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Changes in extreme daily rainfall characteristics in South Africa: 1921–2020

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A R T I C L E I N F O

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A B S T R A C T

Many areas in South Africa are prone to localized flooding. With climate change already said to affect the intensity of rainfall, there is a need to investigate if there is a change in the probability of significant to extreme daily rainfall across South Africa. This was investigated through the analysis of the daily time series of 70 manual rainfall stations, over the period 1921 to 2020. The analysis period was divided into two equal periods of 50 years for comparison. With the application of the gamma distribution, it is shown that most stations experienced an increase in the probability of receiving more than 50 mm per day, defined as significant rainfall, in the latter half of the analysis period. Also, most stations showed an increase in their 1:50- and 1:100-year return period values, with some stations over the eastern parts showing increases of over 100 mm. There was also an increase in the probability of "heavy rainfall" (>75 mm) and "very heavy rainfall" events (>115 mm) between the first and second half of the analysis period for most stations over the country when applying the Peak-Over-Threshold approach. In summary, the results indicate that, although the number of rain days has remained near-constant over the 1921–2020 period, the probability of experiencing significant and extreme daily rainfall events has increased generally for most regions in South Africa. This is of concern as rainfall of this nature can have serious consequences in terms of flooding, erosion, and damage to agriculture and infrastructure.

1. Introduction

Changes, e.g. intensification, in the hydrological cycle have been cited as possible consequences of a changing climate (Lehmann et al., 2018). These changes, especially in terms of frequency, intensity, and duration of precipitation events, can have many social and environmental impacts (Contractor et al., 2021). With rainfall events expected to intensify (increased rainfall over shorter timeframes) globally in a warming world (Trenberth, 2011; Zhongming et al., 2020; Contractor et al., 2021; Du et al., 2022) there is a real threat of increases in flooding events (Hirabayashi et al., 2013) as well as possible damage to infrastructure which may have been designed according to a stationary climate (Smithers, 2012; Johnson et al., 2021). If structures are thus not designed to take into account the potential extreme events in a changing climate, the loss of life and the economic impact could be significant (Johnson and Smithers, 2019). This was witnessed in the recent flooding event in South Africa where over 40 000 people in the KwaZulu-Natal coastal areas suffered the effects of high rainfall with some areas receiving record daily rainfall amounts (Pinto et al., 2022).

Several global studies have found that the annual maximum daily rainfall extremes are increasing over land in intensity and/or frequency (Alexander et al., 2006; Westra et al., 2013; Donat et al., 2013; Lehmann et al., 2015; Dunn et al., 2020; Seneviratne et al., 2021; Lawrence et al., 2022). These global studies show a lack of consistency in patterns of extreme rainfall over Southern Africa as well as a low confidence in the trend over this region due to a lack of data and supportive regional analysis. Regional studies in the Northern Hemisphere (Zhang et al., 2013); UK (Christidis et al., 2021); USA (Mallakpour and Villarini, 2017) and Japan (Yamada et al., 2020) however found increases in intensity and frequency of extreme precipitation events. Lehmann et al. (2015) found for the period 1981 to 2010 a 12% higher occurrence of global record-breaking rainfall events compared to the frequency expected in a stationary climate.

Most of the above studies link the increases in intensity and/or frequency of extreme rainfall events to increases in temperature as a result of anthropogenic climate change. As surface temperatures increase, due to climate change, so the water content of the atmosphere changes. These increases in the water-holding capacity of the atmosphere equate

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to ~7% per degree of warming, assuming constant relative humidity (Clausius-Clapeyron rate) (Allan et al., 2014). With more moisture available, the nature of rainfall events is thus likely to become more intense with increased rainfall rates (Trenberth et al., 2003). Therefore the intensity of extreme precipitation events is likely to increase, even in areas where average precipitation is projected to decrease (Westra et al., 2013). Some studies have even suggested that the atmospheric response could exceed the Clausius-Clapeyron rate, especially for convective precipitation (Lehmann et al., 2015). However, the relationship between extreme rainfall and atmospheric temperatures is complex with other factors such as changes in the atmospheric circulation patterns, atmospheric stability, latent heat, moisture convergence, cloud size, and the degree of mesoscale organisation playing a role (Guerreiro et al., 2018). Thus, changes in extreme rainfall patterns are thought to be highly regionalized (Westra et al., 2013; Contractor et al., 2021).

1.1. Rainfall patterns and extremes in South Africa

South Africa's rainfall distribution is diverse and increases from below 200 mm in the west to above 1200 mm per annum in the east (Kruger, 2007). This is largely due to its geographic position being situated between 22° and 34°S, complex topography and the fact that the southern African subcontinent is surrounded by the warm Agulhas current on the eastern coast and cold Benguela current on the west (Tyson and Preston-Whyte, 2000). The position together with the ocean influences sets up a range of rain-producing mechanisms, ranging from mostly convective rainfall over the central, northern and eastern parts of the country in summer, to mid-latitude cold fronts which move across the south-western Cape and southern coastal regions, mostly in the austral winter (Favre et al., 2016). Therefore, South Africa can generally be divided into four rainfall seasonal zones, with their distinctive rain-producing mechanisms of summer, late summer, winter and all year maxima (Kruger, 2007).

Early research on rainfall patterns from 1880 to 1972 by Tyson et al. (1975) found no evidence of a decrease in annual rainfall over South Africa and showed no spatial clustering with regards to trends. Later research by Sen Roy and Rouault (2013) did find a positive trend in extreme hourly precipitation events during summer for most of South Africa with the strongest trend over the south-east coastal region, extending inland in a north-eastward direction to include the western areas of the country. An increase in trend for annual daily rainfall extremes was also found by Kruger and Nxumalo (2017) over the west of South Africa including the southern interior for the 1921 to 2015 period. When it came to the intensity of extreme rainfall Mason et al. (1999) found that 70% of the country experienced significant increases when comparing the period 1931–1960 with that of 1961–1990. A decrease in extreme rainfall events has also been noted by this study over the north-eastern part of South Africa with Kruger and Nxumalo (2017) also observing a decrease in rainfall in some places over the far north-eastern parts of the country. In summary historical studies showed overwhelming evidence of mostly increases in rainfall extremes over South Africa although there were certain regions which showed an opposite trend.

In conjunction with the observed historical trends, research using model projections of a future climate found the intensity of extreme rainfall is likely to increase in a warming world (Westra et al., 2013). Engelbrecht et al. (2013) and Abiodun et al. (2020) found an increase in projected extreme rainfall events over Southern Africa. Pohl et al. (2017) found a likely increase in rainfall amounts associated with the 1% wettest days by the end of the 21st century over Southern Africa although the number of rain days is expected to decrease.

1.2. Motivation for the research

In a country where rainfall is highly variable such as South Africa (Van Rooyen et al., 2010) there is a real need to understand any changes in the hydrological cycle if effective water resource management is to be planned for (Molobela et al., 2011). There is also a need to understand extreme rainfall events as these are likely to cause flooding. Although flooding in South Africa may not be as frequent or affects as large areas as drought, these events can cause sudden disasters which have consequences for example for human life and settlements, water management, the built environment in general, and agriculture. The 11th to April 13, 2022 severe flood event, caused by a cut-off low, that devastated KwaZulu-Natal is an example of how heavy rainfall can be the cause of severe impact with 443 human casualties and more than 40 000 people displaced (ECHO, 2022). The loss and damage of infrastructure is set to run into billions of South African Rand. Other recent extreme events in the country include the flooding of the Cape Town area on the 28th to June 29, 2021 where an estimated 6 300 people were affected, and more than 3 250 buildings were flooded. The 23rd and January 24, 2021 saw Tropical Cyclone Eloise cause severe flooding over large areas of the Limpopo Province. Other such events include Tropical Cyclone Eline on the 23rd and February 24, 2000 and Tropical Cyclone Domoina the on January 28, 1984 which caused extensive damage to infrastructure and loss of life. One of the most disastrous flooding events in living memory occurred on the January 25, 1981 when a cut-off low was responsible for intense rainfall over the Laingsburg area where 425 mm fell in 24 h causing widespread destruction, with 102 people losing their lives (SAWS, 1991). The very heavy rainfall which occurred during these events was associated with well-organized synoptic scale weather systems. However, localised extreme convective rainfall also occurs over South Africa such as on the November 9, 2016 when 90 mm of rain fell in an hour near OR Tambo International Airport in Gauteng (Simpson and Dyson, 2018). Thus the understanding of any changes in the likelihood of extreme rainfall is critical for strategic planning for future extreme events, town and city planning and possible adaptation of the built environment for the design-life of structures to accommodate any possible increases in extremes (Smithers, 2012).

Osborn et al. (2000) suggested that one should consider the change in the number of wet days or the change in the distribution of intensities or a combination of both, to investigate changes in the distribution of rainfall at a specific location. This paper examines, with applicable statistical analysis, any changes in the probability and return periods of multi-year extremes (with relatively low probabilities) of daily rainfall events over South Africa. The paper is divided into three sections: Firstly, a description of the climate data sets, and statistical methodologies applied, are discussed. The results are presented in the second section, followed by a discussion of these results with concluding remarks, including a comparison to relevant climate projections.

2. Data and methodology

Daily rainfall values from a total of 70 long-term rainfall stations were selected for analysis across South Africa, with locations presented in the map in Fig. 1. The stations are spatially fairly well distributed across the country and have not moved location. All stations used a manual standard rain gauge for the whole study period, with measurements taken at 08:00 local time daily. The stations have near-complete data for the complete analysis period, i.e. at least 90% data availability. High rainfall values were checked where possible with original rainfall returns to ensure that amounts had been correctly captured. A similar approach to Mason et al. (1999) whereby the data period is divided into two successive periods was adopted. In this study the data from each station was divided into two successive periods of 50 years each, i.e. 1921– 1970 and 1971–2020 (referred to as Period 1 (first) and Period 2 (second) hereafter).

2.1. Definition of significant and extreme rainfall events

When considering heavy daily-rainfall events for the Gauteng Province (see Fig. 1 for location), Dyson (2009) recommended that

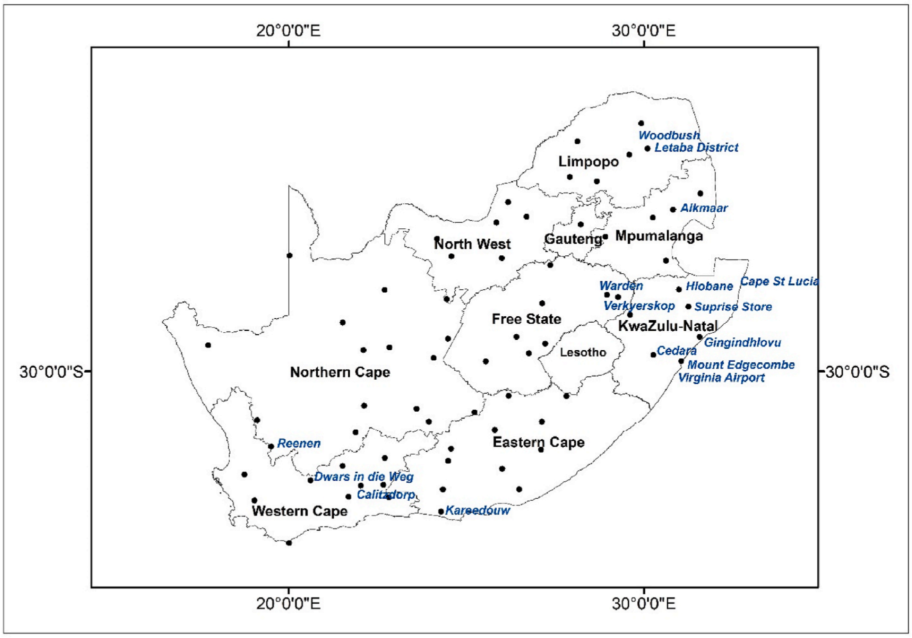

Fig. 1. Locations of the 70 rainfall stations which were used to analyse the changes in the occurrence of daily rainfall extremes over the period 1921–2020. Black text indicates provincial names plus Lesotho and blue text names of stations referred to in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

percentiles be used to identify and consequently define significant (90th percentile), heavy (95th percentile) and very heavy rainfall (99th percentile). Utilizing all available rainfall data over Gauteng, the 90th percentile was determined to be approximately 59 mm. This value was then adjusted to 50 mm, the threshold value for *significant rainfall*, to correspond with what was used operationally by the South African Weather Service when issuing heavy rainfall warnings at the time. Due to the diverse rainfall climate of South Africa (Kruger, 2007), it follows that the categorisation of significant or extreme rainfall events based on percentiles alone can vary significantly on a regional basis, mainly due to the variability in the probabilities of specific rainfall amounts to occur. The 99th percentile was calculated for all the stations in the database and most of the stations had 99th percentile values of between 40 mm and 60 mm for both Periods 1 and 2 (Fig. 2a and b). The threshold of 50 mm was therefore also considered here as the threshold for *significant rainfall* for the country as a whole. There was an increase of 2% on average for the number of wet days from Period 1 to Period 2. This, and the distribution of the actual rainfall values, will affect the percentile values between the two periods. However, examining Fig. 2, the majority of the country exhibits a 99th percentile value of between 40 and 60 mm, regardless of the analysis period.

In terms of extreme rainfall events, daily amounts which are unlikely to occur every year, i.e. a return period of two years or longer, were considered. Extreme, or very heavy daily rainfall was identified by Bradley and Smith (1994) when at least 125 mm occurred at a station in 24 h while Chen et al. (1988) required a total of 130 mm in a day. Dyson (2009) defined very heavy rainfall over Gauteng as a daily amount of 115 mm. This value is somewhat less but in the same range as Bradley and Smith (1994) and Chen et al. (1988), therefore 115 mm was also adopted as the threshold for *very heavy rainfall* in this paper. The same logic was followed by classifying 75 mm as a *heavy rainfall* event. Considering the 99th percentile values depicted in Fig. 2 where values vary between 32 mm and 120 mm, daily rainfall threshold values of 75 mm and 115 mm were accepted to reasonably represent extreme event thresholds over South Africa in general. Using a percentile value alone to define an extreme rainfall event does not take into account the impacts of such events. For example, if an extreme rainfall event is defined as 20 mm according to a percentile based value, the impact will probably be non-significant in terms of likelihoods of flooding or damaged infrastructure. Therefore, we reverted to absolute values of 50 mm, 75 mm and 115 mm as defined above. This definition informs the statistical approach to be followed in the estimation of the probability of specific heavy rainfall events to occur. In addition, the large spatial variability of the 99th percentile value motivated the further investigation of possible changes in the maximum rainfall amounts expected over specified return periods, which is not dependent on an absolute definition of a threshold for an extreme rainfall event.

2.2. Analysis methodology

Contingency tables have been used in various meteorological studies (Ihara et al., 2007; Fowler et al., 2010; Maldonado et al., 2013; Mittermaier et al., 2022). Therefore, as an initial approach, this method was used to examine individual stations' data with respect to changes in the general distribution of daily rainfall intensity. Rainfall events were counted which were pre-defined as below meaningful (i.e. 1 – 5 mm) (meaningful being close to the typical daily evaporation rate), meaningful but not very heavy (5–50 mm) and heavy or extreme (above 50 mm), between Periods 1 and 2. Contingency tables of 3-row (below 5 mm, 5–50 mm and above 50 mm) × 2-column (Periods 1 and 2) were constructed for each station with both row and column totals calculated (Conover, 1999). The χ^2-test for the difference in probabilities was applied to test whether there was any difference in the occurrence of daily rainfall in the predefined categories.

Following on the results of the application of the data to contingency tables, the general distribution of daily rainfall was then examined to see if there were changes between Periods 1 and 2, for each rainfall station. The gamma distribution was used for this as it is a continuous probability distribution that is widely used in studies to model continuous variables such as rainfall that have a right-skewed distribution (Wilks and AuthorAnonymous, 2011; Martinez-Villalobos and Neelin, 2019). The probability density function (pdf) of the gamma distribution is defined as:

$$g(x) = \frac{1}{\beta^{\lambda}\Gamma(\gamma)} x^{\gamma-1} e^{-\frac{x}{\beta}} \tag{1}$$

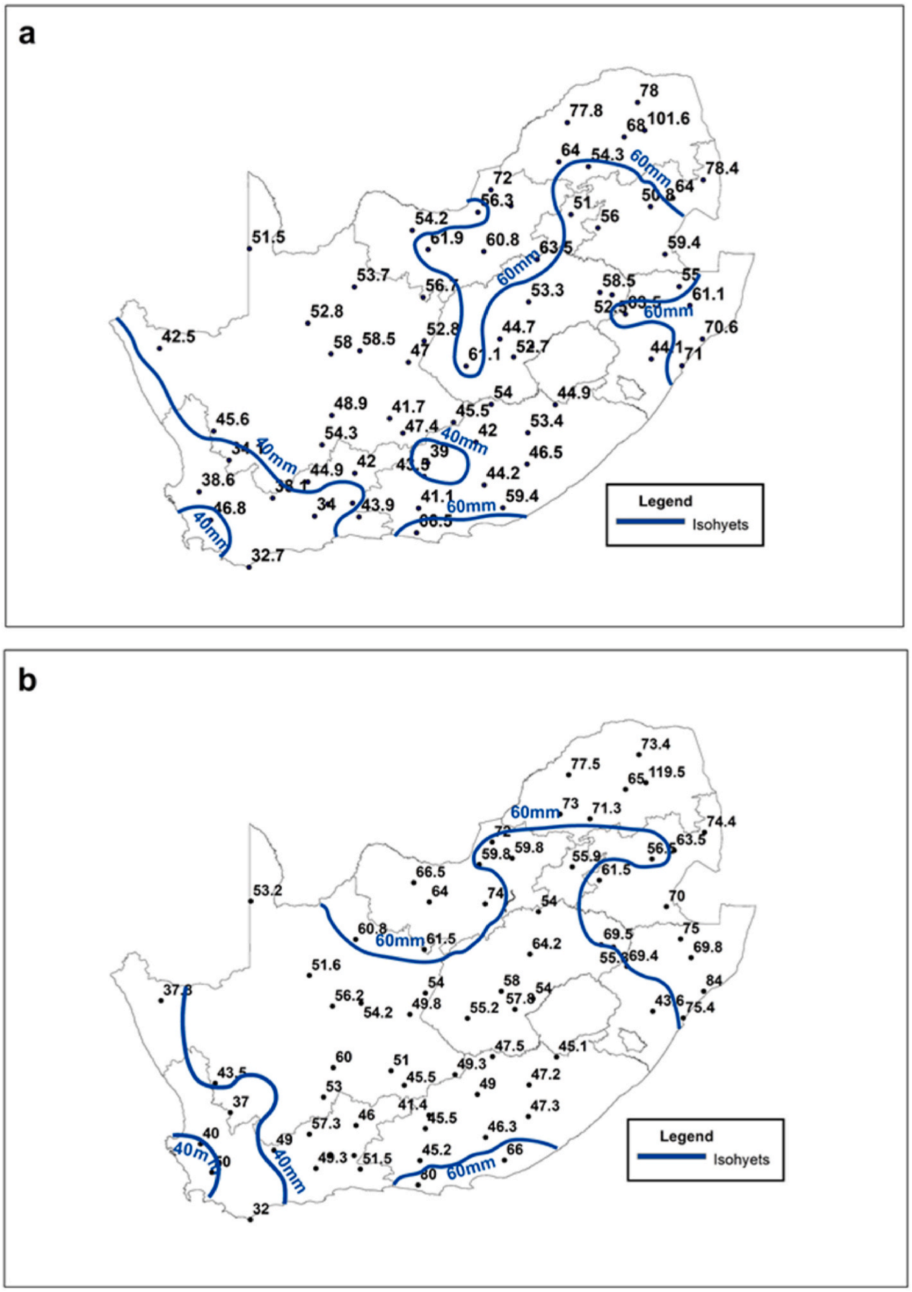

Fig. 2. 99% percentile of all daily rainfall events for Period 1 (a) and Period 2 (b). Isohyets were drawn for the 40 mm and 60 mm values.

β = scale parameter
γ = shape parameter
$\Gamma(\gamma)$ = ordinary gamma function.

However, this research mainly focus on extreme daily rainfall values and the gamma distribution can underestimate extreme behaviour, which is characterised by the right tail of the distribution (Papalexiou et al., 2013; Cavanaugh et al., 2015). Therefore, the analysis of extreme event probabilities was approached through the application of extreme value distributions. The most widely applied extreme value distribution is the Generalised Extreme Value (GEV) distribution, specifically Type I (Gumbel). It is a good fit for extreme rainfall, which has no negative values (Coles et al., 2001).

GEV is defined as:

$$F(x) = e^{-(1-ky)^{1/k}} \quad k \neq 0 \tag{2.1a}$$

$$F(x) = e^{-e^{(-y)}} \quad k = 0 \tag{2.1b}$$

k = shape parameter (determines the type of extreme value distribution)
y = standardised or reduced variate

When the shape parameter is equal to 0, the GEV is considered to be an Extreme Value Distribution Type I (Gumbel).

The standardized or reduced variate y is given by:

$$y = (x - \beta) / \alpha \tag{2.2}$$

α = scale or dispersion parameter

β = mode of the extreme value distribution
x = the extreme value

To estimate α and β we used the method of moments (Wilks and AuthorAnonymous, 2011):

$$\alpha = s\sqrt{6}\Big/\pi \quad (2.3)$$

$$\beta = \overline{x} - \gamma\alpha \quad (2.4)$$

s = standard deviation of sample
$\overline{X}$ = sample mean
λ = 0.57721 … Euler's constant

However, in the application of the GEV significantly underestimation or overestimation of extremes can occur, due to the fact that only a small sample of the total data set can be utilized (i.e. only one block (usually one year) maxima are used as input data). In some cases, some of these values might not even be considered extreme, e.g. the annual maximum during an exceptionally dry year. The Gumbel distribution was therefore only applied to investigate temporal changes in its distribution parameters (α = scale or dispersion parameter, β = mode of the extreme value distribution). Thus, an additional approach was followed to estimate more realistically the return periods for specific threshold values, as well as the expected maxima for specific return periods. Due to the fact that extreme values can occur more than once in a year, the sampling of these events can be improved by the application of e.g. the Peak-Over-Threshold (POT) method, which can then be used to estimate return periods for extreme events (Thiombiano et al., 2017). The advantage of this method is that an extreme event or value is predefined, and utilises all values above this threshold, providing that most of the values are independent, preferably more than 90% (Mailhot et al., 2013). The values above this threshold are known as exceedances and are assumed to have a generalised Pareto distribution with three parameters (Castillo and Hadi, 1997; Coles et al., 2001), which could be simplified to the Exponential distribution with two parameters (e.g. if there is not sufficient motivation to use three distribution parameters). In the POT method, it is important to choose the threshold value in a manner that includes enough values which are considered to be extreme and not include too many non-extreme values, which will probably lead to an underestimation of very extreme low-probability values (Tramblay et al., 2013). The 99th percentile of daily rainfall is widely considered to be the threshold of extreme rainfall (Thiombiano et al., 2017), therefore the stations' 99th percentile rainfall value were considered to be the thresholds for each station for each period. The GPD was fitted to these values:

$$F(X) = 1 - \left[1 - \left(\frac{k}{\alpha}\right)(x - \xi)\right]^{1/k} \quad (3.1)$$

ξ = selected threshold. For $k = 0$ the GPD simplifies to the exponential (EXP) distribution $F(x) = 1 - e^{-[(x-\xi\ /\alpha]}$ (3.2)

The crossing rate of the threshold is defined as

$$\lambda = n/M \quad (3.3)$$

n = total number of exceedances
M = total number of years in time series

Specific return periods (in years) can then be calculated from Abild et al. (1992):

$$X_T = \xi + \left(\frac{\alpha}{k}\right)\left[1 - (\lambda T)^{-k}\right] \quad if\ k \neq 0 \quad (3.4a)$$

$$X_T = \xi + \alpha \ln(\lambda T) \quad if\ k = 0 \quad (3.4b)$$

The distribution parameters α and k can be estimated with

$$\widehat{k} = \left[\frac{b_0}{2b_1 - b_0}\right] - 2 \quad (3.5a)$$

$$\widehat{\alpha} = (1 + \widehat{k})b_0 \quad (3.5b)$$

Using the above method, the return period values (RPVs) for 1:10-, 1:50-, and 1:100-year for each station for each period were estimated. These return periods were selected as these are generally used as input to design periods of infrastructures such as sewers, water-treatment plants and dams (Brière, 2014). The Anderson-Darling test, which is particularly sensitive to differences in the tails of the distribution, was used to test for significant differences between Periods 1 and 2 at the 95% confidence limit. Return periods were then estimated for the predefined 50 mm, 75 mm and 115 mm thresholds.

3. Results

3.1. General distribution of rainfall amounts

When counting the number of wet days (≥ 1 mm) for all the stations we found on average a 2% increase between Periods 1 to 2. When dividing these rain days into three categories of below 1–5 mm, 5–50 mm and greater than 50 mm we found an average percentage increase of 15%, 0.3% and 4% in these events respectively between Period 1 and Period 2. A total of 66% of stations showed a significant difference at the 95% confidence interval when applying contingency tables between categories of 1–5 mm, 5–50 mm and greater than 50 mm between Period 1 and Period 2.

3.2. Spatial change in probability of significant rainfall

To further investigate the findings from the contingency tables the possible difference in probability of receiving 50 mm or more on a rainy day from the gamma distribution (Equation (1)) for the two periods was investigated. 71% of stations were found to have a significantly higher probability of receiving above 50 mm in Period 2, compared to Period 1. These stations are depicted as filled blue triangles in Fig. 3, and apart from a region along the western escarpment, are well distributed throughout South Africa.

Fig. 4(a and b) illustrate the probability of receiving more than 50 mm on a rainy day for Period 1 and Period 2 respectively, while Fig. 4 (c) presents the differences between these probabilities. Most stations showed an increase in Period 2 (Fig. 4c), which corresponds to Fig. 3 in terms of patterns of change but additionally shows where these differences are the largest. The largest difference in increased probability of receiving 50 mm in Period 2 occurred over the northern parts of the country as well as isolated areas over the Free State and northern parts of KwaZulu-Natal (shaded light grey in Fig. 4c), while areas showing less probability were situated over isolated areas in the western as well as northwestern and eastern parts of the country (shaded black in Fig. 4 c). Areas showing a greater likelihood of receiving above 50 mm of rain on a rainy day largely coincide with stations indicating significant change at the 95% confidence level (Student's *t*-test) as depicted in Fig. 3. The averages of the shape and scale parameters of the gamma distribution for all stations, were also found to be statistically different at the 95% confidence level. Some spatial irregularities are evident, e.g. between two stations in the eastern Free State (*Warden Skoolstraat, Verkyerskop*) which are situated very close to each other but show opposite direction of change. This could point to a data quality issue although the data was checked, and no obvious errors could be detected. However, systematic observation errors cannot be excluded, e.g. underreporting of rainfall over an extended time period. The rainfall data for these two stations should be further investigated to try and explain these spatial anomalies.

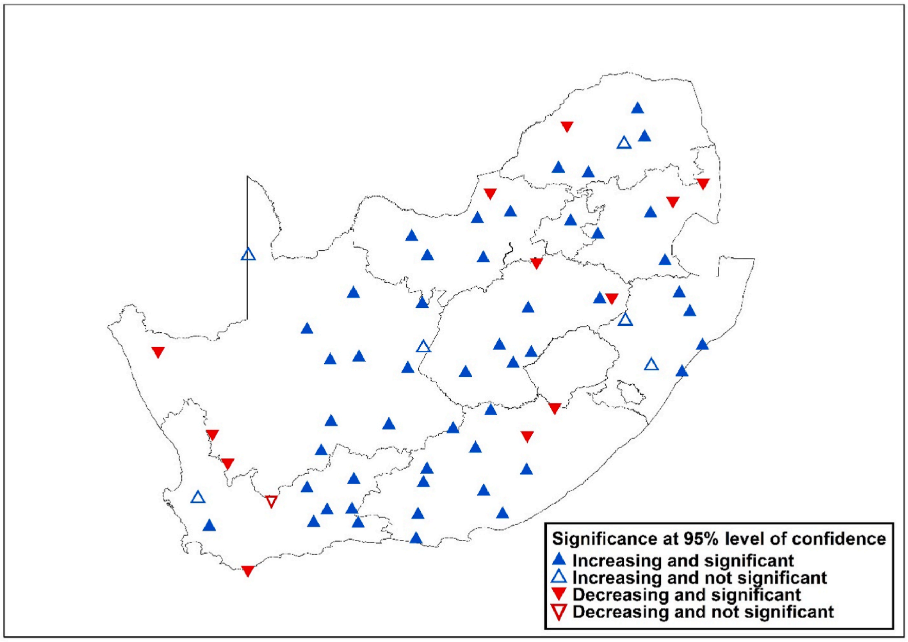

Fig. 3. Difference in the probability of receiving 50 mm of rainfall on a rainy day, estimated from the Gamma distribution. Blue symbols indicate where the probability of receiving above 50 mm is greater in Period 2 (1971–2020) while red symbols indicate where the probability of receiving above 50 mm is greater in Period 1 (1921–1970). Shaded symbols indicate statistical significance at the 95% confidence interval (Student's t-test). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

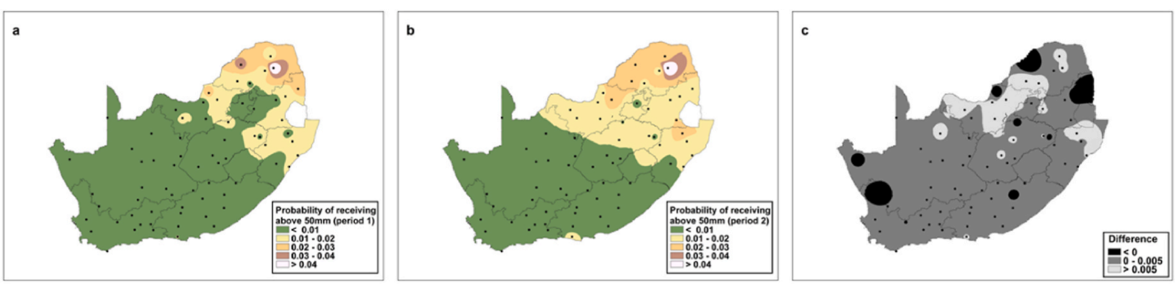

Fig. 4. The probability of receiving above 50 mm of rainfall on a rainy day, estimated from the Gamma distribution – (a) Period 1 (1921–1970) and (b) Period 2 (1971–2020). Difference between Period 1 and Period 2 (c). Inverse distance weighting was used as the interpolation method.

3.3. Temporal change in extreme value distribution parameters

A 30-year moving window with the annual highest daily rainfall amounts was determined for each station for the period 1921–2020, for each year, i.e. 1921 represents a 30-year window of annual maximum values for 1921 to 1950, 1922 to 1951 etc. up to 1991 to 2020. The α and β – parameters were then calculated for these windows from the Gumbel distribution (Equation 2) and averaged for all stations to check for trend and/or any abrupt changes in the window mean over the 1921–2020 analysis period. The α and β – parameters showed positive trends which were significant at the 95% confidence level (inserts in Fig. 5a and b). To investigate any abrupt changes in the mean α and β – parameters the differences in these means before and after every year were tested, starting in 1951. By observing changes from a decrease to an increase in the absolute value of the Student's *t*-test one can identify abrupt changes in the means (McBride et al., 2021). Years of abrupt change in the mean α– parameter were 1975 and 1995, while for the β – parameter it was 1974–1975 (Fig. 5a and b). The years of the most abrupt changes in the α– parameter were interspersed by years of less difference, which can be linked to the decade of above-normal rainfall in the 1970s followed by a very dry period in the 1980s (Dyer and Tyson, 1977). The fact that the largest absolute value of the Student's *t*-test is close to the middle of the time series as a whole, i.e. 1921 to 2020, and visual inspection of the α and β – parameters, it can be assumed that the general change in the parameter is near-monotonous throughout the analysis period, providing confidence in dividing the analysis period into two equal sub-periods of equal length for comparative purposes. The α-parameter gives an indication of the variance and the β – parameters takes into account the mean and variance and thus a steady increase in both these parameters points to an increase in variance over the study period, indicating that there is a greater likelihood of values falling into the tail of the distribution i.e. more extreme events.

3.4. Probabilities of extreme daily rainfall events

The 1:10-, 1:50- and 1:100-year return periods values (RPVs) were calculated for both periods using the POT method (Equation 3) and the results are depicted in Fig. 6. RPVs were lower over the western parts of the country while the eastern parts had higher values which is expected in terms of the rainfall climate of South Africa where rainfall decreases from east to west. However there was an increase in RPVs for most stations across the country in Period 2, compared to Period 1, for all three return periods tested (Fig. 6b,e and h). The difference between 1:10 -year return period between Periods 1 and 2 as a ratio (P2/P1) is largest over the eastern, central, southern and western interior (Fig. 6c). Specifically, *Letaba District* in Mpumalanga and *Gingindhlovu* and *Mount Edgecombe* in the eastern parts of KwaZulu-Natal showed around 80 mm increase from Period 1 to Period 2. For the 1:50-year return period the biggest increase in values was also observed over the southern and western interior and eastern parts of the country for Period 2 (Fig. 6f). The increase in RPVs from Period 1 to Period 2 for *Kareedouw* situated over the southern part of the Eastern Cape (Fig. 1) was 138 mm while

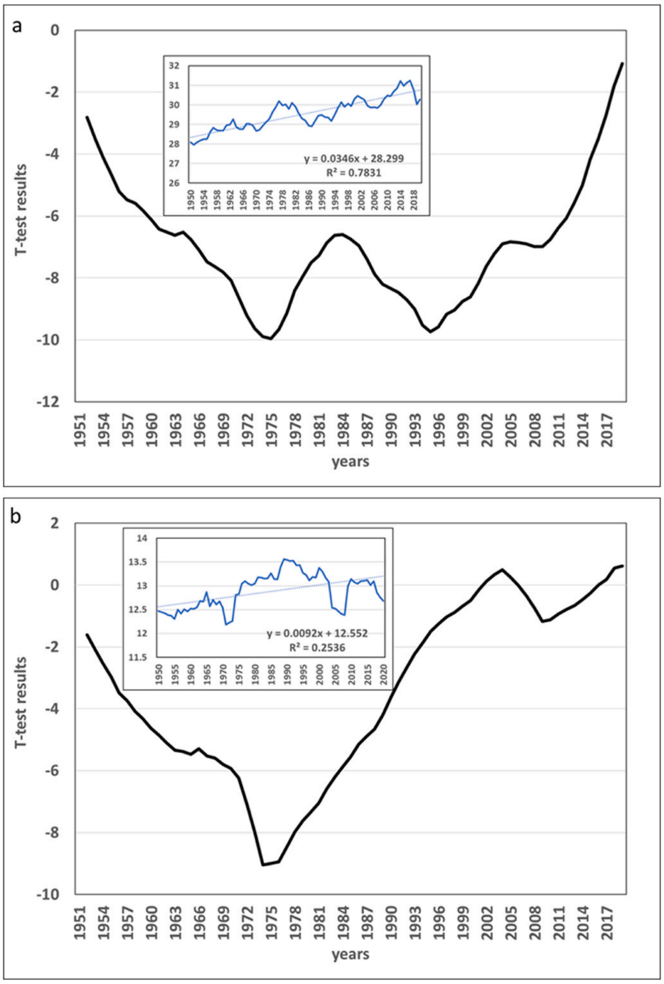

Fig. 5. *Student's t-test results of the difference in average mean α (a) and β (b) values before and after the specific year for the time series 1921 to 2020. Insets are the trends.*

Dwars in die Weg situated in the Western Province showed an increase of 75 mm. The eastern parts of the country saw stations like *Letaba District* and *Gingindhlovu* experiencing an increase of more than 140 mm in Period 2. A similar spatial pattern to the 1-50-year return period values could be seen for the 1:100-year return periods except for the southern parts of the Western Cape where additional stations fell into the upper ratio category. The eastern parts of the country as well as an isolated area in the western interior to southern coastal areas showed increases in RPVs for Period 2 (Fig. 6i). There was an increase in the number of stations over the northern and eastern parts of the country which had RPVs of greater than 400 mm with stations like *Letaba District, Gingindhlovu* and *Mount Edgecombe* having maximum daily rainfall above 600 mm per day as the 1:100-year event.

Isolated areas over the extreme western parts of the Northern Cape and well as over the eastern part of the Free State, Limpopo Province, Mpumalanga and the Eastern Cape showed a reduction in RPVs for the second period for all three return periods (light grey areas depicted in Fig. 6c, f and i). The average difference in RPVs of all stations was found to be significant at the 95% confidence interval (Anderson-Darling test) for the 1:50- and 1:100-year return periods.

3.5. *Return periods for specific thresholds of daily rainfall*

Following on from the fact that most stations were showing an increase in terms of receiving more extreme rainfall for specific return periods in Period 2 compared to Period 1, it is investigated here how this result translated into potentially shortening of return periods for the predefined significant (>50 mm), heavy (>75 mm) and very heavy (>115 mm) rainfall events (Dyson, 2009)). Fig. 7 shows that there was a change in the spatial distribution between Period 1 and 2 in the stations that have estimated return periods of less than a year for 50 mm (highlighted by the grey areas in Fig. 7a and b). Only one station (*Mount Edgecombe*) had a return period of less than a year in Period 1 (Fig. 7a) while in Period 2 this increased to include most of the stations over northern KwaZulu-Natal and eastern Mpumalanga and Limpopo provinces (Fig. 7b). There was a lowering in return periods over the western interior and southern parts as well as the eastern parts of the country (Fig. 7c). The extreme western parts of the country, as well as areas over the eastern interior, showed an increase in return period for the 50 mm return value (Fig. 7c).

Most of the country had a return period of less than 5 years for 75 mm for both Period 1 and 2. The difference between Period 1 and 2 (Fig. 7f) mimics that of 50 mm (Fig. 7c) to a large extent.

In terms of receiving 115 mm or more, the stations in the eastern parts of the country were shown to have return periods of less than 5 years which is once again expected as this region generally receives more rain than the western parts of the country. What is noteworthy is that for most of the country the return period is decreasing for 115 mm. Stations that showed the biggest decreases for this return period presented a similar spatial pattern to the 50 mm and 75 mm return periods (Fig. 7c,f,i). For stations in the Western Cape, *Dwars in die Weg* has its return period for 115 mm decrease from 33-years in Period 1 to 12-years in Period 2, *Reenen* from 71 to 33-years while over KwaZulu-Natal stations like *Surprise Store* from 5 to 2-years and *Hlobane* from 4 to 2-years (specific analysis not shown).

4. Discussion and conclusion

In this study, we investigated if daily rainfall intensities across South Africa had changed during the past century by considering two 50-year periods namely 1921–1970 (Period 1) and 1971–2020 (Period 2). To do this we used observed daily rainfall from 70 stations well-distributed across South Africa. The number of rain days (>1 mm) over the country was slightly higher (2%) in Period 2 compared to Period 1. As the study focused on significant to extreme rainfall events, the focus was on daily rainfall totals of 50 mm or more, deemed by the SAWS weather forecast warning system to be potentially hazardous. Of the 70 stations considered, 64 experienced a statistically significant change in the general distribution of three rainfall categories (1–5 mm, 5–50 mm and >50 mm). In order to understand if this change showed a difference in the probability of receiving above 50 mm, the gamma distribution was fitted to all values above the 99th percentile. This showed a clear increase in the probability of receiving 50 mm of rainfall or more on a rainy day over most parts of the country in the latter half of the analysis period.

The RPVs for 1:10-, 1:50- and 1:100-year were then calculated from the POT method and most stations over the country showed an increase. The highest increase in rainfall values could be found over the north-eastern and eastern parts of the country with some of these areas estimated to receive above 400 mm for the 1:50 and 1:100 RPVs over the latter 50-year period. The central and western interiors also showed an increase in RPVs although these were much lower in value (mm) than the eastern parts. These results support model projections which show increased rainfall in this region, due to expected enhancement of cloud-band formation (Engelbrecht et al., 2009) and convective summer rainfall (Hewitson and Crane, 2006).

The decrease in RPVs in the Northern Cape for the second period also confirms the projections of reduced rainfall reported over this area by Tadross et al. (2005) (Hewitson and Crane, 2006), and (Engelbrecht et al., 2009). This has been linked to the southward displacement of cold fronts in the winter months (Engelbrecht et al., 2009) which could influence this increase in the time interval between extreme events over

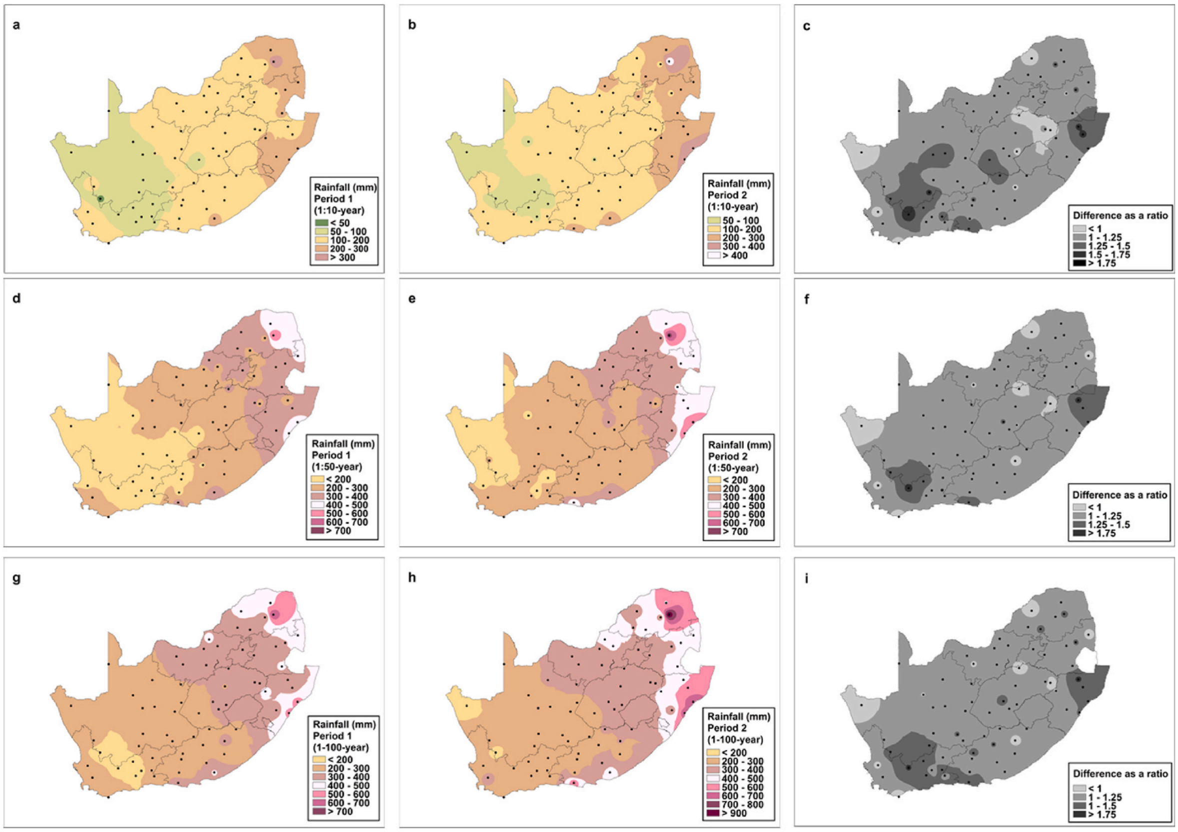

Fig. 6. Spatial distribution in 1:10- (a Period 1; b Period 2), 1:50- (d Period 1; e Period 2), and 1:100-year (g Period 1; h Period 2) return period values using the POT method. The second-period value was divided by the first to give the difference between the period as a ratio (1-10- c, 1-50- f and 1-100-year i). Inverse distance weighting was used as the interpolation method.

this region. Areas over the northern Free State into parts of KwaZulu-Natal and northern parts of the Eastern Cape also showed a decrease in RPVs for Period 2. It does not always follow that with a reduction in total mean rainfall amounts there is accompanying reductions in extremes rainfall events; rather that these extremes occur further apart. This analysis therefore provides improved confidence in the projections of the future rainfall climate of the region.

A similar spatial pattern emerged in the change in the estimated return periods for receiving *significant rainfall* (>50 mm), *heavy (* > 75 mm*) and very heavy (* > 115 mm*)* rainfall. There was a decrease in return periods over the eastern and western interiors stretching southwards to the southern coastal areas. Areas over the eastern parts had return periods for 50 mm of less than a year in Period 2, which was absent in Period 1. Changes in the lowering of return periods could also be seen for 75 mm and 115 mm. Previously the return periods over this region were three to four years which have now decreased to two to three years. This may appear to be a small change but the impact of receiving these large rainfall amounts more frequently poses challenges in terms of localized recovery from events that may have caused flooding, damage to crops and infrastructure.

The decrease in return periods from above to below 5 years for stations over the western interior for receiving significant rainfall (>50 mm) could have positive consequences for the Olifants and Gouritz catchments as significant rainfall in the area could lead to more water in collection storage facilities such as dams. There was however also an increase in the probability of "heavy rainfall" events (>75 mm) and "very heavy rainfall events (>115 mm) in Period 2 over this area which is of concern with regards to the increased possibility of localized flooding. The stations *Dwars in die Weg and Calitzdorp*, by way of example, had in Period 2 return period values of over 200 mm for 1:50-year and around 250 mm for 1-100-year, an increase of 55% and 25% respectively.

With most stations having an increase in the likelihood of extreme rainfall towards the end of the analysis period there is a need to relook how and where we build infrastructure in South Africa. If those in infrastructure planning and design based their work on stationary climate assumptions, they will underestimate the flood risk and this could lead to design failure which will have both social and economic effects. Old and poorly maintained infrastructure is particularly susceptible to heavy rain or flooding and if one considers increased rainfall values for even return periods of 1:10 years, there is a real threat that these structures could fail in the short term. There is thus a need to review engineering design standards (climatological extreme value analysis) and give thought to how to budget for adapting existing infrastructure to climate-change risks. There is also the need to investigate land use planning and where human settlements are located and into which areas cities and towns can expand, considering the change in the extreme rainfall climate. The loss of lives and infrastructure in the recent floods in KwaZulu-Natal was due to land and mudslides which begs the question should houses and other infrastructure have been built on this land in the first place (Hattingh, 2022). In summary the results of this paper suggest, as did Pohl et al. (2017), that extreme rainfall events are likely to become more intense and are to become a "feature of climate change over South Africa".

Contributions of authors

C M McBride developed the conceptualization and methodology of the study. Conducted background literature review, data analysis, interpreting, graphing and mapping of the results and wrote the first draft of the manuscript. C. Kruger assisted with the conceptualization, developing the methodology, statistical approach and analysis. Aided in

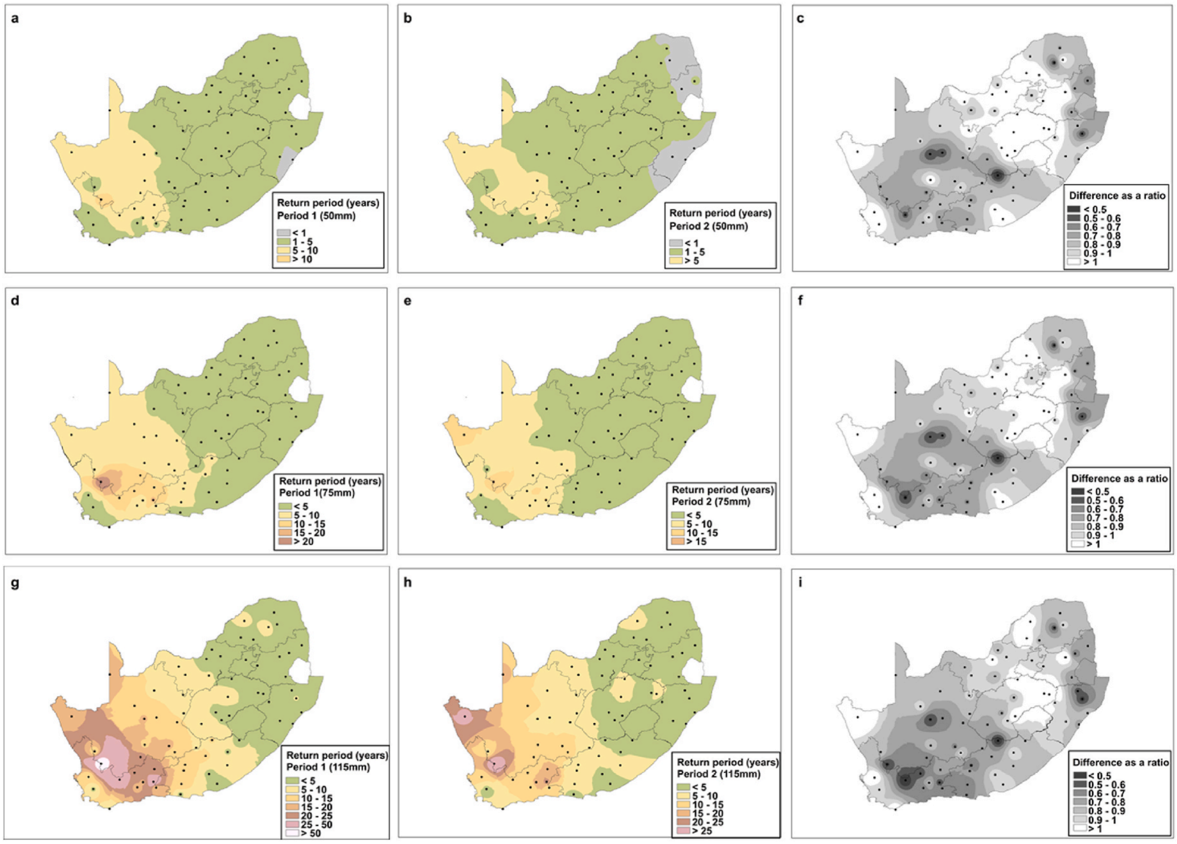

Fig. 7. Return periods for 50 mm, 75 mm and 115 mm for both periods using the POT distribution. 50 mm for period 1 (a), 50 mm for period 2 (b); difference as a ratio Period 2/Period 1 (c); 75 mm for period 1 (d), 75 mm for period 2 (e); difference as a ratio (f) and 115 mm for period 1 (g), 115 mm for period 2 (h); difference as a ratio (i). Grey areas in figures (a and b) represent areas where return periods are less than a year. Inverse distance weighting was used as the interpolation method.

the interpreting of results. Proofreading and editing of the manuscript. Co-supervisor of the PhD study. L Dyson Aided in the interpreting of results as well as proofreading and editing of the manuscript. Co-supervisor of the PhD study. All authors provided critical feedback and helped shape the research, analysis, and manuscript.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Charlotte McBride reports financial support was provided by Government of Flanders.

Data availability

Data will be made available on request.

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