PAPER 5

APPLYING THRESHOLD, SEVERITY, DURATION AND FREQUENCY DIAGRAMS FOR WATER RESOURCE MANAGEMENT IN THE WESTERN CAPE: SOUTH AFRICA

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ABSTRACT

Droughts are significant climate events, that can have severe consequences and impacts on the planning and operation of municipal water supply systems. The drought experienced in Cape Town, during 2015 – 2020 saw storages rapidly depleting and severe restrictions implemented to ensure that water supplies did not fail. Provision of additional information as early as possible to understand the onset and severity of the drought could have assisted with the initial water resource management decisions. This research focuses on the development of an early warning system to assist municipalities in the decision-making process related to the planning of their water resources, using the Western Cape Water Supply System as a case study.

The research approach used the Standardised Precipitation Index (SPI), which allows for the occurrence, duration, and magnitude of historical droughts, to provide an early warning through the setting of threshold precipitation values, which allows for the onset and end of droughts to be determined from rainfall measurements only. Severity, duration, and frequency (SDF) curves were derived for the case study region, enabling the determination of the probability of occurrence of a drought with a certain severity and duration. Maps were also produced to allow drought properties to be determined spatially across the South-Western Cape region. This information can then be used to highlight the onset and severity of a drought to be expected. The functionality of these SDF curves were demonstrated using the updated (till 2023) rainfall data at the Steenbras and Wemmershoek catchments in the case study region, highlighting the support provided to water resource managers when using SPI's and SDF curves.

1. INTRODUCTION

From 2015 to 2018, South Africa's second largest city, Cape Town, and the surrounding region faced a water supply crisis resulting from an extended period of significantly below average rainfall. Cape Town's water supplies rely mainly on surface water resources, and successive years of dry conditions resulted in rapidly declining water storages. To conserve and prevent supplies from running dry, restrictions were placed on water use, reaching 45% restriction on urban use and 60% on agricultural use, which had significant negative impacts on the city and region's economy, environment, and amenities.

The rapid onset of a severe drought meant that decisions on water management and crisis planning needed to be made in quick succession by water planners and city management. The early accessibility of information related to drought occurrences and easy availability thereof could have supported the managers with informed decision making in taking early action and understanding the impacts thereof on the operation of the water supply and distribution system.

The experience in Cape Town prompted research to develop drought relationships and diagrams that can be used to easily identify the occurrence and severity of droughts in the Western Cape Water Supply System (WCWSS) supply area (Du Plessis and Rhode, 2023), as a case study. The approach illustrated serves as an example which can be used by all local authorities in support of the management of water security in their catchments. Using only monthly rainfall measurements, the onset and severity of droughts can be assessed rapidly without the need to understand drought theory and calculate these from first principles. Identifying the onset of a drought at an early stage, will enable water managers in local authorities to take appropriate steps to ensure water security, whether by means of water restrictions or reallocation of water to end-users from different sources.

The research presented in this paper uses rainfall station measurements from the Steenbras and Wemmershoek catchments, and the drought relationships and diagrams developed for the WCWSS supply area, to assess the occurrence and severity of droughts for the period from 2015 to 2023.

2. BACKGROUND & METHODOLOGY

The main objective of the research presented as a case study in this paper, was to use available monthly rainfall data to develop threshold rainfall values which can be used as a tool to inform water resource management decision-making under drought conditions. To achieve this objective, a standardised precipitation index was used to develop threshold values, indicating the start of a drought, as well as the severity and frequency of occurrence.

2.1 Threshold precipitation values and severity, duration, and frequency diagrams

Rahmat et al. (2015) proposed an innovative approach for assessing the occurrence and severity of droughts, using (1) drought precipitation mean and threshold values to determine the start and end of droughts; and (2) assessing the severity of a drought being experienced by using severity, duration, and frequency curves. Both use only rainfall measurements to assess droughts. Their research was focused on the state of Victoria, Australia.

Du Plessis and Rhode (2023) adapted the approach for the WCWSS supply area in the Western Cape Province, South Africa. This approach is outlined below.

2.2 Drought assessments in the WCWSS area

The WCWSS consists out of a network of dams (Berg River, Steenbras Lower, Steenbras Upper, Theewaterskloof, Voëlvlei and Wemmershoek – with a total combined storage capacity of 898 million m^3), pipelines, tunnels and pump stations that supply water to Cape Town and its surrounding region, including irrigation water for agriculture.

Cape Town uses approximately 60% of the water supplied by the WCWSS. The City of Cape Town uses its integrated network of treatment plants, reservoirs, and bulk supply pipelines to preferentially draw water from the different dams, which means it can maximise water availability depending on rainfall and different dam levels. This is an important functionality during extended drought periods, which ensure that demand can be transferred onto dams that have more water available at the time and in doing so, preventing some dams from running dry. This illustrates the importance of having drought information available at a catchment level to inform decision-making.

Figure 1 illustrates the WCWSS area, including the 29 rainfall stations used to develop drought threshold, severity, duration, and frequency relationships (Du Plessis and Rhode, 2023).

FIGURE 1: *WCWSS supply area*

2.3 The Standardised Precipitation Index

Droughts are not the same as arid conditions. Arid climates are normally dry, whereas droughts are periods of lower-than-normal precipitation (Wilhite, 2000). The start, end, duration, and intensity of a drought is difficult to determine. A drought can often only be determined in hindsight. The onset of a dry period does not necessarily mean that a drought is occurring. A dry period may only be classified as a drought once a certain low level of rainfall, compared to the long-term record, has occurred.

Drought indices are used to numerically quantify droughts. Numerous drought 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 (Mishra and Singh, 2010).

In developing drought occurrence values and severity diagrams for Victoria, Australia, Rahmat et al. (2015) used the Standardised Precipitation Index (SPI) drought index. The SPI has the following advantages:

- It only requires precipitation as an input value.
- It is a standardised index, which allows droughts to be spatially compared at different locations.
- It can be determined for different time scales appropriate for the type of drought being assessed, e.g., seasonal trends of 3 months, versus periods of 12-months that removes seasonality.
- It does not need to be calibrated for use in a specific geographical area.
- The World Meteorological Organisation (WMO) has recommended it as the standard index to be used by meteorological organisations globally (World Meteorological Organisation, 2012).

The SPI is 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 is then transformed into a normal cumulative distribution function (CDF) with a mean of zero and standard deviation of one. The SPI calculation procedure first transforms the precipitation data to a two-parameter gamma cumulative distribution, and then transforms the gamma cumulative distribution into a standard normal distribution (around a zero mean) – which is referred to as the SPI value (McKee et al., 1993).

TABLE 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

Table 1 lists the categories of drought severities using the SPI values. These values are used to calculate the start, end, and severity of a drought. A drought begins with the SPI value of a precipitation record moves first below -1 and continues until the SPI value becomes positive (McKee et al., 1993).

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. Shorter drought periods will respond more quickly to changes in monthly precipitation and will move in and out of drought periods more frequently. Alternatively, longer drought periods respond more slowly to monthly changes and periods in and out of drought will be longer. WMO (2012) recommends that averaging periods of 12 – 48 months are more suitable for assessing the impacts on water resource and supply systems. Rahmat et al. (2015) and Du Plessis and Rhode (2023) used a period of 12 months, as this smooths out seasonality and is generally the planning and operation of water resource and supply systems timeframe. The 12-month period is termed the SPI-12 value.

2.4 Threshold precipitation values

While a drought index allows the start, duration, and end of a drought to be determined, it would be easier for water resource practitioners to be able to determine droughts using actual rainfall data. Rahmat et al. (2015) proposed an innovative approach of representing the SPI values of -1 (the

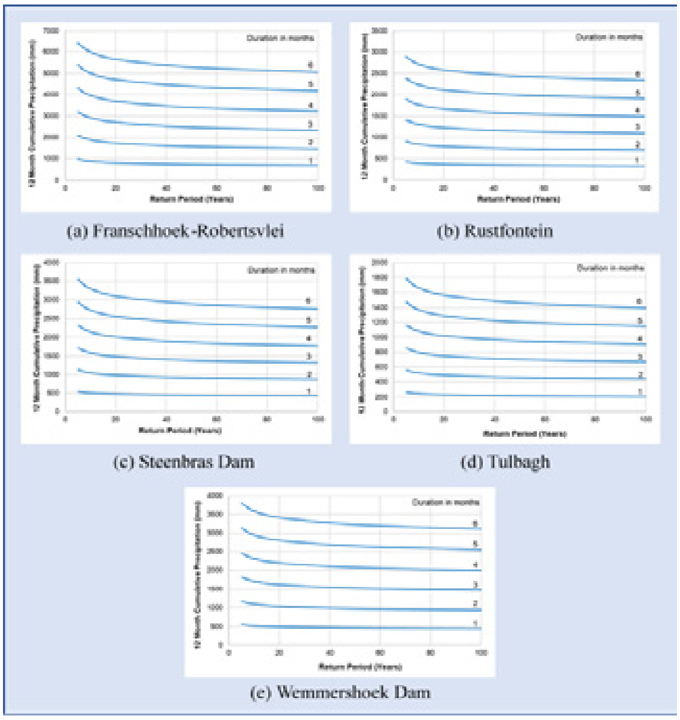

FIGURE 2: *SDF curves for the WCWSS dam catchments*

onset of drought) and 0 (the end of drought) in terms of the precipitation depths of a rainfall station.

Edwards & McKee (1997) determined the cumulative probabilities of the SPI values of 0 and -1 as 0.500 and 0.158 respectively. Using the gamma distribution parameters from the calculation of the SPI-12 values, the precipitation depths associated with each of the cumulative probabilities can be calculated. These precipitation depths become the mean (for SPI = 0) and the threshold (for SPI = -1) values.

Using these values, a drought has started when the moving 12-month total precipitation for a rainfall station falls below the threshold value. The drought ends when the precipitation value moves back above the mean.

Du Plessis and Rhode (2023) developed mean and threshold precipitation values for 29 rainfall stations in the WCWSS. Table 2 lists these values for the catchments of the major dams of the WCWSS.

2.5 Severity, duration, and frequency curves

The threshold precipitation values on their own does not indicate the severity of a drought being experienced. For this reason, severity, duration, and frequency curves are compiled which would allow drought severities to be determined without the need to calculate these from first principles. SPI-12 values were used to determine the severities, expressed as return periods.

TABLE 2: *Mean and threshold 12-month total precipitation values.*

Rainfall station	WCWSS dam catchment	Mean SPI-12 (mm)	Drought threshold SPI-12 (mm)
Franschhoek Robertsvlei	Berg River Dam	1 848	1 455
Rustfontein	Theewaterskloof Dam	764	587
Steenbras	Steenbras Dams	925	734
Tulbagh	Voëlvlei Dam	469	364
Wemmershoek Dam	Wemmershoek Dam	965	746

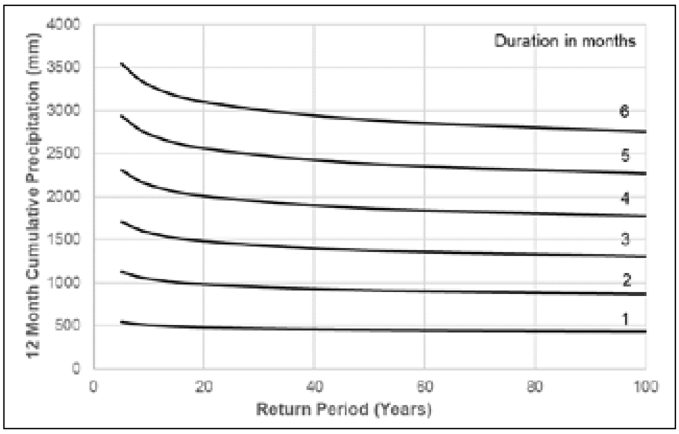

FIGURE 3: *Drought occurrence in the Steenbras catchment, based on 12-month running total rainfall.*

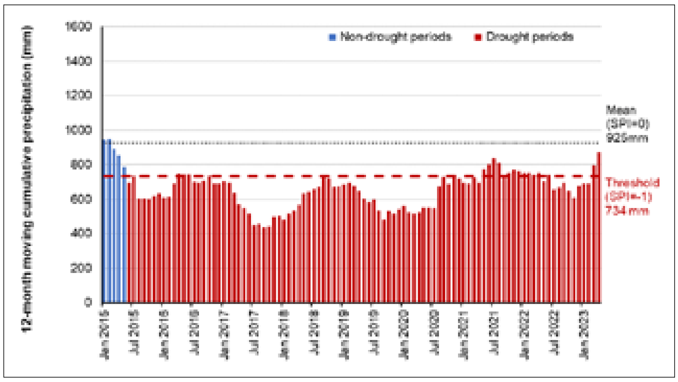

FIGURE 4: *Drought occurrence in the Wemmershoek catchment, based on 12-month running total rainfall.*

Severity, duration, and frequency (SDF) relationships are developed through frequency analysis, involving the fitting of the record of drought events and associated magnitudes to a probability density function, and then calculating the estimated magnitude of droughts for non-exceedance probabilities of 0.2, 0.1, 0.05, 0.02 and 0.01, which corresponds to return periods of 1 in 5-, 10-, 20-, 50- and 100-years.

Du Plessis and Rhode (2023) developed SDF curves for the WCWSS dam catchments, shown in Figure 2.

3. RESULTS

3.1 Assessing the occurrence of droughts directly from drought mean and threshold values

To illustrate the application of the SPI-12 and SDF curves, two (Steenbras Dam and Wemmershoek Dam) of the five rainfall stations at the five main dams of the WCWSS (see Table 2) have been used, using their updated monthly rainfall records available up to April 2023. The mean and threshold SPI-12 values (in mm) used for these rainfall stations are shown in Table 2.

Using the updated rainfall data (till April 2023) for these two rainfall stations, the running 12-month total precipitation was compared to the mean and threshold values for each station respectively, and drought and non-drought periods from January 2015 to April 2023 were identified as an example.

Figures 3 and 4 illustrate the drought and non-drought periods for Steenbras Dam and Wemmershoek Dam.

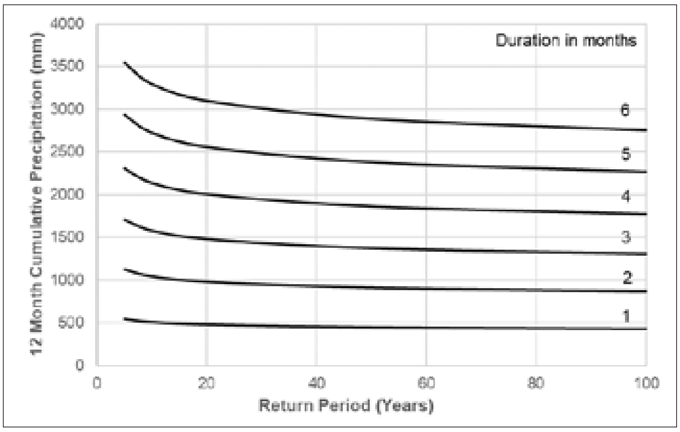

FIGURE 5: *Severity, duration, and frequency curves for the Steenbras catchment*

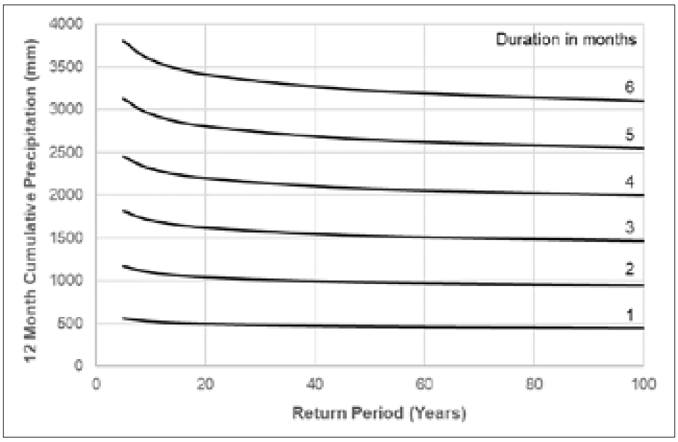

FIGURE 6: *Severity, duration, and frequency curves for the Wemmershoek catchment*

3.2 Assessing the severity of droughts from severity, duration, and frequency curves

The severity, duration, and frequency diagrams for the Steenbras and Wemmershoek catchments (Du Plessis and Rhode, 2023) are shown in Figures 5 and 6 respectively.

Using the series of running 12-month total precipitations, the cumulative six months periods with lower rainfall, from January 2015 to April 2023, were used to determine the severity of droughts being experienced from the above diagrams.

Droughts in the Steenbras catchment

Figure 3 indicates that the Steenbras catchment has been experiencing drought conditions from June 2015 to April 2023.

However, there are a few periods during the drought conditions where rainfall was particularly low; these periods of lowest rainfall were centred around:

- October 2015
- September 2017
- September 2019
- November 2022

Table 3 summarises the calculation of the most severe 6-month drought period, occurring at these dates.

Droughts in the Wemmershoek catchment

Figure 4 indicates that the Wemmershoek catchment has experienced two drought periods from June 2015 to April 2023: the first from August 2015 to April 2018, and the second from August 2022 to April 2023.

There are two periods during the drought conditions where rainfall was particularly low; these periods of lowest rainfall were centred around:

- September 2017
- November 2022

Table 4 summarises the calculation of the most severe 6-month drought period, occurring at these dates.

4. DISCUSSION

4.1 Current occurrence of drought in the Steenbras and Wemmershoek catchments

The rainfall records and threshold and mean SPI values derived by Du Plessis and Rhode (2023) were used to assess the occurrence of droughts in the Steenbras and Wemmershoek catchments. This analysis showed that:

- For the Steenbras catchment, drought conditions started in 2015, and have continued till the end of the analysis period (end April 2023). The most sever period can be categorised as between a moderate and severe drought.
- For the Wemmershoek catchment, drought conditions started in mid-2015, and ended in mid-2018. However, drought conditions started again in August 2022, and have continued through to the present. The most severe period can be categorised as a moderate drought.

4.2 Severity of drought conditions in the Steenbras and Wemmershoek catchments

Analysis of the severity, duration, and frequency relationships for the

TABLE 3: *Severities of drought periods in the Steenbras catchment, January 2015 – April 2023*

Drought period 1		*Drought period 2*		*Drought period 3*		*Drought period 4*	
12-month period ending on	12-month running total rainfall (mm)	12-month period ending on	12-month running total rainfall (mm)	12-month period ending on	12-month running total rainfall (mm)	12-month period ending on	12-month running total rainfall (mm)
Aug 2015	608	Jul 2017	450	**Sep 2019**	482	**Nov 2022**	610
Sep 2015	607	Aug 2017	456	Oct 2019	531	Dec 2022	678
Oct 2015	602	**Sep 2017**	437	Nov 2019	515	Jan 2023	693
Nov 2015	622	Oct 2017	443	Dec 2019	541	Feb 2023	693
Dec 2015	631	Nov 2017	498	Jan 2020	561	Mar 2023	795
Jan 2016	610	Dec 2017	505	Feb 2020	526	Apr 2023	869
Total	*3 679*	*Total*	*2 789*	Total	3 156	Total	4 339
Estimated probability	***> 1:5***	*Estimated probability*	***~1:100***	*Estimated probability*	***~1:20***	*Estimated probability*	***> 1:5***

TABLE 4: *Severities of drought periods in the Wemmershoek catchment, January 2015 – April 2023*

Drought period 1		*Drought period 2*	
12-month period ending on	12-month running total rainfall (mm)	12-month period ending on	12-month running total rainfall (mm)
Jul 2017	601	**Nov 2022**	618
Aug 2017	618	Dec 2022	661
Sep 2017	577	Jan 2023	662
Oct 2017	615	Feb 2023	711
Nov 2017	682	Mar 2023	811
Dec 2017	676	Apr 2023	861
Total	*3 768*	*Total*	*4 324*
Estimated probability	*~ 1:5*	*Estimated probability*	*> 1:5*

Steenbras catchment indicate that there have been four periods of low rainfall. Of these, the more severe period has been July to December 2017, where the six-month cumulative 12-month running total rainfall is classified as a 1:100 year event, and similarly the period from September 2019 to February 2020 is classified as a 1:20 year event. The drought period from November 2022 to April 2023 is classified as a more moderate event, with a probability of occurrence of less than 1:5 year.

Analysis of the severity, duration, and frequency relationships for the Wemmershoek catchment indicate that there have been two periods of lower rainfall. Of these, the more severe period was between July and December 2017, where the six-month period is classified as a 1:5 year event. The drought period from November 2022 to April 2023 is a more moderate event, classified as an event with a probability of occurrence of less than 1:5 years.

Being able to quickly determine the occurrence and severities of droughts (as per the above examples), using only rainfall data, can give water resource managers valuable, almost real time, insights in the unfolding drought scenarios, which can inform water supply system planning and operational decisions.

5. CONCLUSION

Local authorities do have a constitutional obligation to provide water services to the people within their areas of jurisdiction. Limited funding and technical capacity force local authorities to be innovative in their approach to be resilient in the future in managing their water resources, which will most likely be further aggravated by climate change. The research presented in this paper has illustrated through the WCWSS case study, how historical monthly rainfall data can be used to assess the occurrence and severity of droughts using the rainfall data together with drought threshold values and severity, duration, and frequency relationships diagrams, derived only from the monthly rainfall. This can be done without the need to calculate any other climate parameters from first principles. These assessments can provide useful information to water resource managers when making decisions on operating the WCWSS as a case study, but the approach, if applied by local authorities, will also strengthen their resilience in the future to deal with the expected water resource challenges.

Using the SPI-12 values and associated developed SDF graphs, the analysis further illustrates that droughts are currently occurring in both of the 2 catchments of the WCWSS used in the case study, but that these droughts are fortunately generally only moderate. This indicates that water resource managers should monitor the situation in the event that severities worsen and there is a need to act to reduce demand from the system.

Assessing all catchments of the WCWSS would also give a more complete picture of the current climatic position of the WCWSS and it is recommended that the research be extended not only to the WCWSS, but to South Africa as a country.

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