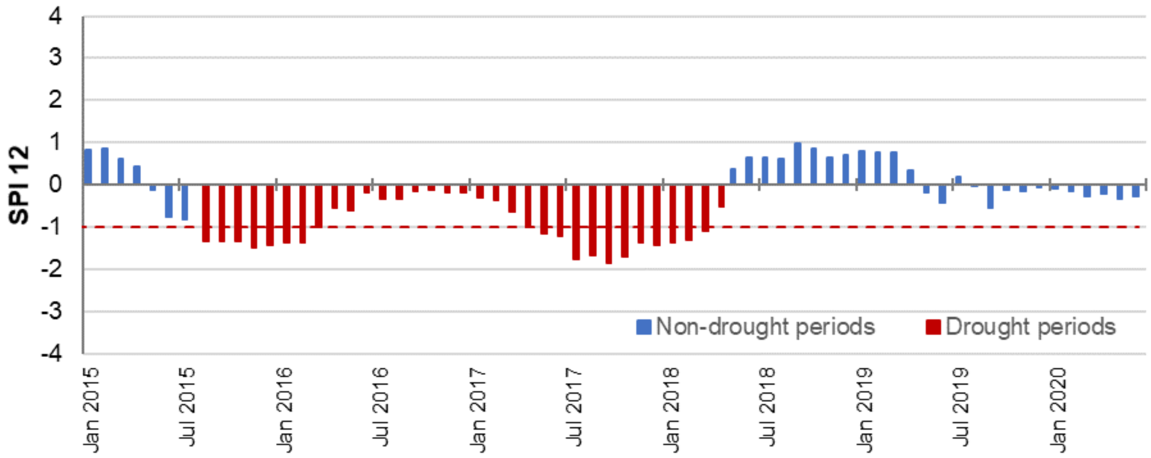


Figure 5.15: SPI-12 values for Wemmershoek Dam, January 2015 to June 2020

The following observations are made on the Wemmershoek Dam precipitation record based on the above graph, as well as the historical SPI record shown in Figure 4.6 and listed in Appendix A, Table A4:

- Of the 11 droughts in the 52-year precipitation record from July 1969 to June 2020, the 2015 – 2020 period experienced a drought that occurred between August 2015 to April 2018, which was:
    - The third largest magnitude drought, with a ΣSPI = -31.8.
    - The third longest drought duration of 33 months.
    - The fourth highest single SPI-12 monthly intensity of -1.86, indicating that the drought during this period was severe, but not extreme.
- The period from May 2018 to June 2020 was a non-drought period.

Summary of the SPI-12 index values for WCWSS catchment areas

The above observations of the SPI-12 index values for the WCWSS catchment area rainfall stations for 2015 – 2020 period indicate the following:

- The catchments of the Berg River, Steenbras Upper and Lower Dams, and the Theewaterskloof Dam experienced some of the most severe droughts over their respective hydrological records and were in drought for the most of the period from June 2015 to June 2020.

- The catchment supplying the off-channel Voëlvlei Dam experienced severe droughts over their hydrological record, but also experienced a 13-month period of non-drought.
- The Wemmershoek Dam catchment did experience a severe drought for 33 months of the 60-month period.
- Of the five catchments of the six major dams of the WCWSS, four catchments, namely the Berg River, Steenbras Upper and Lower, Theewaterskloof and Voëlvlei Dam catchments were still experiencing drought by June 2020.

5.3 Determining drought return periods using SDF curves

The SDF curves derived in Section 4.3 were used to determine the return periods of the droughts experienced during 2015 to 2020.

To do this, the lowest (i.e., most severe) cumulative 12-month precipitation over a continuous 6-month period will be determined for each of the catchment rainfall stations. The return periods can then be read off the SDF curves in Figures 4.22 to 4.26. These are shown in Table 5.1.

Table 5.1: Return periods for droughts in the main WCWSS catchments, 2015 - 2020

Rainfall Station	**Catchment**	**Lowest cumulative 12-month precipitation over 6 months (mm)**	**Approximate return period (years)**
Franschhoek-Robertsvlei	Berg River Dam	5 910	~1:10
Rustfontein	Theewaterskloof Dam	2 350	~ 1:100
Steenbras Dam	Steenbras Upper and Lower Dams	2 789	~ 1:100
Tulbagh	Voëlvlei Dam	1 475	~ 1:50
Wemmershoek Dam	Wemmershoek Dam	3 768	~1:5

The results of the return periods read off from the SDF curves show that even though droughts were experienced in all the catchment areas, there was a wide variation in the return periods of the droughts that occurred.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The research was conducted to analyse drought characteristics over the WCWSS area. The Standardised Precipitation Index was used to determine severity, duration, and frequency relationships of drought events. The following conclusions can be drawn from the analyses and findings of the research:

- Long-term precipitation records are needed to conduct meaningful drought analyses. Rainfall stations were identified that had long-term data and are still active, which could be used for analyses in this research. Only 29 stations could be used, with numerous rainfall stations having significant gaps in recorded data, or stations no longer being active and read. Rainfall stations were statistically analysed, which also assisted with detecting errors in the datasets.
- The precipitation data analysed included rainfall stations in the catchments of the major storage dams of the WCWSS, which can provide information to water resource managers to assist with the planning and operation of the WCWSS.
- The SPI was selected as the drought index to determine the occurrence and severity of droughts in the precipitation records selected for the research. Using the SPI values, the magnitude, duration, and intensity of droughts were determined using only precipitation data from rainfall data.
- Threshold precipitation depths were developed from the SPI values. Using these threshold precipitation depths, the start, duration and end of droughts were determined directly from monthly precipitation measurements.
- SDF relationships were developed for drought return periods of 5, 10, 20, 50 and 100 years for the rainfall stations used in this research. From this research, SDF plots were developed for the rainfall stations in the WCWSS catchment areas. Return periods of drought events were determined from the curves, without needing to conduct statistical frequency analysis.
- Threshold precipitation and SDF isohyets were mapped over the WCWSS area. The maps allowed the occurrence and return periods of droughts to be determined at any location, using only a limited or short period of rainfall measurements at that location.
- The above research was used for a case study of the drought conditions experienced in the major catchments of the WCWSS area from 2015 – 2020. The following observations can be made from this analysis:

  - Droughts were first detected at the start of winter 2015 in all the catchment areas of the storage dams of the WCWSS area.
  - Drought magnitude and durations varied over the catchments of the WCWSS:
    - Steenbras and Theewaterskloof Dam catchments experienced the longest and most severe droughts on record.
    - Berg River Dam and the catchment supplying Voëlvlei Dam experienced severe droughts, although not the most severe on record.
    - Wemmershoek Dam experienced drought, but not as severe as the other catchments.
  - The catchments of Steenbras, Theewaterskloof, Berg River, and Voëlvlei Dam were still experiencing drought by the end of the analysis in June/July 2020.
  - Using mean and threshold values determined from precipitation records up to 2014, the timing of droughts detected during 2015 to 2020 differed only slightly from values based on the full record.
- SDF analysis indicates that the return periods of the droughts experienced varied between the catchments, from 1:5 years for the Wemmershoek Dam catchment to 1:100 years for the Steenbras and Theewaterskloof catchments.

6.2 Recommendations

The following recommendations are made:

- As most of the catchments of the major storage dams of the WCWSS were still in drought at the end of the analysis period of this research, it should be further assessed how much of the storage recovery is due to rainfall and inflow, versus reduced demand.
- Ongoing monitoring and updating of SPI and SDF values can provide useful context to water resource management decision making, especially in detecting the onset of drought before it is reflected in declining dam storage levels.
- Both SPI and SDF information should periodically be updated, as both SPI and SDF values will change with updated information.
- SDF curves can be used to determine the return periods of droughts being experienced without detailed knowledge of statistical frequency analysis and can contribute to informing decision making on the operation of the WCWSS.
- Further assessment should be done on the best probability distributions to produce SDF values.
- Consideration should be given to applying the methodology explored in this research to analyse inflows to the WCWSS storage dams.

- Generation of SDF curves could be expanded to cover the whole of South Africa.
- There should be focus on improving the accuracy and availability of rainfall station and precipitation data across the WCWSS area, and across South Africa.

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APPENDIX A: WEMMERSHOEK DAM DATASET FOR CALCULATING SPI VALUES

Table A1: Wemmershoek Dam monthly rainfall

(Rainfall in mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	22.6	0.8	3.3	133.4	103.1	257.6	110.7	78.2	98.3	59.7	67.1	16.5
1968	25.1	13.2	7.9	121.9	215.1	154.7	255.0	101.6	22.1	163.1	21.1	51.1
1969	33.5	15.2	23.6	64.0	8.1	118.4	90.7	159.3	156.5	100.6	10.2	4.1
1970	5.1	10.3	4.7	4.6	186.1	239.1	163.9	152.0	90.4	44.2	29.5	41.1
1971	5.0	1.5	36.4	2.9	87.3	126.8	195.1	191.5	19.1	23.0	7.3	53.3
1972	31.5	15.9	17.5	83.5	164.6	91.8	68.1	113.3	69.6	21.5	0.0	46.4
1973	2.6	1.0	35.3	12.4	49.8	31.9	391.6	80.5	97.8	52.9	10.7	92.8
1974	6.4	1.2	22.3	1.3	137.3	265.9	117.2	545.3	89.3	111.5	24.2	12.0
1975	26.7	23.3	6.3	90.4	259.9	131.9	219.3	112.4	18.7	85.0	33.0	3.7
1976	0.0	1.3	23.3	27.5	115.0	405.9	325.3	61.8	68.4	17.2	201.9	148.8
1977	33.4	50.0	23.1	133.6	286.7	363.0	277.5	294.6	61.3	38.2	31.5	24.7
1978	16.7	9.6	77.3	48.9	72.0	24.5	28.4	253.7	92.8	39.9	11.0	31.5
1979	30.9	58.5	12.3	11.0	220.3	170.5	76.9	126.8	108.6	104.1	0.7	1.3
1980	41.6	10.3	7.9	58.7	203.9	152.0	53.6	122.1	29.6	30.6	131.3	100.4
1981	84.2	0.0	58.3	48.5	17.3	59.6	301.1	142.6	208.4	23.4	27.7	29.6
1982	50.1	1.0	14.5	82.1	107.9	179.5	114.3	81.5	24.5	91.7	31.4	59.9
1983	6.4	84.8	52.3	15.2	287.2	261.5	175.5	85.9	162.8	11.4	23.5	31.1
1984	12.0	7.3	73.3	53.2	306.4	126.6	162.9	94.8	168.1	125.4	1.4	86.8
1985	35.3	41.0	126.8	88.0	86.0	165.5	186.0	181.0	87.6	13.5	9.8	15.4
1986	20.3	20.9	69.5	67.4	77.1	279.0	164.1	240.7	73.4	11.7	23.4	0.5
1987	23.5	21.5	14.0	52.5	204.5	188.0	167.7	175.5	110.9	5.7	3.0	65.4
1988	2.5	0.0	17.5	114.8	103.9	39.0	139.7	199.5	103.0	17.0	13.0	33.0
1989	13.0	52.7	115.0	47.5	126.3	101.9	159.0	166.9	123.9	57.2	25.0	5.1
1990	13.6	40.2	7.4	261.5	110.9	187.6	272.0	78.6	43.5	4.7	28.2	53.8
1991	5.0	7.5	13.0	45.0	229.5	393.2	295.0	71.1	212.2	37.6	19.0	7.2
1992	0.5	68.5	42.5	84.1	90.0	468.7	193.6	86.3	65.1	166.3	22.2	3.5
1993	8.0	34.0	12.0	246.0	144.0	131.5	433.5	98.0	28.0	6.5	12.5	29.4
1994	12.8	3.5	11.5	57.0	48.5	420.3	103.0	29.3	87.5	25.0	7.0	16.0
1995	14.0	8.0	15.4	10.1	94.8	129.4	203.5	148.8	35.0	103.9	12.1	64.0
1996	8.0	50.7	29.0	38.2	108.3	397.4	133.4	178.2	174.5	92.0	78.4	53.8
1997	12.5	1.0	11.5	27.7	63.5	290.5	77.0	113.2	8.5	4.5	75.5	25.8
1998	23.5	0.0	8.7	47.3	218.8	73.5	171.8	60.9	43.5	14.8	59.2	26.6
1999	1.5	1.0	0.0	76.0	90.1	161.3	152.3	217.0	152.5	0.0	31.2	1.0
2000	24.5	2.0	17.7	4.1	64.8	102.5	144.0	93.1	133.5	6.0	17.3	10.5
2001	16.5	10.5	0.0	45.0	191.1	82.3	383.0	253.0	144.0	61.0	12.0	10.5
2002	141.3	23.3	13.5	76.7	145.8	87.5	202.8	152.5	50.0	48.5	29.0	59.0
2003	15.5	7.5	59.3	42.1	33.1	12.0	69.2	205.3	89.4	55.3	0.0	42.5
2004	11.2	0.0	21.5	74.9	1.9	114.1	97.9	120.4	51.9	100.8	1.0	2.8
2005	46.7	6.0	12.6	92.0	152.5	167.1	103.1	225.3	49.3	24.1	43.9	0.3
2006	1.1	8.3	9.3	75.4	187.9	90.6	109.0	195.8	30.1	35.0	74.0	14.5
2007	0.0	27.5	39.5	85.5	232.3	228.3	204.5	126.2	26.9	32.2	64.1	35.4
2008	13.1	6.7	4.2	6.5	71.4	120.5	244.9	121.7	185.8	12.0	68.1	22.7
2009	0.0	3.5	0.0	41.9	133.6	225.8	107.7	106.6	117.8	64.8	179.8	8.3
2010	0.0	5.8	10.8	22.8	246.4	187.2	60.0	104.0	32.3	83.7	117.1	32.2
2011	27.5	3.0	13.1	57.4	160.1	213.7	44.3	98.9	72.9	44.2	63.8	43.7
2012	2.5	4.1	27.4	75.3	69.2	133.5	138.4	260.7	100.4	38.1	19.8	1.2
2013	14.6	25.3	26.9	152.8	113.0	290.0	144.4	479.6	219.5	46.3	175.5	0.1
2014	46.1	1.7	65.6	51.7	184.1	293.1	231.4	209.1	59.9	6.5	43.3	5.1
2015	22.4	6.3	4.0	3.4	51.6	144.6	225.1	110.1	52.7	10.0	22.5	22.0
2016	27.8	12.9	65.2	99.3	36.9	232.6	198.0	111.9	90.0	17.5	9.1	22.0
2017	4.2	0.0	3.4	19.9	9.1	206.0	108.0	128.3	49.6	55.8	75.2	16.2
2018	6.8	19.1	36.7	137.8	216.3	280.6	104.4	123.1	153.3	14.8	15.0	31.8
2019	31.4	10.4	35.2	33.4	90.1	214.6	262.7	65.2	34.0	112.4	7.2	60.3
2020	21.1	0.0	1.5	49.6	63.4	218.3						

Table A2: Wemmershoek Dam moving 12-month cumulative rainfall

(Rainfall in mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967												951
1968	954	966	971	959	1 071	968	1 113	1 136	1 060	1 163	1 117	1 152
1969	1 160	1 162	1 178	1 120	913	877	713	770	905	842	831	784
1970	756	751	732	673	851	971	1 045	1 037	971	915	934	971
1971	971	962	994	992	893	781	812	852	780	759	737	749
1972	776	790	771	852	929	894	767	689	739	738	731	724
1973	695	680	698	627	512	452	775	743	771	802	813	859
1974	863	863	850	839	927	1 161	886	1 351	1 343	1 401	1 415	1 334
1975	1 354	1 376	1 360	1 449	1 572	1 438	1 540	1 107	1 037	1 010	1 019	1 011
1976	984	962	979	916	771	1 045	1 151	1 101	1 150	1 082	1 251	1 396
1977	1 430	1 479	1 478	1 584	1 756	1 713	1 665	1 898	1 891	1 912	1 742	1 618
1978	1 601	1 561	1 615	1 530	1 315	977	728	687	718	720	700	706
1979	721	769	704	667	815	961	1 009	882	898	962	952	922
1980	933	884	880	928	911	893	870	865	786	712	843	942
1981	985	974	1 025	1 015	828	736	983	1 004	1 182	1 175	1 072	1 001
1982	967	968	924	957	1 048	1 168	981	920	736	804	808	838
1983	795	879	916	849	1 029	1 111	1 172	1 176	1 315	1 234	1 226	1 198
1984	1 203	1 126	1 147	1 185	1 204	1 069	1 056	1 065	1 071	1 185	1 163	1 218
1985	1 242	1 275	1 329	1 364	1 143	1 182	1 205	1 291	1 211	1 099	1 107	1 036
1986	1 021	1 001	944	923	914	1 028	1 006	1 065	1 051	1 049	1 063	1 048
1987	1 051	1 052	996	981	1 109	1 018	1 021	956	994	988	967	1 032
1988	1 011	990	993	1 056	955	806	778	802	794	805	815	783
1989	793	846	944	876	899	962	981	948	969	1 009	1 021	994
1990	994	982	874	1 088	1 073	1 158	1 271	1 183	1 103	1 050	1 053	1 102
1991	1 093	1 061	1 066	850	968	1 174	1 197	1 190	1 358	1 391	1 382	1 335
1992	1 331	1 392	1 421	1 460	1 321	1 396	1 295	1 310	1 163	1 292	1 295	1 291
1993	1 299	1 264	1 234	1 396	1 450	1 113	1 352	1 364	1 327	1 167	1 158	1 183
1994	1 188	1 158	1 157	968	873	1 162	831	762	822	840	835	821
1995	823	827	831	784	830	540	640	760	707	786	791	839
1996	833	876	889	917	931	1 199	1 129	1 158	1 298	1 286	1 352	1 342
1997	1 346	1 297	1 279	1 269	1 224	1 117	1 061	996	830	742	739	711
1998	722	721	718	738	893	676	771	719	754	764	748	749
1999	727	728	719	748	619	707	687	843	952	938	910	884
2000	907	908	926	854	828	770	761	637	618	624	611	620
2001	612	621	603	644	770	750	989	1 149	1 159	1 214	1 209	1 209
2002	1 334	1 347	1 360	1 392	1 346	1 352	1 171	1 071	977	964	981	1 030
2003	904	888	934	900	787	711	578	631	670	677	648	631
2004	627	619	582	614	583	685	714	629	592	637	638	598
2005	634	640	631	648	799	852	857	962	959	883	925	923
2006	877	880	876	860	895	819	825	795	776	787	817	831
2007	830	849	879	889	934	1 072	1 167	1 097	1 094	1 091	1 082	1 102
2008	1 116	1 095	1 059	980	820	712	752	748	907	886	890	878
2009	865	861	857	893	955	1 060	923	908	840	893	1 004	990
2010	990	992	1 003	984	1 097	1 058	1 010	1 008	922	941	878	902
2011	930	927	929	964	878	904	888	883	924	884	831	843
2012	818	819	833	851	760	680	774	936	963	957	913	871
2013	883	904	903	981	1 025	1 181	1 187	1 406	1 525	1 533	1 689	1 688
2014	1 720	1 696	1 735	1 634	1 705	1 708	1 795	1 524	1 365	1 325	1 193	1 198
2015	1 174	1 179	1 117	1 069	936	788	781	682	675	679	658	675
2016	680	687	748	844	829	917	890	892	929	937	923	923
2017	900	887	825	746	718	691	601	618	577	615	682	676
2018	678	697	731	849	1 056	1 130	1 127	1 122	1 225	1 184	1 124	1 140
2019	1 164	1 156	1 154	1 050	924	858	1 016	958	839	936	928	957
2020	947	936	903	919	892	896						
Gamma distribution parameters												
Shape (α)	17.00	17.88	17.08	17.01	17.29	15.26	16.45	16.32	15.74	16.53	17.08	17.74
Scale (β)	57.94	55.09	57.68	57.81	56.85	64.33	59.96	60.41	62.56	59.65	57.65	55.54

Table A3: Wemmershoek Dam gamma cumulative distribution function probabilities

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967												0.47
1968	0.48	0.50	0.51	0.49	0.67	0.51	0.72	0.75	0.65	0.78	0.73	0.77
1969	0.78	0.79	0.80	0.74	0.41	0.36	0.12	0.19	0.40	0.29	0.27	0.20
1970	0.17	0.15	0.14	0.08	0.31	0.52	0.62	0.61	0.51	0.41	0.45	0.51
1971	0.51	0.49	0.55	0.55	0.38	0.22	0.25	0.31	0.21	0.18	0.14	0.15
1972	0.19	0.21	0.19	0.31	0.44	0.39	0.19	0.10	0.16	0.15	0.14	0.12
1973	0.10	0.08	0.10	0.05	0.01	0.00	0.20	0.16	0.20	0.23	0.25	0.31
1974	0.33	0.32	0.30	0.29	0.44	0.78	0.37	0.92	0.92	0.94	0.95	0.92
1975	0.93	0.94	0.93	0.96	0.99	0.95	0.98	0.71	0.61	0.57	0.59	0.57
1976	0.53	0.49	0.52	0.42	0.19	0.63	0.77	0.70	0.76	0.68	0.87	0.95
1977	0.96	0.97	0.97	0.99	1.00	0.99	0.99	1.00	1.00	1.00	1.00	0.99
1978	0.99	0.99	0.99	0.98	0.91	0.53	0.14	0.10	0.13	0.13	0.10	0.11
1979	0.13	0.18	0.11	0.08	0.25	0.50	0.57	0.36	0.39	0.49	0.48	0.42
1980	0.44	0.36	0.35	0.44	0.41	0.39	0.34	0.33	0.22	0.12	0.29	0.46
1981	0.53	0.51	0.60	0.58	0.27	0.16	0.53	0.56	0.80	0.79	0.67	0.56
1982	0.50	0.50	0.43	0.49	0.64	0.78	0.52	0.42	0.15	0.24	0.24	0.28
1983	0.22	0.35	0.42	0.31	0.61	0.72	0.79	0.79	0.90	0.85	0.85	0.82
1984	0.82	0.74	0.77	0.81	0.83	0.66	0.64	0.65	0.66	0.80	0.78	0.84
1985	0.86	0.89	0.92	0.93	0.77	0.80	0.82	0.89	0.82	0.70	0.72	0.62
1986	0.59	0.56	0.46	0.43	0.41	0.60	0.56	0.65	0.63	0.63	0.66	0.63
1987	0.64	0.64	0.55	0.53	0.72	0.59	0.59	0.48	0.55	0.54	0.50	0.61
1988	0.58	0.54	0.55	0.65	0.48	0.25	0.20	0.23	0.23	0.24	0.25	0.20
1989	0.22	0.29	0.46	0.35	0.39	0.50	0.52	0.47	0.51	0.57	0.59	0.55
1990	0.55	0.53	0.34	0.69	0.67	0.77	0.88	0.80	0.71	0.63	0.64	0.71
1991	0.70	0.65	0.66	0.31	0.51	0.79	0.81	0.81	0.92	0.94	0.94	0.92
1992	0.92	0.95	0.95	0.97	0.91	0.94	0.89	0.90	0.78	0.89	0.90	0.90
1993	0.90	0.88	0.85	0.95	0.96	0.72	0.92	0.93	0.91	0.78	0.78	0.81
1994	0.81	0.78	0.78	0.51	0.34	0.78	0.28	0.18	0.27	0.29	0.28	0.25
1995	0.26	0.26	0.27	0.21	0.27	0.02	0.06	0.18	0.12	0.21	0.21	0.28
1996	0.28	0.34	0.37	0.42	0.44	0.81	0.74	0.77	0.89	0.89	0.93	0.93
1997	0.92	0.90	0.89	0.88	0.85	0.73	0.65	0.55	0.28	0.15	0.15	0.11
1998	0.13	0.12	0.12	0.15	0.38	0.10	0.19	0.13	0.18	0.18	0.16	0.15
1999	0.13	0.13	0.12	0.16	0.04	0.13	0.10	0.30	0.48	0.45	0.40	0.36
2000	0.40	0.40	0.43	0.31	0.27	0.20	0.18	0.06	0.05	0.05	0.04	0.04
2001	0.04	0.04	0.04	0.06	0.19	0.18	0.54	0.76	0.77	0.83	0.83	0.83
2002	0.92	0.93	0.93	0.95	0.93	0.92	0.79	0.66	0.52	0.50	0.53	0.61
2003	0.39	0.36	0.45	0.39	0.21	0.13	0.03	0.06	0.09	0.09	0.06	0.05
2004	0.05	0.04	0.03	0.04	0.03	0.11	0.12	0.05	0.04	0.06	0.06	0.03
2005	0.05	0.05	0.05	0.06	0.23	0.32	0.32	0.49	0.49	0.36	0.43	0.42
2006	0.35	0.35	0.35	0.32	0.38	0.27	0.27	0.22	0.20	0.21	0.25	0.27
2007	0.27	0.30	0.35	0.37	0.45	0.67	0.78	0.70	0.69	0.69	0.68	0.71
2008	0.73	0.70	0.65	0.53	0.26	0.13	0.17	0.16	0.41	0.37	0.37	0.35
2009	0.33	0.32	0.32	0.38	0.48	0.65	0.43	0.40	0.30	0.38	0.56	0.54
2010	0.54	0.54	0.56	0.53	0.71	0.65	0.57	0.57	0.43	0.46	0.35	0.39
2011	0.44	0.43	0.44	0.50	0.35	0.41	0.37	0.36	0.43	0.36	0.27	0.29
2012	0.25	0.25	0.28	0.31	0.17	0.10	0.19	0.45	0.50	0.48	0.41	0.33
2013	0.36	0.39	0.39	0.53	0.60	0.80	0.80	0.95	0.97	0.98	0.99	0.99
2014	1.00	1.00	1.00	0.99	1.00	0.99	1.00	0.98	0.93	0.91	0.82	0.82
2015	0.80	0.80	0.73	0.67	0.45	0.23	0.20	0.09	0.09	0.09	0.07	0.08
2016	0.09	0.09	0.16	0.30	0.27	0.43	0.37	0.38	0.44	0.45	0.43	0.42
2017	0.39	0.36	0.26	0.16	0.12	0.11	0.04	0.05	0.03	0.05	0.09	0.08
2018	0.09	0.10	0.14	0.30	0.65	0.74	0.74	0.73	0.84	0.80	0.74	0.76
2019	0.78	0.78	0.77	0.64	0.43	0.33	0.58	0.49	0.30	0.45	0.44	0.48
2020	0.47	0.45	0.39	0.42	0.38	0.39						

Table A4: Wemmershoek Dam SPI-12 values

▨ = drought month

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967												-0.07
1968	-0.05	0.00	0.02	-0.02	0.44	0.03	0.58	0.67	0.38	0.77	0.61	0.75
1969	0.77	0.80	0.84	0.63	-0.22	-0.35	-1.17	-0.88	-0.25	-0.54	-0.60	-0.84
1970	-0.96	-1.02	-1.09	-1.39	-0.50	0.04	0.32	0.29	0.03	-0.22	-0.14	0.02
1971	0.02	-0.02	0.12	0.12	-0.31	-0.77	-0.68	-0.49	-0.80	-0.93	-1.06	-1.02
1972	-0.86	-0.82	-0.89	-0.50	-0.15	-0.27	-0.90	-1.28	-1.00	-1.04	-1.09	-1.15
1973	-1.28	-1.40	-1.26	-1.65	-2.36	-2.60	-0.85	-1.01	-0.85	-0.73	-0.69	-0.48
1974	-0.45	-0.47	-0.51	-0.55	-0.16	0.76	-0.34	1.42	1.38	1.60	1.67	1.42
1975	1.46	1.57	1.49	1.79	2.20	1.67	2.03	0.56	0.29	0.18	0.22	0.19
1976	0.08	-0.02	0.06	-0.21	-0.89	0.33	0.72	0.53	0.71	0.47	1.11	1.64
1977	1.72	1.92	1.88	2.21	2.75	2.48	2.41	3.05	2.98	3.10	2.68	2.35
1978	2.26	2.18	2.30	2.05	1.35	0.06	-1.09	-1.29	-1.10	-1.13	-1.26	-1.25
1979	-1.14	-0.92	-1.23	-1.42	-0.67	0.00	0.17	-0.36	-0.28	-0.02	-0.06	-0.20
1980	-0.14	-0.37	-0.38	-0.16	-0.23	-0.28	-0.42	-0.44	-0.78	-1.17	-0.55	-0.11
1981	0.08	0.03	0.24	0.21	-0.61	-0.99	0.07	0.15	0.83	0.82	0.43	0.15
1982	0.00	0.00	-0.18	-0.03	0.35	0.78	0.06	-0.19	-1.02	-0.72	-0.71	-0.58
1983	-0.77	-0.39	-0.21	-0.51	0.27	0.58	0.80	0.81	1.29	1.03	1.02	0.93
1984	0.93	0.66	0.72	0.87	0.95	0.42	0.36	0.40	0.42	0.85	0.78	1.01
1985	1.07	1.22	1.38	1.50	0.72	0.83	0.92	1.22	0.93	0.53	0.57	0.29
1986	0.23	0.15	-0.10	-0.18	-0.22	0.26	0.16	0.40	0.34	0.34	0.40	0.34
1987	0.35	0.36	0.13	0.07	0.59	0.23	0.22	-0.04	0.12	0.09	0.01	0.28
1988	0.19	0.10	0.11	0.38	-0.04	-0.66	-0.84	-0.72	-0.74	-0.71	-0.68	-0.85
1989	-0.78	-0.55	-0.09	-0.38	-0.28	0.00	0.06	-0.07	0.02	0.18	0.23	0.11
1990	0.12	0.06	-0.40	0.50	0.45	0.75	1.15	0.84	0.54	0.34	0.36	0.56
1991	0.52	0.39	0.41	-0.51	0.02	0.80	0.89	0.86	1.43	1.56	1.56	1.43
1992	1.39	1.63	1.69	1.82	1.37	1.54	1.24	1.29	0.76	1.23	1.26	1.27
1993	1.27	1.18	1.05	1.61	1.81	0.58	1.43	1.47	1.33	0.79	0.77	0.87
1994	0.88	0.78	0.76	0.02	-0.40	0.76	-0.59	-0.91	-0.61	-0.55	-0.58	-0.66
1995	-0.64	-0.64	-0.60	-0.82	-0.60	-2.04	-1.55	-0.93	-1.16	-0.81	-0.79	-0.58
1996	-0.59	-0.41	-0.33	-0.20	-0.14	0.89	0.64	0.75	1.23	1.21	1.46	1.45
1997	1.44	1.30	1.21	1.18	1.03	0.60	0.38	0.12	-0.58	-1.02	-1.05	-1.22
1998	-1.13	-1.17	-1.16	-1.05	-0.31	-1.28	-0.88	-1.13	-0.93	-0.91	-1.01	-1.02
1999	-1.11	-1.14	-1.15	-1.00	-1.70	-1.13	-1.30	-0.53	-0.05	-0.12	-0.24	-0.37
2000	-0.25	-0.26	-0.17	-0.49	-0.61	-0.83	-0.92	-1.56	-1.63	-1.64	-1.75	-1.73
2001	-1.74	-1.73	-1.79	-1.55	-0.89	-0.92	0.09	0.71	0.75	0.96	0.96	0.97
2002	1.40	1.47	1.49	1.60	1.46	1.40	0.80	0.42	0.05	-0.01	0.07	0.27
2003	-0.27	-0.35	-0.14	-0.28	-0.81	-1.11	-1.91	-1.60	-1.35	-1.36	-1.54	-1.66
2004	-1.65	-1.74	-1.92	-1.72	-1.91	-1.24	-1.16	-1.60	-1.78	-1.57	-1.59	-1.86
2005	-1.61	-1.62	-1.63	-1.53	-0.75	-0.46	-0.47	-0.02	-0.02	-0.36	-0.17	-0.19
2006	-0.39	-0.39	-0.39	-0.46	-0.30	-0.60	-0.62	-0.76	-0.83	-0.80	-0.67	-0.62
2007	-0.60	-0.53	-0.38	-0.33	-0.13	0.43	0.78	0.52	0.51	0.50	0.47	0.56
2008	0.60	0.53	0.38	0.07	-0.65	-1.11	-0.97	-0.99	-0.24	-0.34	-0.33	-0.40
2009	-0.44	-0.47	-0.48	-0.31	-0.04	0.39	-0.18	-0.25	-0.53	-0.32	0.16	0.10
2010	0.10	0.11	0.16	0.08	0.54	0.38	0.18	0.17	-0.17	-0.11	-0.38	-0.28
2011	-0.15	-0.17	-0.16	0.00	-0.38	-0.23	-0.33	-0.35	-0.17	-0.35	-0.60	-0.56
2012	-0.66	-0.68	-0.59	-0.50	-0.94	-1.27	-0.86	-0.13	0.00	-0.04	-0.23	-0.43
2013	-0.36	-0.28	-0.27	0.07	0.26	0.83	0.86	1.60	1.95	2.02	2.53	2.57
2014	2.61	2.60	2.66	2.36	2.60	2.46	2.77	1.98	1.45	1.34	0.90	0.93
2015	0.82	0.86	0.61	0.43	-0.12	-0.74	-0.83	-1.32	-1.32	-1.35	-1.48	-1.42
2016	-1.36	-1.36	-1.01	-0.53	-0.61	-0.18	-0.33	-0.32	-0.14	-0.12	-0.18	-0.19
2017	-0.29	-0.36	-0.63	-1.01	-1.16	-1.21	-1.77	-1.67	-1.86	-1.69	-1.35	-1.41
2018	-1.37	-1.30	-1.09	-0.51	0.38	0.65	0.63	0.61	0.98	0.85	0.64	0.71
2019	0.79	0.77	0.75	0.35	-0.17	-0.43	0.20	-0.03	-0.54	-0.13	-0.16	-0.04
2020	-0.08	-0.13	-0.27	-0.20	-0.31	-0.27						

APPENDIX B: SPI VALUES AND RAINFALL FOR WCWSS CATCHMENT AREAS

Table B1: Franschhoek-Robertsvlei (Berg River Dam catchment) SPI-12 values

▨ = drought month

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1920									0.17	0.28	0.36	0.49
1921	0.64	0.76	0.84	0.91	0.48	0.97	0.93	1.09	0.75	0.58	0.56	0.62
1922	0.76	0.69	0.81	0.80	1.04	0.46	0.12	0.19	0.20	0.19	0.22	0.09
1923	-0.15	-0.21	-0.41	-0.24	0.30	0.33	0.61	0.44	0.52	0.60	1.09	1.07
1924	1.02	1.01	1.09	0.92	0.53	0.19	-0.07	0.04	0.03	0.15	-0.15	-0.18
1925	-0.06	-0.03	-0.18	-0.17	-0.21	0.61	0.91	0.77	0.61	0.63	0.47	0.55
1926	0.42	0.56	0.56	0.58	0.88	-0.29	-0.35	-0.27	-0.19	0.13	0.06	-0.05
1927	-0.07	0.02	0.01	0.13	-0.14	-0.13	-0.32	-0.28	-0.27	-0.94	-0.69	-0.45
1928	-0.33	-0.56	-0.38	-0.53	-1.00	0.04	0.15	-0.03	0.20	0.25	0.02	-0.06
1929	-0.14	-0.15	-0.30	-0.05	0.41	-0.51	-0.36	-0.36	-0.71	-0.65	-0.64	-0.60
1930	-0.51	-0.43	-0.20	-0.47	-1.18	-1.35	-1.42	-1.40	-0.64	-0.56	-0.40	-0.50
1931	-0.65	-0.63	-0.72	-0.49	-0.10	-0.03	-0.27	-0.37	-0.96	-0.72	-1.02	-1.07
1932	-0.97	-0.84	-0.99	-1.43	-0.82	-0.46	-0.36	-0.60	-0.68	-1.03	-1.02	-1.02
1933	-1.01	-1.22	-1.22	-1.27	-1.60	-1.22	-1.17	-1.16	-1.45	-1.29	-1.28	-1.29
1934	-1.30	-1.31	-1.20	-1.25	-0.99	-1.46	-1.56	-1.89	-1.75	-1.67	-1.54	-1.61
1935	-1.57	-1.49	-1.47	-1.08	-1.09	-0.97	-0.76	-0.74	-0.79	-1.01	-1.00	-0.84
1936	-0.58	-0.62	-0.63	-1.09	-1.16	-1.14	-1.30	-1.12	-0.94	-0.88	-0.90	-0.83
1937	-0.99	-1.09	-1.01	-0.66	-0.48	0.45	0.87	0.66	0.50	0.59	0.53	0.30
1938	0.42	0.48	0.33	0.44	0.45	-0.45	-0.82	-0.80	-0.44	-0.46	-0.21	-0.16
1939	-0.43	-0.21	-0.21	-0.31	0.00	-0.07	-0.15	0.07	-0.27	-0.36	-0.43	-0.21
1940	-0.15	-0.12	0.02	0.18	-0.19	0.38	0.41	0.13	0.25	0.42	0.58	0.39
1941	0.60	0.38	0.26	0.64	0.96	0.94	1.16	1.41	1.96	1.99	1.76	1.84
1942	1.67	1.63	1.60	0.97	0.96	1.45	1.15	1.33	0.67	0.53	0.43	0.34
1943	0.40	0.46	0.62	0.74	0.11	-1.00	-0.76	-0.88	-0.77	-0.67	-0.41	-0.46
1944	-0.53	-0.61	-0.78	-0.82	-0.09	0.74	0.93	0.93	1.05	1.12	1.11	1.31
1945	1.24	1.22	1.19	1.28	1.60	1.66	2.05	2.10	1.95	1.84	1.79	1.71
1946	1.72	1.82	1.94	1.97	1.23	0.16	-0.74	-0.94	-0.23	-0.01	-0.07	-0.14
1947	-0.18	-0.30	-0.17	-0.26	0.02	0.11	0.81	0.77	0.26	0.16	0.14	0.10
1948	0.10	0.16	-0.07	-0.12	-0.15	0.09	-0.41	-0.57	-0.05	-0.02	-0.03	0.08
1949	0.12	0.08	0.03	0.25	-0.10	-0.24	-0.42	-0.31	-0.66	-0.76	-0.53	-0.60
1950	-0.64	-0.64	-0.65	-0.30	-0.48	-0.52	0.22	-0.20	0.02	-0.05	0.10	0.25
1951	0.43	0.43	0.42	0.47	0.69	1.55	1.03	1.29	1.16	1.19	1.05	0.88
1952	0.70	0.73	0.87	0.53	0.66	-0.36	-0.48	-0.01	0.34	0.34	0.51	0.53
1953	0.55	0.53	0.48	1.00	1.25	1.24	1.38	1.05	0.51	0.43	0.32	0.35
1954	0.38	0.44	0.49	0.15	0.53	0.71	1.05	1.28	1.40	1.47	1.29	1.38
1955	1.31	1.75	1.66	1.40	0.42	0.24	0.06	0.40	0.46	0.58	0.84	0.77
1956	0.81	0.26	0.34	0.50	1.03	1.55	1.36	1.29	1.47	1.33	1.03	1.09
1957	1.06	1.32	1.35	1.30	1.88	1.63	1.68	1.51	1.48	1.79	1.80	1.71
1958	1.70	1.68	1.66	1.66	1.15	0.70	-0.02	-0.11	-0.20	-0.65	-0.50	-0.50
1959	-0.46	-0.74	-0.79	-0.35	-0.10	-0.30	-0.26	-0.44	-0.46	-0.35	-0.52	-0.44
1960	-0.42	-0.43	-0.36	-0.83	-1.58	-0.72	-0.69	-1.12	-1.22	-1.41	-1.42	-1.45
1961	-1.32	-1.34	-1.54	-1.81	-1.92	-1.51	-1.44	-0.93	-0.42	-0.46	-0.49	-0.47
1962	-0.61	-0.38	0.00	0.40	0.03	1.01	1.18	1.39	1.24	1.67	1.91	1.85
1963	1.81	1.66	1.41	1.10	1.24	-0.33	0.26	0.09	0.14	-0.47	-0.63	-0.39
1964	-0.40	0.07	0.01	0.07	0.22	0.54	0.08	-0.21	-0.54	-0.32	-0.25	-0.42
1965	-0.27	-0.63	-0.21	0.07	0.31	-0.19	-0.23	0.03	0.23	0.11	0.09	0.27
1966	0.13	-0.01	0.50	0.40	0.18	0.49	1.09	0.98	1.31	1.22	1.10	1.07
1967	1.26	1.24	0.45	0.97	1.19	1.78	1.06	0.84	0.73	1.07	1.30	1.17
1968	1.23	1.26	1.23	1.17	1.92	1.06	1.55	1.84	1.66	1.88	1.65	1.76
1969	1.75	1.77	1.78	1.50	0.07	0.26	-0.39	-0.35	0.03	-0.24	-0.27	-0.44
1970	-0.77	-0.76	-0.79	-1.15	-0.24	0.19	0.37	0.41	0.25	-0.03	0.06	0.29
1971	0.29	0.23	0.36	0.54	0.10	-0.32	0.00	0.06	-0.12	-0.07	-0.13	-0.31
1972	-0.22	-0.15	-0.29	-0.53	-0.45	-0.50	-1.20	-1.98	-1.87	-1.97	-2.04	-1.99
1973	-2.09	-2.21	-2.18	-2.24	-2.65	-3.49	-1.72	-1.90	-1.87	-1.67	-1.61	-1.55
1974	-1.49	-1.45	-1.46	-1.55	-1.16	-0.28	-1.07	-0.03	-0.16	-0.06	0.05	-0.06
1975	0.00	0.01	0.05	0.59	1.34	1.29	1.83	1.13	1.01	0.99	0.95	0.91
1976	0.80	0.77	0.83	0.43	-0.54	0.47	0.17	0.04	0.15	-0.08	0.62	1.05
1977	1.15	1.24	1.19	1.72	2.47	2.47	2.46	3.26	3.39	3.37	2.88	2.77

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1978	2.69	2.68	2.71	2.45	1.44	-0.35	-1.29	-1.75	-1.52	-1.30	-1.39	-1.47
1979	-1.46	-1.21	-1.28	-1.42	-0.87	0.06	0.31	-0.25	-0.14	0.21	0.18	-0.06
1980	0.13	-0.06	-0.10	0.30	0.54	0.39	0.17	0.18	-0.19	-0.64	-0.21	0.09
1981	0.29	0.19	0.43	0.01	-0.85	-1.08	-0.22	-0.32	0.34	0.27	0.05	-0.15
1982	-0.41	-0.38	-0.58	-0.42	-0.09	0.15	-0.41	-0.40	-1.23	-0.92	-0.91	-0.64
1983	-0.84	-0.67	-0.54	-0.73	-0.36	0.14	0.43	0.19	0.87	0.59	0.47	0.22
1984	0.29	0.14	0.12	0.20	0.42	0.02	-0.21	-0.38	-0.58	-0.12	-0.18	0.17
1985	0.19	0.48	0.77	0.89	0.29	-0.03	0.46	0.92	0.63	0.39	0.44	0.13
1986	0.11	-0.14	-0.37	-0.24	0.23	0.67	0.51	0.61	0.75	0.59	0.61	0.57
1987	0.72	0.72	0.58	0.34	0.69	0.46	0.29	0.40	0.44	0.51	0.53	0.82
1988	0.61	0.53	0.55	0.81	0.44	0.19	0.25	0.01	-0.07	-0.04	-0.08	-0.36
1989	-0.33	-0.17	0.04	-0.24	-0.25	-0.20	-0.07	0.04	0.18	0.28	0.55	0.50
1990	0.46	0.53	0.23	0.98	0.59	0.86	1.47	1.07	0.80	0.58	0.39	0.41
1991	0.39	0.31	0.35	-0.53	0.07	1.01	0.51	0.64	1.29	1.45	1.40	1.36
1992	1.34	1.39	1.58	1.84	1.55	1.47	1.42	1.24	0.86	1.24	1.29	1.37
1993	1.37	1.28	1.04	1.37	1.58	0.65	1.30	1.55	1.30	0.76	0.67	0.71
1994	0.87	0.81	0.81	0.41	-0.20	0.97	-0.10	-0.20	0.25	0.33	0.34	0.25
1995	0.17	0.21	0.28	0.05	0.19	-1.04	-0.25	-0.04	-0.34	0.18	0.19	0.30
1996	0.20	0.30	0.37	0.56	0.50	1.08	0.32	0.42	1.26	1.06	1.33	1.46
1997	1.46	1.33	1.21	1.21	1.13	0.74	0.53	0.57	-0.46	-0.88	-0.91	-1.23
1998	-1.17	-1.17	-1.06	-0.78	0.10	-0.48	0.18	-0.36	-0.13	-0.02	-0.11	-0.03
1999	-0.09	-0.08	-0.19	-0.40	-0.81	-0.44	-0.73	-0.10	0.13	0.00	-0.09	-0.20
2000	0.06	0.07	0.11	-0.17	0.10	-0.31	-0.48	-0.83	-0.87	-0.76	-0.88	-0.80
2001	-1.02	-0.90	-0.97	-0.71	-0.75	-0.83	0.05	0.40	0.54	0.63	0.60	0.55
2002	0.76	0.75	0.80	0.84	0.47	0.85	0.59	0.05	-0.44	-0.44	-0.28	-0.20
2003	-0.47	-0.55	-0.41	-0.61	-0.95	-1.60	-2.65	-2.30	-2.05	-1.94	-2.21	-2.10
2004	-2.12	-2.13	-2.27	-2.03	-2.07	-1.36	-0.80	-0.54	-0.87	-0.67	-0.63	-0.84
2005	-0.43	-0.45	-0.52	-0.63	0.15	0.51	0.66	0.50	0.66	0.42	0.49	0.46
2006	0.09	0.11	0.13	0.08	0.39	-0.13	-0.34	-0.56	-0.76	-0.81	-0.60	-0.45
2007	-0.44	-0.35	-0.34	-0.24	-0.81	-0.12	0.20	0.18	0.23	0.25	0.61	0.54
2008	0.63	0.63	0.60	0.37	0.67	0.41	0.64	0.64	1.28	1.23	0.97	1.06
2009	0.97	0.89	0.88	0.94	0.80	1.30	0.43	0.20	-0.17	-0.07	0.28	0.13
2010	0.11	0.12	0.16	0.16	0.07	-0.79	-0.70	-0.77	-1.31	-1.06	-1.76	-1.73
2011	-1.70	-1.69	-1.72	-1.69	-1.62	-1.27	-1.40	-1.49	-1.28	-1.65	-1.66	-1.65
2012	-1.60	-1.62	-1.50	-1.34	-1.71	-1.94	-1.48	-1.11	-1.22	-1.15	-1.29	-1.40
2013	-1.37	-1.28	-1.30	-1.19	-0.86	-0.43	-0.33	0.61	0.93	1.05	1.45	1.47
2014	1.54	1.47	1.58	1.34	1.31	1.36	1.43	0.46	0.02	-0.19	-0.57	-0.55
2015	-0.57	-0.55	-0.79	-0.96	-1.15	-2.24	-1.80	-2.22	-2.26	-2.25	-2.29	-2.28
2016	-2.29	-2.32	-2.24	-1.75	-2.03	-0.89	-1.11	-1.48	-1.56	-1.47	-1.64	-1.67
2017	-1.68	-1.69	-1.70	-2.30	-2.33	-2.32	-2.95	-2.45	-2.37	-2.21	-2.01	-2.04
2018	-2.03	-1.94	-1.93	-1.55	-0.83	-0.53	-0.61	-0.79	-0.51	-0.67	-0.81	-0.65
2019	-0.51	-0.52	-0.48	-0.84	-1.10	-1.51	-0.23	-0.36	-0.94	-0.84	-0.85	-0.95
2020	-1.08	-1.14	-1.23	-1.19	-1.23	-1.27	-2.20					

Table B2: Franschhoek-Robertsvlei moving cumulative 12-month rainfall

Mean: 1 848 mm
Threshold: 1 455 mm

▨ = drought month

(Rainfall in mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1920									1 920	1 972	2 005	2 059
1921	2 132	2 187	2 226	2 246	2 058	2 306	2 294	2 363	2 183	2 104	2 095	2 120
1922	2 186	2 154	2 211	2 195	2 318	2 053	1 893	1 935	1 937	1 930	1 943	1 888
1923	1 787	1 763	1 681	1 755	1 978	1 991	2 128	2 048	2 076	2 115	2 347	2 329
1924	2 311	2 306	2 349	2 253	2 079	1 926	1 809	1 867	1 864	1 915	1 785	1 775
1925	1 824	1 838	1 776	1 783	1 760	2 124	2 281	2 203	2 118	2 126	2 054	2 087
1926	2 032	2 093	2 095	2 097	2 242	1 716	1 686	1 734	1 773	1 903	1 877	1 829
1927	1 819	1 857	1 853	1 904	1 788	1 786	1 698	1 732	1 739	1 484	1 575	1 670
1928	1 714	1 624	1 696	1 644	1 458	1 858	1 909	1 838	1 937	1 958	1 858	1 825
1929	1 791	1 787	1 727	1 832	2 028	1 626	1 679	1 697	1 569	1 590	1 594	1 612
1930	1 644	1 676	1 767	1 665	1 394	1 307	1 267	1 306	1 597	1 624	1 687	1 651
1931	1 590	1 598	1 564	1 660	1 806	1 827	1 720	1 694	1 478	1 562	1 455	1 440
1932	1 472	1 519	1 464	1 330	1 523	1 643	1 682	1 600	1 580	1 448	1 452	1 460
1933	1 457	1 385	1 382	1 381	1 253	1 353	1 357	1 393	1 310	1 358	1 362	1 365
1934	1 355	1 352	1 389	1 389	1 462	1 269	1 220	1 147	1 214	1 233	1 276	1 262
1935	1 268	1 292	1 299	1 447	1 425	1 446	1 517	1 546	1 538	1 458	1 463	1 522
1936	1 617	1 600	1 598	1 444	1 400	1 380	1 311	1 408	1 485	1 502	1 499	1 528
1937	1 463	1 429	1 458	1 594	1 650	2 049	2 259	2 153	2 066	2 107	2 083	1 978
1938	2 031	2 060	1 993	2 035	2 045	1 651	1 490	1 525	1 673	1 664	1 761	1 785
1939	1 676	1 761	1 761	1 729	1 848	1 809	1 771	1 881	1 739	1 702	1 673	1 763
1940	1 787	1 799	1 859	1 924	1 767	2 014	2 028	1 909	1 954	2 032	2 102	2 018
1941	2 113	2 012	1 959	2 125	2 280	2 289	2 417	2 528	2 794	2 814	2 692	2 722
1942	2 645	2 621	2 605	2 273	2 281	2 560	2 411	2 486	2 142	2 083	2 038	1 995
1943	2 023	2 049	2 121	2 169	1 894	1 434	1 516	1 495	1 548	1 581	1 681	1 668
1944	1 634	1 604	1 541	1 538	1 809	2 189	2 294	2 285	2 323	2 362	2 355	2 449
1945	2 420	2 412	2 397	2 423	2 608	2 674	2 931	2 918	2 786	2 735	2 703	2 652
1946	2 670	2 720	2 791	2 775	2 414	1 911	1 524	1 472	1 754	1 845	1 820	1 791
1947	1 774	1 725	1 780	1 749	1 854	1 891	2 229	2 204	1 963	1 917	1 909	1 892
1948	1 894	1 920	1 818	1 804	1 785	1 883	1 657	1 612	1 830	1 841	1 838	1 884
1949	1 900	1 883	1 862	1 956	1 807	1 736	1 655	1 719	1 590	1 548	1 636	1 612
1950	1 593	1 594	1 589	1 733	1 651	1 619	1 941	1 765	1 859	1 829	1 892	1 957
1951	2 036	2 038	2 031	2 049	2 154	2 612	2 345	2 464	2 375	2 395	2 325	2 238
1952	2 158	2 174	2 238	2 076	2 137	1 688	1 628	1 848	1 997	1 996	2 070	2 080
1953	2 092	2 081	2 057	2 291	2 425	2 443	2 534	2 345	2 073	2 037	1 987	2 000
1954	2 014	2 041	2 065	1 915	2 078	2 172	2 358	2 459	2 495	2 539	2 443	2 484
1955	2 457	2 682	2 638	2 479	2 028	1 948	1 866	2 030	2 049	2 103	2 224	2 191
1956	2 212	1 961	1 998	2 063	2 316	2 616	2 526	2 467	2 531	2 465	2 318	2 339
1957	2 333	2 458	2 476	2 431	2 759	2 662	2 710	2 585	2 538	2 707	2 711	2 652
1958	2 659	2 649	2 636	2 612	2 376	2 170	1 830	1 800	1 767	1 589	1 645	1 651
1959	1 662	1 555	1 536	1 711	1 804	1 713	1 724	1 668	1 665	1 708	1 641	1 675
1960	1 680	1 676	1 702	1 535	1 258	1 540	1 545	1 408	1 389	1 319	1 317	1 312
1961	1 349	1 341	1 274	1 210	1 153	1 252	1 261	1 476	1 682	1 661	1 652	1 661
1962	1 604	1 694	1 847	2 018	1 860	2 326	2 423	2 518	2 414	2 644	2 771	2 729
1963	2 719	2 636	2 510	2 338	2 418	1 698	1 959	1 890	1 911	1 658	1 599	1 694
1964	1 685	1 881	1 852	1 878	1 943	2 093	1 877	1 761	1 634	1 719	1 747	1 680
1965	1 739	1 598	1 761	1 882	1 980	1 757	1 735	1 864	1 950	1 897	1 886	1 966
1966	1 904	1 847	2 069	2 020	1 924	2 066	2 375	2 309	2 453	2 408	2 349	2 329
1967	2 431	2 418	2 047	2 273	2 397	2 746	2 359	2 236	2 172	2 334	2 452	2 380
1968	2 417	2 428	2 414	2 368	2 780	2 353	2 633	2 765	2 633	2 754	2 632	2 682
1969	2 684	2 696	2 703	2 532	1 876	1 958	1 669	1 701	1 865	1 751	1 738	1 674
1970	1 544	1 548	1 537	1 422	1 746	1 929	2 012	2 032	1 957	1 837	1 873	1 972
1971	1 974	1 950	2 007	2 082	1 890	1 704	1 838	1 877	1 801	1 821	1 795	1 725
1972	1 757	1 786	1 730	1 643	1 665	1 627	1 348	1 120	1 176	1 141	1 122	1 144
1973	1 105	1 069	1 078	1 083	944	696	1 166	1 144	1 176	1 232	1 252	1 280
1974	1 294	1 306	1 301	1 290	1 400	1 721	1 395	1 838	1 786	1 823	1 872	1 824
1975	1 851	1 854	1 872	2 104	2 472	2 472	2 797	2 382	2 302	2 298	2 279	2 255
1976	2 207	2 193	2 220	2 034	1 628	2 056	1 918	1 866	1 912	1 815	2 121	2 322

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1977	2 375	2 421	2 394	2 644	3 093	3 163	3 191	3 647	3 644	3 646	3 331	3 247
1978	3 222	3 215	3 235	3 032	2 519	1 689	1 314	1 193	1 286	1 354	1 327	1 306
1979	1 304	1 388	1 361	1 333	1 505	1 868	1 983	1 745	1 790	1 939	1 928	1 825
1980	1 906	1 826	1 806	1 975	2 084	2 017	1 918	1 929	1 772	1 592	1 761	1 889
1981	1 973	1 930	2 034	1 855	1 513	1 405	1 740	1 715	1 995	1 964	1 870	1 787
1982	1 682	1 696	1 616	1 687	1 808	1 910	1 659	1 681	1 384	1 488	1 492	1 598
1983	1 520	1 581	1 631	1 572	1 700	1 903	2 040	1 934	2 239	2 106	2 052	1 942
1984	1 976	1 908	1 902	1 933	2 029	1 848	1 746	1 691	1 621	1 800	1 774	1 922
1985	1 932	2 059	2 191	2 238	1 974	1 828	2 055	2 276	2 125	2 017	2 040	1 906
1986	1 896	1 793	1 700	1 754	1 945	2 154	2 079	2 129	2 179	2 110	2 120	2 099
1987	2 167	2 169	2 104	1 993	2 153	2 052	1 974	2 027	2 039	2 074	2 082	2 211
1988	2 117	2 083	2 090	2 201	2 037	1 927	1 953	1 854	1 822	1 834	1 815	1 704
1989	1 713	1 778	1 867	1 754	1 745	1 755	1 808	1 866	1 927	1 971	2 091	2 064
1990	2 051	2 079	1 948	2 280	2 105	2 249	2 587	2 354	2 206	2 105	2 019	2 026
1991	2 020	1 982	2 000	1 643	1 876	2 325	2 080	2 141	2 443	2 530	2 502	2 474
1992	2 472	2 496	2 598	2 707	2 579	2 569	2 560	2 439	2 233	2 418	2 442	2 478
1993	2 487	2 441	2 322	2 467	2 594	2 143	2 494	2 608	2 446	2 186	2 145	2 162
1994	2 238	2 209	2 212	2 022	1 762	2 305	1 793	1 764	1 955	1 994	1 998	1 958
1995	1 920	1 938	1 970	1 872	1 928	1 419	1 726	1 832	1 712	1 927	1 930	1 976
1996	1 936	1 978	2 009	2 088	2 068	2 361	1 986	2 037	2 427	2 331	2 465	2 523
1997	2 532	2 467	2 403	2 391	2 365	2 188	2 091	2 110	1 665	1 504	1 493	1 385
1998	1 400	1 400	1 440	1 550	1 890	1 636	1 924	1 699	1 797	1 841	1 804	1 837
1999	1 813	1 815	1 772	1 693	1 525	1 653	1 525	1 805	1 906	1 850	1 813	1 768
2000	1 875	1 877	1 895	1 784	1 888	1 707	1 630	1 515	1 512	1 547	1 503	1 539
2001	1 455	1 497	1 470	1 577	1 550	1 500	1 860	2 027	2 083	2 125	2 114	2 091
2002	2 189	2 184	2 207	2 215	2 055	2 242	2 118	1 874	1 671	1 669	1 734	1 767
2003	1 659	1 629	1 684	1 616	1 475	1 222	884	1 024	1 122	1 149	1 072	1 109
2004	1 096	1 093	1 053	1 144	1 107	1 304	1 499	1 625	1 512	1 583	1 596	1 522
2005	1 675	1 668	1 640	1 607	1 913	2 078	2 154	2 077	2 141	2 033	2 061	2 047
2006	1 887	1 896	1 905	1 885	2 016	1 785	1 690	1 619	1 552	1 530	1 608	1 671
2007	1 670	1 705	1 711	1 754	1 525	1 789	1 929	1 931	1 947	1 956	2 119	2 086
2008	2 129	2 127	2 112	2 006	2 144	2 027	2 145	2 140	2 436	2 415	2 287	2 324
2009	2 286	2 250	2 246	2 261	2 205	2 477	2 039	1 936	1 781	1 819	1 968	1 905
2010	1 898	1 900	1 918	1 917	1 877	1 514	1 538	1 535	1 358	1 440	1 207	1 223
2011	1 223	1 230	1 218	1 245	1 246	1 334	1 276	1 277	1 366	1 241	1 238	1 249
2012	1 256	1 252	1 287	1 359	1 217	1 111	1 247	1 409	1 386	1 406	1 359	1 328
2013	1 334	1 365	1 356	1 407	1 507	1 656	1 694	2 126	2 267	2 324	2 525	2 528
2014	2 574	2 535	2 594	2 449	2 456	2 509	2 565	2 058	1 859	1 772	1 622	1 631
2015	1 621	1 629	1 535	1 487	1 405	1 019	1 139	1 047	1 062	1 058	1 047	1 059
2016	1 046	1 038	1 061	1 229	1 119	1 476	1 380	1 280	1 275	1 299	1 246	1 242
2017	1 231	1 228	1 222	1 067	1 030	997	806	981	1 029	1 070	1 130	1 128
2018	1 124	1 150	1 152	1 289	1 520	1 616	1 575	1 529	1 647	1 581	1 529	1 593
2019	1 645	1 641	1 653	1 530	1 421	1 250	1 738	1 698	1 486	1 516	1 516	1 485
2020	1 434	1 412	1 378	1 409	1 376	1 334	1 014					

Table B3: Rustfontein SPI-12 values

▨ = drought month

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1921									0.74	0.65	0.61	0.62
1922	0.69	0.67	0.69	0.55	0.72	0.55	0.04	0.08	-0.23	-0.13	0.41	0.28
1923	0.14	-0.02	-0.18	0.16	0.59	0.29	0.52	0.19	0.25	0.24	0.22	0.22
1924	0.16	0.16	0.2	-0.05	-0.86	-0.44	-0.82	-0.38	-0.39	-0.34	-0.79	-0.8
1925	-0.63	-0.57	-0.6	-0.71	-0.66	-0.05	0.26	-0.2	-0.21	-0.14	-0.15	-0.15
1926	-0.27	-0.23	-0.18	-0.19	0.18	-1.08	-0.87	-0.69	-0.66	-0.46	-0.57	-0.57
1927	-0.58	-0.65	-0.64	-0.52	-0.64	-0.46	-1.12	-0.6	-0.71	-1.2	-0.97	-0.81
1928	-0.67	-0.71	-0.62	-0.85	-1.25	-0.64	-0.27	-0.47	-0.08	-0.09	-0.23	-0.23
1929	-0.4	-0.35	-0.42	-0.14	0.15	-0.58	-0.25	-0.18	-0.64	-0.6	-0.71	-0.72
1930	-0.56	-0.42	-0.29	-0.52	-0.77	-0.78	-1.6	-1.27	-0.38	-0.37	-0.34	-0.44
1931	-0.47	-0.53	-0.68	-0.05	0.07	-0.08	0.25	0.12	-0.35	0.19	0.01	0.05
1932	0.11	0.27	0.32	-0.37	-0.18	0.05	0.45	0.03	0.18	-0.21	-0.15	-0.11
1933	-0.23	-0.51	-0.55	-0.53	-0.64	0.37	0.62	0.76	0.49	0.44	0.41	0.34
1934	0.35	0.37	0.43	0.43	0.56	-0.19	-1.1	-1.03	-0.91	-0.76	-0.76	-0.83
1935	-0.94	-0.99	-1.01	-0.64	-0.4	-0.39	-0.4	-0.69	-0.95	-1.29	-0.82	-0.79
1936	-0.5	-0.52	-0.52	-0.92	-0.99	-1.19	-0.55	0.09	0.09	0.14	0.1	0.58
1937	0.34	0.34	0.45	0.76	0.61	1.81	1.74	1.22	1.21	1.28	1.07	0.65
1938	0.8	0.85	0.84	0.8	1.12	-0.36	-0.96	-0.54	-0.16	-0.16	-0.23	-0.27
1939	-0.35	-0.15	-0.35	-0.55	-0.71	-0.99	-1.02	-1.27	-1.84	-2.03	-2.07	-1.97
1940	-2.13	-2.06	-2.03	-1.04	-1.19	-0.33	-0.25	-0.27	-0.20	-0.15	0.25	0.16
1941	0.42	0.16	0.14	-0.18	0.93	1.14	1.63	2.06	2.64	2.76	2.51	2.70
1942	2.54	2.55	2.54	2.27	1.32	2.13	1.48	1.28	0.41	0.26	0.26	0.26
1943	0.49	0.60	0.79	0.80	0.48	-1.06	-0.57	-0.38	-0.14	-0.14	0.08	-0.17
1944	-0.44	-0.53	-0.66	-0.57	-0.35	0.88	0.94	1.05	1.09	1.22	1.14	1.20
1945	1.16	1.14	1.05	1.13	1.43	1.20	2.21	2.31	2.06	2.01	2.09	2.09
1946	2.12	2.20	2.33	2.30	1.90	0.72	-0.76	-1.38	-0.60	-0.79	-0.90	-0.97
1947	-1.04	-1.15	-0.84	-0.90	-0.87	-0.86	-0.37	-0.44	-0.97	-0.85	-0.83	-0.82
1948	-0.76	-0.73	-0.81	-0.82	-0.47	-0.02	-0.26	-0.41	0.40	0.49	0.43	0.49
1949	0.48	0.47	0.15	0.36	0.17	-0.19	-0.42	-0.43	-1.01	-1.10	-0.70	-0.77
1950	-0.84	-0.85	-0.89	-0.70	-1.05	-1.06	0.08	-0.21	-0.14	-0.09	0.01	0.08
1951	0.30	0.30	0.35	0.22	0.40	1.51	0.60	0.89	0.84	0.93	0.90	0.85
1952	0.64	0.68	0.66	0.41	0.53	-0.68	-0.48	0.03	-0.03	0.02	0.03	0.02
1953	0.01	-0.02	-0.04	0.96	1.35	1.21	1.16	0.89	0.50	0.18	-0.05	-0.07
1954	-0.01	0.08	0.28	-0.64	0.49	1.01	1.73	1.92	2.21	2.23	2.23	2.33
1955	2.30	2.73	2.58	2.60	1.16	0.82	0.44	0.90	0.64	0.79	0.84	0.85
1956	0.92	0.37	0.47	0.37	0.70	1.09	0.60	-0.34	-0.18	-0.31	-0.45	-0.44
1957	-0.56	-0.34	-0.14	-0.14	0.30	0.26	0.85	1.06	1.07	1.29	1.33	1.19
1958	1.20	1.11	1.05	1.19	0.91	0.41	-0.68	-0.72	-0.97	-1.23	-1.03	-1.03
1959	-0.93	-1.04	-1.21	-0.73	0.44	0.20	0.34	0.27	0.27	0.18	-0.02	0.09
1960	0.07	0.03	0.05	-0.49	-2.22	-1.44	-1.52	-2.12	-1.47	-1.74	-1.65	-1.70
1961	-1.57	-1.59	-1.65	-1.69	-1.67	-1.65	-1.43	-0.83	-0.79	-0.60	-0.74	-0.79
1962	-0.90	-0.80	-0.66	-0.23	-0.46	0.48	0.60	1.29	0.89	1.24	1.47	1.44
1963	1.43	1.37	1.28	0.90	0.96	-0.16	-0.05	-0.54	-0.40	-1.00	-1.19	-0.97
1964	-1.05	-0.59	-0.52	-0.44	-0.42	0.26	0.20	-0.04	-0.09	-0.11	-0.03	-0.20
1965	-0.13	-0.38	-0.14	0.02	0.25	-0.49	-0.69	-0.83	-0.73	-0.60	-0.65	-0.36
1966	-0.45	-0.65	-0.69	-0.74	-1.04	-0.30	-0.08	-0.11	-0.12	-0.33	-0.48	-0.81
1967	-0.80	-0.79	-1.10	-0.99	-0.64	-0.70	-0.97	-1.02	-1.11	-0.94	-0.81	-0.80
1968	-0.77	-0.75	-0.79	-0.84	-0.68	-0.97	-0.23	0.02	-0.19	0.26	0.18	0.24
1969	0.26	0.25	0.30	0.18	-0.42	-0.61	-1.58	-1.66	-1.19	-1.36	-1.29	-1.37
1970	-1.44	-1.36	-1.40	-1.73	-1.10	-0.89	-0.32	-0.33	-0.48	-0.82	-1.00	-0.84
1971	-0.83	-0.93	-0.82	-0.80	-0.82	-0.87	-0.84	-0.62	-0.87	-0.99	-0.93	-0.96
1972	-0.77	-0.69	-0.65	-0.39	0.05	-0.02	-0.67	-1.01	-0.85	-0.87	-1.04	-1.10
1973	-1.30	-1.44	-1.55	-1.81	-3.00	-3.46	-2.14	-1.43	-1.27	-1.30	-1.29	-1.23
1974	-1.24	-1.21	-1.21	-1.46	-1.05	-0.31	-0.91	0.86	0.84	1.06	1.10	1.05
1975	1.08	1.13	1.09	1.37	1.79	1.54	1.71	0.03	-0.10	-0.21	-0.18	-0.23
1976	-0.32	-0.33	-0.10	-0.26	-0.81	0.26	0.47	-0.04	0.03	-0.01	0.52	0.93
1977	1.01	1.16	1.05	1.54	2.33	1.90	2.07	2.85	2.77	2.66	2.38	2.22
1978	2.23	2.10	2.09	1.76	0.54	-0.24	-1.12	-1.70	-1.45	-1.34	-1.59	-1.57
1979	-1.55	-1.17	-1.26	-1.49	-0.82	0.00	-0.14	-0.47	-0.49	-0.38	-0.40	-0.63
1980	-0.69	-1.04	-1.06	-0.86	-1.09	-1.66	-1.26	-1.19	-1.61	-1.60	-1.00	-0.69

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	-0.02	-0.04	0.23	0.18	-0.27	-0.55	0.32	0.46	1.44	1.31	0.93	0.70
1982	0.13	0.10	-0.13	0.34	0.68	1.08	0.18	-0.02	-1.22	-1.09	-1.16	-1.18
1983	-1.33	-1.03	-0.82	-1.59	-0.75	-0.07	0.98	0.78	1.11	0.99	1.06	1.08
1984	1.12	0.96	0.86	1.05	1.21	0.57	-0.29	-0.16	0.28	0.67	0.66	0.89
1985	1.07	1.24	1.63	1.75	0.86	0.98	1.41	1.81	1.27	1.10	1.17	1.06
1986	0.82	0.83	0.53	0.40	0.38	0.51	0.15	0.21	0.24	0.01	0.16	0.04
1987	0.05	-0.09	-0.33	-0.29	0.67	0.45	0.13	0.17	0.22	0.15	-0.05	0.10
1988	0.07	-0.03	-0.03	0.22	-0.71	-0.85	-0.87	-1.35	-1.37	-1.29	-1.34	-1.56
1989	-1.49	-1.33	-0.72	-0.67	-0.52	-0.41	-0.09	0.07	0.21	0.49	0.59	0.59
1990	0.55	0.67	0.25	0.36	0.41	0.58	0.41	0.21	-0.12	-0.39	-0.44	-0.35
1991	-0.33	-0.62	-0.68	-1.26	-1.13	-0.33	0.26	0.09	0.58	0.74	0.71	0.65
1992	0.61	0.83	1.04	1.17	0.94	1.01	0.72	0.77	0.29	0.83	0.84	0.84
1993	0.83	0.88	0.67	1.44	1.62	0.87	1.99	1.96	1.99	1.28	1.30	1.50
1994	1.52	1.34	1.36	0.53	0.27	1.56	0.14	-0.12	0.19	0.29	0.26	0.34
1995	0.34	0.34	0.39	0.23	0.65	-0.87	-0.90	-0.53	-0.70	-0.39	-0.25	-0.12
1996	-0.16	-0.06	-0.07	0.02	-0.24	0.62	0.85	1.18	1.44	1.51	1.78	1.62
1997	1.60	1.56	1.49	1.59	1.69	1.79	1.38	1.09	0.54	0.08	-0.06	-0.20
1998	-0.08	-0.14	-0.07	-0.10	0.47	-1.00	-0.12	-0.30	-0.20	-0.21	-0.15	0.31
1999	0.26	0.28	0.21	0.40	-0.28	0.02	-0.48	0.21	0.58	0.59	0.35	-0.12
2000	-0.03	0.00	0.25	-0.02	-0.19	-0.27	0.12	-0.49	-0.64	-0.60	-0.62	-0.60
2001	-0.66	-0.72	-1.05	-0.78	-0.17	-0.21	0.42	1.00	1.31	1.51	1.56	1.60
2002	1.87	1.93	1.94	1.94	1.68	1.66	1.45	1.28	0.96	0.83	0.95	0.97
2003	0.54	0.51	0.72	0.58	0.23	-0.10	-1.23	-1.11	-0.86	-0.76	-1.03	-0.98
2004	-0.97	-1.00	-1.13	-0.87	-1.10	-0.50	-0.38	-0.94	-1.46	-1.12	-1.12	-1.22
2005	-0.83	-0.81	-0.92	-0.35	0.18	0.33	0.25	0.65	0.77	0.36	0.62	0.52
2006	0.19	0.21	0.24	-0.23	-0.30	-0.55	-0.39	-0.23	-0.38	-0.35	-0.44	-0.35
2007	-0.35	-0.16	-0.11	-0.15	0.36	1.06	1.28	1.02	1.01	1.13	1.51	1.57
2008	1.58	1.51	1.49	1.37	0.88	0.21	0.90	0.94	1.70	1.54	1.75	1.85
2009	1.83	1.93	1.84	1.86	1.95	2.33	1.62	1.56	0.89	1.05	0.60	0.35
2010	0.33	0.13	0.13	0.06	0.32	-0.21	-0.45	-0.96	-1.22	-1.28	-1.59	-1.57
2011	-1.57	-1.60	-1.55	-1.40	-1.28	-0.51	-0.75	-0.87	-0.54	-0.70	-0.64	-0.51
2012	-0.51	-0.52	-0.37	-0.31	-1.14	-1.82	-1.52	0.21	0.29	0.42	0.32	0.21
2013	0.25	0.39	0.28	0.51	0.70	1.17	1.09	1.14	1.16	1.17	1.57	1.57
2014	2.00	1.95	2.11	1.97	2.16	1.99	2.26	1.40	1.24	1.05	0.75	0.74
2015	0.23	0.20	-0.04	-0.25	-0.85	-1.14	-0.93	-0.93	-0.99	-0.98	-1.08	-1.03
2016	-1.04	-1.03	-0.80	-0.23	-0.28	-0.49	-0.61	-0.97	-1.07	-1.11	-1.30	-1.35
2017	-1.20	-1.24	-1.48	-2.17	-2.26	-1.90	-2.80	-2.58	-2.50	-2.22	-2.00	-2.01
2018	-2.31	-2.24	-2.14	-1.78	-0.59	-0.39	-0.10	0.04	0.18	0.11	0.00	0.06
2019	0.11	0.05	0.20	-0.16	-1.13	-1.51	-0.71	-1.07	-1.33	-0.72	-0.79	-0.76
2020	-0.26	-0.26	-0.47	-0.48	-0.28	-0.01						

Table B4: Rustfontein moving cumulative 12-month rainfall

Mean: 764 mm
Threshold: 587 mm

▨ = drought month

(Rainfall in mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1921									919	900	889	889
1922	906	900	906	873	909	874	773	778	719	739	847	821
1923	792	762	732	795	881	820	868	800	814	813	807	807
1924	797	797	804	757	616	682	619	690	689	698	622	622
1925	650	662	655	640	648	754	816	723	722	736	737	737
1926	715	722	731	730	800	575	611	635	641	677	660	660
1927	659	647	648	672	651	678	570	649	632	550	592	619
1928	644	637	653	618	554	647	713	673	747	746	721	722
1929	691	700	687	740	794	658	719	727	644	650	635	634
1930	662	688	711	673	630	624	498	538	690	693	701	682
1931	678	668	641	756	779	748	814	786	696	803	766	775
1932	787	819	828	699	732	774	854	767	800	722	736	743
1933	722	673	665	672	652	837	890	923	865	855	847	832
1934	835	837	851	848	875	728	572	576	598	623	627	616
1935	598	592	588	653	693	692	691	634	591	535	617	623
1936	673	671	670	607	594	557	665	780	780	793	783	883
1937	833	831	854	915	886	1 166	1 147	1 028	1 026	1 048	991	896
1938	931	940	938	924	996	697	596	661	733	732	722	714
1939	700	737	699	668	639	589	586	538	455	428	432	446
1940	425	437	438	588	563	703	717	709	724	734	813	797
1941	849	796	793	733	954	1 005	1 121	1 244	1 408	1 452	1 355	1 407
1942	1 366	1 361	1 363	1 268	1 041	1 250	1 084	1 044	847	816	816	817
1943	864	885	927	925	859	578	661	690	735	736	780	733
1944	683	668	645	665	701	945	960	989	1 000	1 033	1 006	1 019
1945	1 010	1 004	984	996	1 066	1 018	1 268	1 314	1 244	1 237	1 242	1 240
1946	1 249	1 265	1 302	1 277	1 179	910	628	522	651	618	604	592
1947	582	566	615	610	614	610	696	678	587	606	616	618
1948	629	634	620	623	681	761	715	684	845	867	851	862
1949	861	858	794	836	797	728	686	680	582	566	637	626
1950	615	614	606	642	584	577	780	722	735	747	767	780
1951	825	824	833	808	844	1 093	885	952	942	963	953	940
1952	896	903	899	845	870	640	677	767	757	768	771	769
1953	768	762	756	959	1 048	1 021	1 009	951	865	800	755	752
1954	763	780	820	652	861	976	1 146	1 206	1 284	1 298	1 278	1 305
1955	1 298	1 411	1 373	1 357	1 004	934	852	954	896	933	937	940
1956	956	837	859	836	904	993	885	697	728	703	681	683
1957	663	702	739	740	823	815	938	991	993	1 050	1 049	1 018
1958	1 022	998	985	1 008	949	846	641	628	588	544	583	584
1959	599	584	556	638	850	804	831	818	818	801	760	783
1960	779	771	775	678	420	519	509	417	508	469	489	483
1961	502	500	491	493	492	489	522	610	618	651	631	623
1962	604	622	644	724	682	860	885	1 047	951	1 039	1 083	1 075
1963	1 075	1 056	1 039	945	960	734	755	661	687	582	558	593
1964	580	659	669	686	689	816	804	754	745	742	759	727
1965	741	696	739	769	814	674	640	611	628	651	647	698
1966	683	648	640	636	587	708	749	740	740	701	675	620
1967	622	624	574	595	651	636	594	578	564	592	619	621
1968	626	632	623	619	645	592	721	766	727	818	801	812
1969	818	814	824	799	689	652	501	480	553	525	542	530
1970	520	534	527	487	577	606	705	700	672	613	588	614
1971	616	601	619	626	622	608	615	647	604	583	599	595
1972	626	641	647	695	775	760	644	580	608	603	582	573
1973	542	523	504	477	331	276	424	513	539	534	542	552
1974	551	558	555	525	585	706	603	944	941	994	996	985
1975	993	1 002	993	1 049	1 153	1 099	1 141	769	743	723	731	721
1976	706	705	747	718	623	815	858	754	769	763	870	957
1977	978	1 008	985	1 089	1 291	1 189	1 232	1 473	1 448	1 420	1 320	1 274

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1978	1 278	1 239	1 238	1 140	871	719	570	474	512	528	497	501
1979	504	563	548	521	622	764	738	672	671	691	691	650
1980	639	584	580	616	578	487	548	551	488	489	589	639
1981	761	757	811	801	716	663	827	856	1 082	1 053	959	908
1982	791	785	740	832	900	990	799	758	547	568	562	559
1983	537	586	618	507	633	750	967	928	1 003	977	988	993
1984	1 002	963	943	977	1 016	879	710	732	820	905	899	948
1985	992	1 027	1 121	1 138	938	967	1 066	1 179	1 041	1 005	1 014	988
1986	934	935	871	842	838	867	795	804	811	766	795	772
1987	776	748	704	712	898	855	790	797	807	793	755	784
1988	779	760	759	807	639	612	609	526	525	535	535	503
1989	513	539	636	647	672	687	748	776	806	865	885	883
1990	877	901	815	834	844	880	846	806	740	688	683	699
1991	703	653	642	555	572	701	815	780	882	921	910	897
1992	889	935	981	1 005	957	976	912	925	821	940	939	937
1993	937	946	900	1 066	1 110	943	1 211	1 217	1 225	1 047	1 044	1 089
1994	1 098	1 050	1 057	869	817	1 105	791	738	802	823	817	831
1995	834	832	843	810	895	608	605	663	633	689	718	742
1996	736	754	752	770	721	890	939	1 020	1 083	1 106	1 161	1 120
1997	1 115	1 103	1 089	1 100	1 130	1 161	1 061	999	874	779	752	726
1998	750	739	752	747	857	587	742	705	724	723	735	825
1999	816	820	806	842	713	768	677	805	884	887	834	741
2000	759	765	814	762	731	713	789	670	644	651	651	655
2001	645	636	581	629	734	725	848	978	1 052	1 105	1 107	1 114
2002	1 185	1 195	1 199	1 185	1 127	1 129	1 077	1 044	969	941	963	966
2003	875	867	911	879	809	744	553	565	606	623	583	591
2004	593	591	568	615	577	671	695	592	510	562	568	554
2005	617	621	601	702	800	830	813	898	926	838	891	868
2006	803	806	812	724	710	662	692	717	691	696	683	699
2007	699	735	744	738	835	986	1 036	981	979	1 011	1 093	1 108
2008	1 110	1 091	1 089	1 049	944	804	949	964	1 150	1 113	1 153	1 177
2009	1 174	1 194	1 175	1 165	1 192	1 304	1 117	1 113	953	991	887	833
2010	831	790	790	778	828	724	682	588	547	537	498	501
2011	501	500	505	535	549	669	630	604	661	632	649	671
2012	671	670	696	710	571	465	510	805	822	851	828	806
2013	815	843	820	865	905	1 012	992	1 010	1 014	1 020	1 108	1 108
2014	1 217	1 200	1 245	1 193	1 247	1 213	1 283	1 074	1 035	991	918	915
2015	811	805	757	720	617	566	601	593	584	585	576	583
2016	583	585	622	723	714	673	654	586	571	564	541	534
2017	557	553	514	430	415	454	346	360	371	404	441	441
2018	402	414	424	481	660	691	746	771	800	787	765	777
2019	788	776	803	737	572	509	636	570	531	629	622	627
2020	717	716	678	680	713	763						

Table B5: Steenbras Dam SPI-12 values

▨ = drought month

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1916												1.11
1917	1.14	0.93	0.83	0.88	1.50	1.27	1.72	1.55	1.58	1.50	1.63	1.49
1918	1.21	1.27	1.18	0.93	0.91	0.90	0.71	0.04	0.02	0.41	0.73	0.88
1919	1.17	1.30	1.26	1.32	0.66	0.33	0.30	0.67	0.82	0.41	0.22	0.22
1920	-0.10	-0.23	-0.24	-0.30	0.40	1.11	1.11	1.14	1.05	1.15	1.24	1.39
1921	1.62	1.77	1.80	1.92	1.08	1.04	0.85	0.90	0.89	0.85	0.57	0.46
1922	0.39	0.21	0.20	0.27	0.53	0.14	-0.19	-0.18	-0.51	-0.43	-0.40	-0.65
1923	-0.66	-0.69	-0.67	-0.39	0.22	0.25	0.62	0.68	0.86	0.78	1.48	1.55
1924	1.44	1.46	1.61	1.26	0.83	0.65	0.23	0.17	0.15	0.40	-0.30	-0.43
1925	-0.25	-0.21	-0.55	-0.72	-0.95	-0.29	0.07	-0.09	-0.08	0.02	0.00	0.09
1926	-0.16	0.02	0.09	0.25	0.68	-0.32	-0.56	-0.53	-0.49	-0.47	-0.64	-0.79
1927	-0.77	-0.85	-0.83	-0.81	-0.83	-0.74	-1.03	-0.65	-0.89	-1.60	-1.36	-1.10
1928	-0.92	-1.13	-0.96	-1.19	-2.03	-1.67	-1.85	-2.34	-2.06	-1.96	-2.26	-2.61
1929	-2.82	-2.75	-2.95	-2.37	-1.94	-2.29	-1.75	-1.74	-1.86	-1.84	-1.76	-1.41
1930	-1.18	-0.80	-0.63	-0.88	-1.33	-1.18	-1.54	-1.49	-0.89	-0.82	-0.74	-1.12
1931	-1.34	-1.62	-1.84	-1.46	-1.18	-1.18	-1.10	-0.76	-1.28	-0.82	-1.10	-1.00
1932	-0.78	-0.48	-0.39	-0.89	-0.28	0.06	-0.16	-0.44	-0.35	-0.86	-0.82	-0.98
1933	-1.02	-1.45	-1.48	-1.33	-2.06	-1.63	-1.48	-1.26	-1.51	-1.39	-1.32	-1.47
1934	-1.56	-1.61	-1.33	-1.48	-1.24	-1.99	-2.26	-2.28	-2.00	-1.81	-1.46	-1.46
1935	-1.40	-1.43	-1.47	-0.97	-0.94	-0.74	-0.55	-0.61	-0.62	-0.82	-1.08	-1.13
1936	-0.62	-0.56	-0.62	-1.00	-1.25	-1.34	-1.71	-1.55	-1.46	-1.48	-1.57	-1.25
1937	-1.63	-1.71	-1.50	-1.19	-1.22	0.00	0.56	0.51	0.45	0.59	0.57	0.28
1938	0.38	0.39	0.25	0.47	0.59	-0.42	-0.86	-0.85	-0.53	-0.46	-0.33	-0.29
1939	-0.59	-0.24	-0.33	-0.57	-0.80	-0.78	-0.99	-0.73	-1.19	-1.45	-1.41	-1.19
1940	-1.04	-1.04	-0.70	-0.61	-0.54	0.11	0.17	-0.27	0.02	0.17	0.18	0.10
1941	0.17	-0.18	-0.40	0.15	0.68	0.65	0.74	0.83	0.94	1.00	1.00	0.98
1942	0.94	1.03	1.04	0.41	0.16	0.37	0.04	0.36	-0.05	-0.17	-0.43	-0.49
1943	-0.31	-0.25	-0.15	-0.07	-0.30	-1.08	-0.81	-0.96	-0.89	-0.95	-0.79	-0.93
1944	-0.99	-1.18	-1.30	-1.48	-1.02	0.16	0.29	0.59	1.13	1.27	1.24	1.41
1945	1.19	1.18	1.13	1.37	1.84	1.57	1.81	1.68	0.96	0.93	0.96	0.90
1946	0.99	1.03	1.32	1.22	0.34	-0.35	-0.78	-0.84	-0.09	-0.17	-0.31	-0.35
1947	-0.41	-0.46	-0.49	-0.52	-0.40	-0.54	-0.06	-0.21	-0.78	-0.91	-0.84	-0.99
1948	-0.98	-0.90	-1.12	-1.27	-1.32	-0.92	-1.29	-1.35	-1.02	-0.52	-0.52	-0.40
1949	-0.34	-0.37	-0.45	-0.10	-0.19	-0.22	-0.44	-0.10	-0.15	-0.58	-0.50	-0.51
1950	-0.52	-0.56	-0.53	-0.20	-0.43	-0.62	0.01	-0.52	-0.33	-0.17	-0.08	0.09
1951	0.33	0.32	0.28	0.30	0.67	1.66	1.14	1.32	1.45	1.35	1.47	1.23
1952	0.98	1.02	1.24	0.73	0.53	-0.62	-0.71	-0.52	-0.78	-0.77	-0.82	-0.78
1953	-0.72	-0.72	-0.95	-0.40	0.22	0.22	0.31	0.16	-0.30	-0.30	-0.43	-0.46
1954	-0.43	-0.32	-0.29	-0.70	-0.24	-0.02	0.50	0.96	1.21	1.33	1.27	1.38
1955	1.29	1.82	1.79	1.76	0.68	0.55	0.27	0.31	0.37	0.56	0.64	0.60
1956	0.69	0.05	0.18	0.35	1.14	1.52	1.11	0.87	0.64	0.54	0.37	0.46
1957	0.51	0.65	0.52	0.41	0.72	0.50	0.86	0.83	1.06	1.31	1.34	1.13
1958	1.06	1.19	1.22	1.10	0.77	0.56	-0.14	-0.15	-0.17	-0.58	-0.49	-0.53
1959	-0.40	-0.71	-0.60	0.02	0.60	0.23	0.39	0.37	0.27	0.33	0.21	0.37
1960	0.22	0.19	0.12	-0.50	-1.58	-0.72	-0.81	-1.14	-1.30	-1.68	-1.75	-1.77
1961	-1.17	-1.22	-1.30	-1.54	-1.70	-1.81	-1.69	-1.07	-0.67	-0.50	-0.52	-0.63
1962	-1.02	-0.80	-0.63	-0.14	-0.38	0.30	0.40	0.27	0.05	0.38	0.57	0.52
1963	0.48	0.25	0.08	-0.38	-0.40	-1.19	-0.33	-0.11	-0.21	-0.76	-0.53	-0.31
1964	-0.39	-0.10	-0.13	0.03	0.47	0.69	0.16	0.07	0.20	0.44	0.40	0.23
1965	0.38	0.40	0.75	0.90	0.75	0.32	0.05	-0.16	-0.22	-0.25	-0.61	-0.48
1966	-0.62	-0.80	-0.74	-0.88	-0.82	-0.80	-0.21	-0.13	0.07	-0.19	-0.04	-0.17
1967	-0.09	-0.25	-0.42	0.30	0.14	0.64	0.09	-0.06	-0.17	0.21	0.21	0.11
1968	0.30	0.54	0.30	-0.40	0.08	0.07	0.40	0.55	0.43	0.49	0.33	0.58
1969	0.58	0.52	0.69	0.73	0.04	-0.24	-0.68	-0.66	-0.51	-0.58	-0.51	-0.86
1970	-1.11	-1.22	-1.37	-1.67	-0.78	-0.68	-0.39	-0.08	-0.04	-0.12	-0.13	0.05
1971	0.05	-0.03	0.01	0.00	-0.53	-0.70	-0.90	-0.77	-0.89	-0.94	-0.92	-1.14
1972	-1.02	-0.65	-0.58	-0.08	0.31	0.29	0.13	-0.26	-0.13	-0.30	-0.43	-0.24
1973	-0.34	-0.69	-0.71	-1.31	-1.75	-1.91	-1.31	-1.33	-1.09	-1.07	-0.84	-1.03
1974	-0.94	-0.92	-0.92	-0.96	-0.25	0.30	-0.16	0.89	0.88	1.20	1.17	1.09
1975	1.19	1.20	1.14	1.34	1.16	0.98	1.50	0.53	0.19	0.03	0.13	0.11

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1976	-0.16	-0.10	0.08	0.37	-0.06	0.73	0.24	0.21	0.64	0.47	0.87	1.18
1977	1.28	1.37	1.43	1.37	1.91	1.63	1.89	1.98	1.90	1.88	1.45	1.24
1978	1.18	1.24	1.20	1.09	0.48	-0.47	-1.24	-1.20	-1.11	-0.89	-0.86	-0.81
1979	-0.73	-0.13	-0.33	-0.72	0.07	0.49	0.72	0.46	0.34	0.89	0.80	0.69
1980	0.69	0.09	0.04	0.50	0.30	0.48	0.17	0.18	0.02	-0.69	-0.18	0.15
1981	0.70	0.55	1.28	1.21	0.47	0.02	1.18	1.53	1.85	1.72	1.47	1.37
1982	0.95	0.96	0.26	0.32	0.48	0.65	-0.41	-0.55	-1.22	-1.14	-1.07	-0.88
1983	-1.06	-0.48	-0.01	-0.31	0.51	1.00	1.26	1.17	1.69	1.63	1.47	1.25
1984	1.25	0.85	0.60	0.78	0.79	0.16	0.00	-0.25	-0.53	-0.02	-0.05	0.53
1985	0.56	0.70	0.96	1.11	0.45	0.47	0.87	1.21	1.14	0.79	0.79	0.20
1986	0.06	0.05	-0.11	-0.14	-0.11	0.36	0.16	0.55	0.51	0.49	0.59	0.58
1987	0.86	0.78	0.55	0.54	1.08	0.74	0.96	0.76	0.98	0.92	0.91	1.05
1988	0.79	0.70	0.73	0.68	0.31	0.31	0.01	-0.08	-0.24	0.05	0.04	-0.19
1989	-0.20	-0.02	0.69	0.65	0.87	0.99	1.21	1.17	1.24	1.37	1.54	1.55
1990	1.62	1.59	0.76	1.48	1.37	1.42	1.67	1.38	1.18	0.80	0.73	0.86
1991	0.82	0.72	0.85	-0.12	0.04	-0.03	-0.05	-0.09	0.26	0.50	0.39	0.34
1992	0.27	0.43	0.37	0.77	0.84	1.14	0.57	0.77	0.82	0.93	1.03	1.00
1993	1.03	1.17	1.15	1.97	2.02	1.73	2.07	2.09	1.61	1.25	1.12	1.20
1994	1.28	1.03	0.99	-0.26	-0.77	0.01	-0.35	-0.47	-0.18	-0.07	0.02	-0.08
1995	-0.22	-0.23	-0.09	-0.17	0.19	-0.60	-0.25	-0.06	-0.15	0.13	0.13	0.74
1996	0.69	1.10	1.19	1.24	0.89	0.92	0.62	0.57	1.09	1.28	1.51	1.36
1997	1.41	1.05	0.82	0.94	1.13	1.19	0.83	0.92	0.25	-0.26	-0.16	-0.64
1998	-0.53	-0.58	-0.46	-0.45	0.41	-0.04	0.24	0.12	0.31	0.33	0.49	0.72
1999	0.57	0.61	0.49	0.71	-0.21	-0.08	0.04	0.34	0.57	0.46	0.01	-0.36
2000	-0.15	-0.19	-0.05	-0.60	-0.40	-0.47	-0.83	-0.94	-0.90	-0.90	-1.01	-0.85
2001	-0.99	-0.79	-0.89	-0.61	-0.12	-0.16	0.75	0.95	0.94	1.41	1.38	1.38
2002	1.84	1.82	1.90	2.03	1.87	2.03	1.53	1.20	0.91	0.57	0.71	0.59
2003	0.05	-0.04	0.30	0.03	-0.12	-0.63	-1.06	-0.57	-0.31	-0.31	-0.51	-0.29
2004	-0.28	-0.33	-0.62	-0.36	-0.99	-0.58	-0.20	-0.49	-0.69	-0.18	-0.17	-0.24
2005	-0.12	-0.11	-0.17	-0.04	0.52	0.98	0.61	0.76	0.76	0.29	0.42	0.20
2006	0.00	0.10	0.03	-0.22	0.03	-0.66	-0.02	-0.05	0.06	0.03	0.25	0.40
2007	0.43	0.53	0.75	0.90	0.68	1.12	1.18	1.11	1.00	1.24	1.31	1.32
2008	1.37	1.33	1.25	0.90	0.81	0.56	0.68	0.69	1.42	1.22	1.32	1.37
2009	1.30	1.22	1.05	1.23	1.28	1.39	1.17	1.11	0.72	0.88	0.87	0.73
2010	0.68	0.81	0.86	0.82	1.32	1.23	0.75	0.47	0.00	-0.14	-0.53	-0.46
2011	-0.40	-0.61	-0.63	-0.57	-1.38	-1.21	-1.35	-1.20	-1.06	-1.14	-0.98	-0.94
2012	-0.92	-0.81	-0.63	-0.44	-0.40	-0.46	0.28	0.75	1.07	1.42	1.28	1.11
2013	1.15	1.32	1.33	1.31	1.41	1.64	1.24	1.52	1.47	1.29	1.72	1.77
2014	1.88	1.65	1.67	1.54	1.55	1.50	1.57	1.35	0.99	0.71	0.21	0.21
2015	0.10	0.12	-0.14	-0.35	-0.73	-1.20	-1.01	-1.75	-1.76	-1.79	-1.67	-1.66
2016	-1.78	-1.75	-1.26	-0.91	-0.97	-0.92	-1.22	-1.20	-1.14	-0.99	-1.24	-1.27
2017	-1.19	-1.25	-1.58	-2.01	-2.20	-2.34	-2.92	-2.83	-2.98	-2.92	-2.52	-2.54
2018	-2.66	-2.43	-2.26	-2.02	-1.65	-1.50	-1.45	-1.36	-0.97	-1.09	-1.37	-1.39
2019	-1.31	-1.25	-1.33	-1.52	-1.81	-1.88	-1.85	-2.24	-2.63	-2.26	-2.40	-2.27
2020	-2.10	-2.36	-2.39	-2.35	-2.17	-2.08						

Table B6: Steenbras Dam moving cumulative 12-month rainfall

Mean: 925 mm
Threshold: 734 mm

▨ = drought month

(Rainfall in mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1916												1 168
1917	1 179	1 129	1 105	1 116	1 259	1 211	1 323	1 282	1 288	1 268	1 299	1 260
1918	1 195	1 207	1 189	1 128	1 119	1 123	1 080	933	928	1 012	1 082	1 115
1919	1 186	1 215	1 209	1 221	1 064	993	989	1 070	1 102	1 012	970	971
1920	906	879	877	864	1 008	1 172	1 170	1 179	1 157	1 183	1 203	1 236
1921	1 298	1 334	1 346	1 375	1 158	1 156	1 110	1 123	1 119	1 111	1 045	1 023
1922	1 008	969	967	982	1 036	952	887	888	822	836	844	803
1923	798	792	793	848	970	976	1 057	1 072	1 113	1 093	1 261	1 274
1924	1 252	1 254	1 297	1 207	1 101	1 064	974	960	954	1 010	864	843
1925	876	883	817	785	747	864	940	905	907	928	923	945
1926	894	929	944	976	1 068	857	815	819	826	830	798	776
1927	778	764	764	769	769	777	731	797	752	631	671	722
1928	750	715	741	702	576	617	597	521	561	576	535	495
1929	463	474	444	520	589	524	614	611	591	593	608	672
1930	706	772	802	755	684	698	647	650	751	764	780	719
1931	679	635	596	657	708	698	719	775	684	764	715	739
1932	777	832	847	755	869	934	894	837	852	756	765	744
1933	732	662	654	679	571	623	655	688	646	664	679	662
1934	643	637	678	655	697	569	538	530	570	598	655	663
1935	670	666	655	740	749	777	818	804	800	765	720	718
1936	806	817	803	734	697	671	620	640	654	650	638	697
1937	631	621	650	702	701	921	1 044	1 033	1 020	1 050	1 047	984
1938	1 005	1 007	978	1 025	1 049	838	760	759	818	832	858	869
1939	811	877	860	812	773	769	739	781	700	655	664	707
1940	730	731	788	806	820	946	962	870	927	960	962	947
1941	960	889	845	957	1 067	1 064	1 085	1 107	1 132	1 146	1 145	1 138
1942	1 130	1 152	1 154	1 011	958	1 001	934	1 000	913	889	838	831
1943	864	875	894	910	865	716	770	740	752	740	771	751
1944	739	707	683	654	735	956	987	1 051	1 178	1 212	1 201	1 241
1945	1 191	1 185	1 177	1 234	1 343	1 289	1 345	1 315	1 135	1 129	1 136	1 121
1946	1 143	1 152	1 223	1 197	995	852	775	762	904	889	862	858
1947	844	836	828	822	846	814	913	882	772	748	762	741
1948	740	755	714	689	684	743	687	672	729	821	821	848
1949	858	852	835	905	887	877	839	904	893	809	825	827
1950	823	816	819	883	841	800	928	820	858	889	908	945
1951	995	992	984	987	1 066	1 311	1 179	1 222	1 257	1 232	1 259	1 196
1952	1 140	1 149	1 203	1 081	1 035	799	789	821	772	773	766	779
1953	787	788	743	846	969	969	991	957	864	863	839	836
1954	840	862	866	788	877	917	1 031	1 137	1 197	1 226	1 208	1 233
1955	1 214	1 346	1 344	1 332	1 067	1 041	982	990	1 003	1 044	1 062	1 052
1956	1 075	936	963	998	1 172	1 275	1 171	1 116	1 063	1 039	1 002	1 022
1957	1 033	1 064	1 035	1 012	1 076	1 031	1 112	1 106	1 160	1 221	1 228	1 173
1958	1 159	1 188	1 198	1 168	1 088	1 044	898	894	889	809	826	824
1959	847	789	806	929	1 051	972	1 008	1 002	981	994	968	1 003
1960	972	966	950	826	643	781	771	709	680	618	610	614
1961	708	701	684	644	625	596	622	721	791	825	821	805
1962	734	772	801	897	851	986	1 009	980	935	1 004	1 047	1 036
1963	1 027	978	942	849	846	698	861	902	880	775	819	865
1964	848	905	899	931	1 022	1 073	959	939	966	1 017	1 008	975
1965	1 006	1 009	1 089	1 121	1 084	991	937	891	878	872	804	834
1966	806	774	781	756	770	766	883	898	937	884	916	893
1967	908	877	840	988	952	1 061	944	911	889	967	968	950
1968	989	1 040	988	845	942	938	1 010	1 043	1 014	1 029	993	1 048
1969	1 049	1 035	1 074	1 081	933	873	794	795	821	808	823	764
1970	718	700	671	624	776	788	848	907	915	898	897	937
1971	935	921	927	924	822	784	755	774	751	743	747	715
1972	734	799	811	909	989	984	954	872	896	863	838	880

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	858	793	787	682	617	580	683	677	716	719	761	734
1974	747	752	748	742	875	986	893	1 119	1 116	1 195	1 184	1 163
1975	1 191	1 190	1 179	1 226	1 178	1 140	1 268	1 038	962	930	951	948
1976	894	905	941	1 001	914	1 082	976	969	1 062	1 025	1 114	1 184
1977	1 212	1 232	1 251	1 235	1 361	1 305	1 368	1 396	1 374	1 368	1 253	1 198
1978	1 188	1 202	1 193	1 167	1 025	827	695	698	714	751	759	773
1979	785	900	859	785	940	1 029	1 082	1 022	996	1 119	1 097	1 071
1980	1 074	945	934	1 031	985	1 027	961	962	927	788	887	957
1981	1 076	1 041	1 213	1 194	1 023	926	1 188	1 276	1 358	1 327	1 259	1 229
1982	1 134	1 134	980	991	1 025	1 064	845	815	694	707	720	760
1983	726	832	923	862	1 030	1 145	1 208	1 187	1 317	1 302	1 259	1 201
1984	1 205	1 108	1 053	1 093	1 093	956	926	873	818	919	913	1 037
1985	1 045	1 075	1 137	1 170	1 018	1 024	1 114	1 196	1 179	1 098	1 095	968
1986	938	936	903	896	903	1 000	959	1 042	1 033	1 029	1 051	1 048
1987	1 112	1 094	1 044	1 040	1 157	1 084	1 136	1 089	1 140	1 127	1 124	1 153
1988	1 096	1 074	1 084	1 070	989	989	929	907	875	933	933	889
1989	885	921	1 073	1 063	1 109	1 142	1 196	1 187	1 205	1 235	1 276	1 275
1990	1 297	1 286	1 089	1 261	1 226	1 250	1 310	1 238	1 190	1 099	1 083	1 110
1991	1 104	1 080	1 111	901	933	916	916	905	979	1 031	1 005	996
1992	981	1 016	1 002	1 091	1 104	1 180	1 047	1 092	1 103	1 129	1 150	1 142
1993	1 153	1 184	1 182	1 388	1 389	1 330	1 415	1 424	1 296	1 207	1 173	1 191
1994	1 213	1 151	1 144	873	778	924	855	830	887	909	928	911
1995	883	880	906	890	963	804	875	912	892	950	952	1 083
1996	1 074	1 168	1 191	1 201	1 115	1 126	1 058	1 047	1 166	1 214	1 269	1 229
1997	1 245	1 155	1 103	1 131	1 171	1 192	1 106	1 128	976	870	890	804
1998	821	813	833	836	1 009	913	975	949	990	993	1 029	1 080
1999	1 047	1 054	1 029	1 078	884	907	935	996	1 046	1 023	925	857
2000	896	887	914	807	847	828	766	743	750	750	732	766
2001	738	775	753	806	900	889	1 089	1 134	1 132	1 246	1 235	1 232
2002	1 352	1 346	1 372	1 403	1 352	1 409	1 276	1 195	1 125	1 047	1 076	1 051
2003	936	918	987	932	901	798	725	811	862	860	822	869
2004	870	860	804	854	741	806	885	826	787	886	889	880
2005	901	905	889	916	1 034	1 141	1 057	1 089	1 088	985	1 013	968
2006	926	946	931	880	932	792	922	913	935	929	976	1 009
2007	1 017	1 039	1 087	1 121	1 068	1 176	1 188	1 173	1 146	1 205	1 220	1 219
2008	1 233	1 223	1 207	1 122	1 097	1 042	1 072	1 074	1 248	1 198	1 222	1 231
2009	1 217	1 196	1 157	1 200	1 206	1 243	1 186	1 173	1 081	1 117	1 115	1 081
2010	1 072	1 101	1 113	1 102	1 215	1 201	1 088	1 023	924	894	820	836
2011	846	808	802	812	676	693	678	698	722	707	737	751
2012	751	771	801	837	847	830	985	1 086	1 162	1 249	1 211	1 169
2013	1 180	1 219	1 225	1 219	1 238	1 305	1 202	1 273	1 260	1 217	1 322	1 330
2014	1 363	1 302	1 311	1 276	1 270	1 271	1 285	1 230	1 142	1 079	968	970
2015	947	951	896	854	785	696	734	608	607	602	622	631
2016	610	615	690	750	743	743	698	698	708	734	691	693
2017	703	695	637	573	551	518	450	456	437	443	498	505
2018	484	516	534	571	633	645	660	672	737	717	670	674
2019	685	695	678	648	608	584	598	536	482	531	515	541
2020	561	526	516	523	555	555						

Table B7: Tulbagh SPI-12 values

▨ = drought month

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1900												1.18
1901	1.87	2.08	1.88	1.59	2.07	1.87	1.74	1.07	0.96	0.21	0.28	0.31
1902	-0.41	-0.69	0.52	0.73	0.26	0.35	0.28	0.90	1.87	2.03	1.97	1.90
1903	1.96	1.89	1.06	1.26	1.19	2.05	1.67	1.43	0.74	0.93	0.79	0.77
1904	0.61	0.61	0.49	0.74	0.26	-0.40	-0.39	0.05	0.04	-0.14	0.15	0.19
1905	0.13	0.15	0.29	-0.53	0.03	-0.18	-0.08	-0.59	-0.46	-0.37	-0.72	-0.76
1906	-0.78	-0.76	-0.77	-0.56	-0.81	-0.83	-0.83	-0.18	-0.73	-1.00	-0.88	-0.24
1907	-0.26	-0.25	-0.42	-0.30	0.37	-0.07	-0.21	-1.05	-0.51	-0.37	-0.52	-1.09
1908	-0.94	-0.90	-0.80	-0.10	-0.90	-0.73	-0.60	-0.20	-0.75	-0.83	-0.74	-0.88
1909	-1.01	-1.03	-0.80	-1.85	-1.44	-1.23	-1.04	-0.44	-0.40	0.11	0.00	0.30
1910	0.29	0.38	0.13	0.09	-0.04	0.82	1.29	1.13	1.19	0.64	0.85	0.59
1911	0.62	0.54	0.59	0.52	0.40	-0.42	-0.22	-0.91	-0.74	-0.57	-0.77	-0.56
1912	-0.61	-0.53	-0.49	-0.38	-0.25	-0.19	-1.19	-0.91	-0.31	-0.27	-0.06	-0.31
1913	-0.23	-0.31	-0.44	-0.49	-0.21	-0.47	0.13	0.38	-0.21	-0.19	-0.12	0.05
1914	-0.02	0.00	0.05	0.31	-0.27	0.83	1.03	1.11	1.15	0.95	0.73	0.65
1915	0.64	0.65	0.78	1.02	1.27	0.48	0.46	0.32	0.44	0.66	0.65	0.59
1916	0.74	0.72	0.77	0.70	1.17	1.38	1.03	1.34	1.43	1.35	1.30	1.31
1917	1.32	1.27	1.16	1.15	0.78	0.69	1.70	1.08	0.83	0.95	0.98	0.86
1918	0.69	0.72	0.91	0.58	0.94	1.14	-0.25	-0.54	-0.24	-0.04	0.11	0.18
1919	0.37	0.34	0.06	0.00	-0.77	-1.68	-0.89	-0.54	-0.39	-1.02	-1.17	-1.28
1920	-1.54	-1.52	-1.49	-1.39	-0.59	0.56	0.39	1.06	0.87	1.13	1.28	1.40
1921	1.53	1.80	1.84	2.05	1.31	1.94	2.12	1.73	1.84	1.60	1.51	1.59
1922	1.73	1.52	1.53	1.57	1.86	0.64	-0.13	0.19	-0.20	-0.12	-0.10	-0.43
1923	-0.53	-0.62	-0.69	-0.42	-0.07	-0.04	0.09	-0.30	-0.12	-0.10	0.13	0.16
1924	-0.13	-0.13	-0.07	-0.47	-1.17	-1.04	-1.15	-0.99	-0.93	-0.52	-0.73	-0.78
1925	-0.68	-0.62	-0.73	-0.98	-0.86	0.26	0.69	0.26	0.02	0.20	0.45	0.48
1926	0.38	0.52	0.52	0.62	1.01	-0.99	-0.98	-0.91	-0.87	-0.74	-0.98	-1.03
1927	-0.94	-1.02	-1.03	-0.86	-1.33	-0.92	-1.79	-1.22	-1.18	-2.10	-1.80	-1.66
1928	-1.55	-1.70	-1.53	-1.93	-2.28	-1.18	-0.86	-1.21	-1.14	-0.88	-1.24	-1.30
1929	-1.45	-1.41	-1.51	-1.22	-0.66	-1.29	-0.80	-0.72	-0.91	-0.97	-1.06	-0.84
1930	-0.70	-0.44	-0.42	-0.65	-1.16	-1.84	-2.44	-2.70	-1.68	-1.40	-1.29	-1.56
1931	-1.68	-1.94	-1.97	-1.54	-0.75	-0.58	-0.49	0.13	-0.39	-0.37	-0.58	-0.46
1932	-0.41	0.42	0.47	0.02	-0.07	0.35	0.49	-0.02	-0.01	-0.13	-0.08	-0.15
1933	-0.13	-0.99	-0.97	-1.01	-0.77	-0.35	0.24	0.26	0.05	0.00	0.07	0.24
1934	0.25	0.21	0.38	0.43	0.18	-0.28	-1.24	-1.42	-0.94	-0.25	-0.01	-0.30
1935	-0.32	-0.28	-0.37	0.10	0.11	0.21	0.35	0.78	0.42	-0.21	-0.34	-0.33
1936	-0.10	-0.18	-0.24	-0.72	-0.58	-1.02	-0.86	-0.79	-0.22	-0.07	-0.19	0.23
1937	0.01	0.01	0.26	0.52	0.39	1.07	1.41	1.02	0.29	0.37	0.27	-0.07
1938	0.03	0.06	-0.33	0.02	0.23	-0.43	-1.16	-0.87	-0.45	-0.47	-0.36	-0.35
1939	-0.48	-0.29	-0.32	-0.91	-0.95	-0.96	-1.05	-0.91	-1.03	-1.18	-1.16	-1.25
1940	-1.17	-1.05	-1.00	-0.64	-1.20	-0.73	-0.70	-1.29	-1.37	-1.19	-1.07	-1.04
1941	-0.56	-0.90	-0.96	-0.87	0.19	0.56	0.83	1.26	1.86	2.08	2.00	1.99
1942	1.65	1.64	1.64	1.23	0.81	1.44	1.17	1.06	0.18	-0.02	-0.09	-0.10
1943	0.17	0.38	0.61	0.70	0.24	-0.99	-0.20	0.31	0.68	0.62	0.94	0.83
1944	0.61	0.40	0.33	0.54	1.21	1.64	0.92	0.97	1.03	0.99	0.96	1.09
1945	1.00	1.00	0.86	0.93	1.41	1.36	1.89	1.68	1.42	1.38	1.27	1.16
1946	1.16	1.16	1.32	1.23	0.14	-0.94	-1.72	-2.34	-0.97	-0.92	-1.04	-1.01
1947	-1.01	-1.02	-0.72	-0.94	-0.84	-0.98	-0.01	-0.03	-1.00	-0.85	-0.85	-0.95
1948	-0.90	-0.67	-0.37	-0.01	0.17	0.47	0.21	0.01	0.62	0.58	0.59	0.63
1949	0.64	0.45	-0.24	-0.24	-0.62	-0.56	-0.94	-0.55	-1.03	-0.77	-0.11	-0.09
1950	-0.13	-0.13	-0.09	0.51	0.36	0.13	0.81	0.39	0.97	0.90	0.87	0.95
1951	1.22	1.21	1.17	0.71	0.93	1.84	1.27	1.73	1.19	1.06	0.81	0.61
1952	0.31	0.44	0.57	0.31	1.02	0.31	0.63	0.90	0.97	0.88	1.16	1.18
1953	1.14	1.02	0.96	1.84	1.76	1.34	1.39	1.14	0.84	0.70	0.54	0.73
1954	0.80	0.83	0.92	0.46	1.22	1.39	1.66	2.07	2.32	2.33	2.08	2.08
1955	1.99	2.36	2.39	2.17	0.75	1.14	0.77	1.05	1.07	1.41	1.55	1.36
1956	1.46	1.06	0.97	0.91	1.34	1.21	0.76	-0.17	-0.13	-0.76	-1.01	-0.89
1957	-0.94	-0.30	-0.09	0.09	-0.52	-0.40	0.03	0.30	0.38	1.17	1.25	1.04
1958	0.98	0.63	0.42	0.37	1.04	0.50	-0.28	-1.13	-1.27	-2.28	-2.15	-2.14
1959	-2.10	-2.24	-2.07	-1.24	-0.47	-0.60	-0.58	0.15	0.16	0.42	0.25	0.46

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1960	0.41	0.27	0.38	-0.24	-1.20	-0.58	-0.47	-1.05	-1.19	-1.58	-1.49	-1.63
1961	-1.39	-1.38	-1.60	-1.70	-2.01	-2.57	-2.06	-1.50	-0.87	-0.84	-0.96	-1.03
1962	-1.12	-0.89	-0.36	-0.17	-0.16	1.13	1.26	1.73	1.36	1.99	2.25	2.20
1963	2.12	1.99	1.62	1.36	1.14	0.16	0.17	0.40	0.34	-0.54	-0.40	-0.19
1964	-0.20	-0.10	-0.05	0.05	0.41	0.50	0.45	-0.01	0.21	0.29	0.30	0.14
1965	0.24	0.59	0.89	1.16	1.26	0.77	0.37	-0.29	-0.52	-0.35	-0.79	-0.72
1966	-0.84	-1.43	-1.52	-1.72	-2.18	-1.43	-0.68	-0.77	-0.63	-0.98	-1.01	-1.17
1967	-1.09	-1.07	-1.47	-1.13	-1.07	-0.40	-0.79	-0.48	-0.55	-0.18	0.08	0.06
1968	0.10	0.17	0.11	-0.05	0.38	-0.30	-0.03	0.07	-0.23	0.55	0.38	0.38
1969	0.34	0.28	0.38	0.34	-0.31	-0.63	-1.17	-1.27	-0.80	-1.08	-1.15	-1.17
1970	-1.22	-1.20	-1.33	-1.92	-1.03	-0.21	0.27	0.48	0.39	-0.24	-0.20	-0.17
1971	-0.12	-0.17	0.17	0.20	-0.30	-0.86	-0.89	-1.19	-1.73	-1.90	-2.06	-2.02
1972	-1.85	-1.73	-2.10	-1.39	-0.81	-0.88	-1.08	-1.38	-1.18	-0.92	-0.98	-0.63
1973	-0.80	-0.83	-0.68	-1.39	-2.00	-2.41	-1.51	-1.19	-0.99	-0.85	-0.77	-0.82
1974	-0.78	-0.82	-1.01	-0.84	0.05	0.65	-0.03	1.67	1.73	1.84	1.94	1.73
1975	1.77	1.81	1.81	1.96	1.92	1.43	1.51	-0.06	-0.40	-0.40	-0.50	-0.54
1976	-0.62	-0.58	-0.49	-0.06	-1.00	0.26	0.46	0.13	0.20	-0.12	0.75	1.13
1977	1.18	1.24	1.23	1.06	1.90	1.53	1.87	2.14	2.40	2.32	1.73	1.43
1978	1.41	1.28	1.46	1.32	0.31	-0.53	-1.99	-1.70	-1.82	-1.77	-1.96	-1.84
1979	-1.77	-1.31	-1.69	-2.01	-1.32	-0.78	-0.35	-0.96	-1.02	-0.79	-0.81	-1.08
1980	-1.00	-1.31	-1.34	-1.20	-1.32	-1.37	-1.74	-1.31	-1.76	-1.75	-0.29	0.08
1981	0.48	0.37	0.55	0.58	0.22	-0.03	0.77	0.81	1.47	1.36	0.34	0.12
1982	-0.25	-0.24	-0.10	0.64	0.76	1.14	0.54	0.07	-0.80	-0.52	-0.53	-0.49
1983	-0.69	-0.27	-0.34	-1.45	-0.13	0.13	0.34	0.44	0.70	0.52	0.59	0.44
1984	0.41	0.05	0.54	0.82	0.97	0.15	0.10	0.04	0.68	0.94	0.83	1.23
1985	1.50	1.77	1.71	1.85	0.85	1.20	1.53	1.93	1.57	1.13	1.17	0.83
1986	0.48	0.23	-0.23	-0.54	-0.75	-0.45	-0.70	-0.49	-0.58	-0.47	-0.38	-0.50
1987	-0.48	-0.49	-0.68	-0.47	0.39	0.53	0.34	0.06	0.11	0.01	-0.04	0.04
1988	-0.01	0.01	0.08	0.51	-0.33	-0.79	-0.98	-1.11	-1.12	-0.98	-0.97	-1.09
1989	-1.01	-0.88	-0.30	-0.55	-0.30	0.04	0.28	0.60	0.81	1.02	1.07	1.02
1990	1.05	1.05	0.53	0.76	1.18	1.06	1.10	0.71	0.14	-0.19	-0.13	0.04
1991	0.00	-0.12	-0.13	-0.79	-1.44	-0.82	0.20	0.02	0.48	0.74	0.68	0.54
1992	0.48	0.65	0.76	1.04	1.13	0.88	0.10	0.54	0.31	0.55	0.63	0.60
1993	0.62	0.48	0.38	0.88	1.27	0.96	1.18	0.92	0.86	0.34	0.24	0.28
1994	0.33	0.20	0.18	-0.26	-0.85	-0.02	-0.53	-0.79	-0.20	-0.04	-0.06	-0.16
1995	-0.23	-0.22	-0.11	-0.67	-0.01	-0.89	-0.47	0.25	-0.30	0.11	0.13	0.56
1996	0.59	0.78	0.86	0.94	0.44	0.54	0.40	0.77	1.27	0.92	1.23	1.17
1997	1.16	0.96	0.88	0.89	0.86	1.13	0.62	-0.20	-0.99	-1.08	-1.19	-1.36
1998	-0.72	-0.71	-0.73	-0.80	-0.12	-0.87	-0.45	-0.58	-0.53	-0.41	-0.30	-0.31
1999	-0.94	-0.91	-1.02	-0.78	-1.50	-1.39	-1.47	-0.61	0.02	-0.10	-0.45	-0.54
2000	-0.41	-0.43	-0.37	-0.70	-0.95	-0.88	-0.27	-0.82	-0.72	-0.68	-0.65	-0.90
2001	-0.93	-0.84	-0.91	-0.73	-0.07	-0.23	0.25	0.47	0.33	0.55	0.63	0.61
2002	0.97	1.01	1.16	1.38	1.49	1.58	0.97	1.02	0.68	0.72	0.68	0.75
2003	0.40	0.31	0.43	0.18	-0.50	-0.88	-1.74	-1.04	-0.91	-0.84	-0.97	-0.79
2004	-0.82	-0.83	-1.12	-0.94	-1.21	-0.50	-0.15	-0.84	-1.17	-0.81	-0.84	-1.12
2005	-1.06	-1.03	-1.06	-0.78	-0.61	-0.69	-0.80	-0.30	-0.31	-0.85	-0.74	-0.75
2006	-0.89	-0.85	-0.88	-0.56	0.78	0.65	0.72	0.31	0.22	0.42	0.70	0.80
2007	0.79	0.90	1.13	0.78	-0.15	0.69	1.16	1.17	1.21	1.14	0.91	0.99
2008	1.01	1.08	0.90	0.50	0.31	-0.49	-0.10	0.20	1.28	1.16	1.29	1.24
2009	1.19	1.15	1.15	1.23	1.49	1.90	1.14	0.99	0.12	0.30	0.45	0.23
2010	0.23	0.11	0.18	0.28	1.05	0.66	0.71	0.54	0.43	0.44	0.16	0.29
2011	0.38	0.29	0.25	0.58	-0.13	0.19	-0.01	-0.25	-0.11	-0.18	-0.04	-0.07
2012	-0.17	-0.17	0.01	0.07	-0.42	-0.89	-0.60	0.22	0.47	0.31	0.13	0.05
2013	0.08	0.16	-0.08	-0.05	-0.06	0.88	0.97	1.40	1.48	1.55	1.74	1.66
2014	1.95	1.90	2.14	1.88	2.10	1.79	1.78	1.04	0.68	0.49	0.62	0.61
2015	0.29	0.29	0.04	-0.11	-0.65	-1.08	-1.20	-1.93	-2.13	-2.01	-2.73	-2.50
2016	-2.56	-2.51	-2.13	-1.55	-1.50	-1.09	-1.03	-0.60	-0.32	-0.35	-0.32	-0.26
2017	-0.30	-0.36	-0.67	-1.11	-1.19	-1.66	-1.79	-2.06	-2.65	-2.16	-1.98	-2.17
2018	-2.12	-1.93	-1.84	-1.53	-0.72	-0.47	0.59	0.81	1.16	0.96	0.84	0.98
2019	0.99	0.96	1.12	0.92	0.53	0.22	-0.81	-1.27	-1.83	-1.28	-1.35	-1.46
2020	-1.18	-1.29	-1.63	-1.73	-1.75	-1.35	-0.64	-0.24				

Table B8: Tulbagh moving cumulative 12-month rainfall

Mean: 469 mm
Threshold: 364 mm
▨ = drought month

(Rainfall in mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1900												616
1901	718	753	720	668	733	714	699	604	583	493	500	505
1902	424	394	532	555	499	510	502	580	707	740	725	720
1903	732	723	602	623	611	741	689	654	555	583	562	562
1904	543	543	527	555	499	425	425	475	474	452	486	492
1905	485	486	503	413	472	448	460	403	420	428	392	389
1906	385	387	386	410	386	381	379	448	394	363	376	442
1907	440	440	423	437	511	461	445	357	416	427	412	357
1908	369	372	384	458	377	391	403	445	392	380	390	377
1909	363	360	383	294	329	343	359	419	427	481	469	504
1910	503	515	484	479	464	568	633	612	613	546	570	540
1911	544	534	540	529	514	422	443	371	393	406	387	409
1912	403	411	415	428	442	448	345	371	436	438	462	435
1913	443	434	421	418	447	417	484	514	446	447	455	475
1914	467	469	475	504	440	570	598	609	608	586	554	547
1915	547	549	564	591	621	526	524	507	520	547	545	540
1916	559	557	563	551	609	643	599	642	645	639	629	635
1917	638	632	615	608	560	552	693	606	567	585	587	574
1918	554	557	582	536	580	610	440	409	443	464	480	491
1919	513	509	476	470	390	304	374	409	428	362	349	339
1920	314	315	318	332	408	536	515	602	571	609	626	646
1921	668	709	713	733	627	725	757	698	702	675	658	673
1922	698	667	668	664	703	545	454	491	448	455	457	422
1923	411	401	395	424	462	465	479	435	456	457	483	488
1924	455	454	462	420	353	360	348	363	374	411	391	386
1925	396	401	391	369	381	499	553	500	472	492	521	526
1926	514	532	532	541	589	365	364	371	380	389	367	362
1927	370	361	361	380	338	372	292	341	351	268	295	306
1928	313	299	315	288	262	348	376	342	355	375	343	337
1929	322	325	316	348	401	337	383	390	376	367	360	381
1930	393	420	423	401	354	290	241	221	308	326	338	314
1931	302	279	278	320	392	407	415	484	427	428	407	420
1932	424	519	525	471	461	509	528	466	468	454	459	453
1933	455	364	367	367	390	430	498	500	475	468	476	498
1934	499	494	514	518	489	438	340	323	374	440	467	437
1935	433	437	428	481	481	494	510	564	518	445	431	433
1936	458	448	443	395	409	363	376	382	446	460	447	496
1937	471	471	499	529	513	600	651	596	502	512	499	461
1938	472	477	433	472	495	422	348	374	422	417	429	431
1939	416	436	434	376	372	368	358	371	365	347	350	342
1940	348	358	364	402	350	391	393	335	335	346	359	362
1941	408	372	367	379	491	536	572	630	706	748	730	732
1942	685	685	683	618	564	651	616	603	490	466	459	458
1943	489	515	543	551	496	366	446	506	548	543	582	570
1944	544	517	508	532	614	680	584	591	593	591	585	604
1945	594	594	575	579	641	640	723	692	643	644	626	613
1946	615	617	638	619	485	371	297	247	370	371	361	364
1947	362	361	391	373	383	366	467	465	368	378	379	370
1948	374	396	428	468	488	524	494	470	541	538	538	545
1949	546	524	442	443	404	409	369	408	365	386	456	459
1950	454	454	459	528	510	484	569	515	584	579	572	585
1951	624	624	617	552	579	710	631	698	613	599	566	542
1952	506	522	537	504	589	505	545	580	585	576	611	616
1953	613	598	588	702	689	638	648	613	568	553	531	558
1954	567	572	583	522	615	645	688	752	773	787	741	747
1955	737	798	799	751	557	611	564	601	597	648	664	641
1956	657	602	590	577	631	620	562	449	455	387	364	375
1957	369	435	459	480	415	425	472	504	512	615	623	598

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958	592	547	519	511	592	528	437	350	344	254	267	267
1959	268	256	270	345	420	404	406	486	488	518	498	524
1960	518	501	514	444	350	406	416	357	351	311	320	308
1961	328	327	308	306	282	234	270	315	380	379	369	362
1962	352	373	429	451	452	609	630	699	636	733	768	765
1963	757	739	681	636	605	488	488	516	507	409	425	448
1964	447	458	463	475	516	528	523	467	493	502	503	486
1965	498	542	579	609	621	562	513	436	414	430	386	393
1966	380	323	316	305	269	325	395	385	404	366	364	349
1967	355	356	320	356	362	424	383	415	412	448	477	476
1968	481	489	482	464	512	436	465	477	445	534	513	514
1969	510	503	514	508	436	401	347	336	386	356	351	349
1970	343	344	333	288	365	445	501	526	514	442	446	450
1971	456	449	489	492	437	378	374	344	304	284	274	276
1972	288	297	268	332	386	376	355	326	352	371	367	401
1973	384	380	395	332	283	246	316	344	369	378	387	383
1974	386	381	363	383	474	546	465	690	686	711	721	694
1975	703	710	708	719	712	650	665	461	426	424	415	410
1976	402	405	415	463	368	499	524	484	492	455	558	609
1977	618	628	625	596	709	665	719	762	786	785	690	650
1978	651	634	658	631	504	411	275	298	296	295	282	291
1979	295	334	301	281	339	386	430	365	366	384	384	357
1980	364	333	331	349	340	330	296	333	302	297	436	478
1981	527	514	535	537	493	466	564	569	651	641	508	483
1982	441	442	458	543	557	610	534	476	387	412	412	416
1983	395	439	431	327	455	484	510	522	551	531	538	522
1984	518	475	533	565	584	486	480	474	548	584	568	623
1985	664	704	694	704	568	618	668	728	664	610	612	570
1986	527	497	443	412	392	420	393	414	408	417	427	415
1987	417	415	395	419	514	532	509	476	482	470	464	474
1988	469	471	478	528	434	385	364	351	357	365	368	357
1989	363	374	436	412	438	474	502	542	564	594	599	594
1990	600	602	533	559	611	599	608	556	485	447	454	474
1991	469	456	455	387	329	382	492	470	524	557	549	533
1992	527	549	562	594	604	576	480	534	504	534	543	541
1993	545	527	514	573	622	586	618	583	571	509	496	503
1994	508	493	490	441	382	466	410	382	447	463	462	451
1995	444	445	456	400	468	375	417	498	438	481	483	536
1996	540	565	574	580	519	533	517	564	624	582	620	615
1997	615	589	578	575	570	609	544	446	369	356	348	332
1998	391	391	390	387	456	377	419	404	414	424	435	435
1999	369	372	362	389	324	328	319	401	471	457	420	411
2000	423	421	428	397	373	376	439	380	395	395	399	375
2001	371	379	372	393	461	443	498	525	507	534	543	543
2002	590	596	616	639	651	671	590	597	548	556	549	560
2003	518	507	520	490	416	376	296	358	376	379	368	385
2004	382	379	352	373	349	415	451	378	353	382	380	353
2005	358	360	358	388	405	395	383	434	436	378	390	390
2006	375	377	375	410	560	547	557	505	494	518	552	567
2007	567	582	611	561	452	551	616	617	616	610	578	591
2008	595	605	580	526	504	416	458	492	625	613	628	624
2009	620	616	614	618	651	719	612	593	482	504	521	496
2010	496	482	490	500	594	547	556	534	519	520	487	503
2011	515	504	498	536	455	491	468	440	457	448	464	462
2012	450	450	470	477	425	375	403	494	524	505	483	475
2013	479	488	460	464	463	576	589	650	652	668	691	684
2014	730	725	760	708	738	703	706	600	549	526	542	542
2015	504	504	473	458	401	357	344	279	272	275	225	240
2016	233	236	265	319	324	356	360	402	435	430	433	441
2017	436	429	396	357	351	305	291	269	235	263	280	265
2018	266	280	288	321	395	417	540	569	609	586	569	589
2019	593	590	610	578	530	494	381	336	296	338	333	323
2020	347	336	306	304	303	332	399	442				