Water SA 50(4) 330–344 / Oct 2024
https://doi.org/10.17159/wsa/2024.v50.i4.4111

Forecasting extreme hourly rainfall in South Africa for disaster risk reduction: thresholds and return periods

Jan H Vermeulen[1,2], David W Hedding[2] and Nthabiseng Letsatsi[3]

[1]Disaster Risk Reduction, South African Weather Service, Centurion, South Africa
[2]Department of Geography, University of South Africa, Johannesburg 1710, South Africa
[3]Climate Service, South African Weather Service, Centurion, South Africa

Highest and percentile values determined for daily, hourly and 5-min rainfall data (July 1994 to June 2021) from 64 automatic weather stations across South Africa were used to define extreme hourly and 5-min rainfall intensity. Internationally, 99.9th and 99.99th percentiles are typically considered as thresholds for hourly and sub-hourly extreme rainfall when forecasting for disaster risk reduction assessments. In South Africa (SA), the average of the 99.9th percentile for hourly rainfall values is 29.9 mm/h. This represents a good indicator of extreme hourly rainfall in SA and is a useful threshold for forecasting flash floods. The average highest of the hourly rainfalls for SA, 53.9 mm/h, should be a good indicator of more extreme hourly rainfalls for the country. The average of the 99.99th percentile for 5-min rainfall values is 12.8 mm/5 min, which equates to 2.6 mm/min. Significantly, the 5-min rainfall data is used to establish South African categories based on rainfall intensity and total rainfall, whereby an event can be classified as a cloudburst, downpour or shower. Using the newly established local categories, the severe thunderstorm of 4 April 2000 at Hoedspruit that produced 132.2 mm in 25 min from an intensifying upper air trough system was classified as a cloudburst. Interestingly, the 66.2 mm recorded in 5 min during this event makes it the world record holder for all-time highest 5-min rainfall, passing the previous world 5-min rainfall record of 63.0 mm in 5 min recorded at Porto Bello, Panama, on 29 November 1911. Return periods of expected maximum daily, hourly and 5-min rainfall, based on yearly highest values, were also calculated for South Africa. This study presents expected maximums for 5-min rainfall in return periods of 10, 25, 50 and 100 years, a first for South Africa, which can inform strategies for disaster risk reduction.

CORRESPONDENCE
Jan H Vermeulen

EMAIL
janhverm@yahoo.co.uk

DATES
Received: 8 December 2023
Accepted: 15 October 2024

KEYWORDS
rainfall
hourly rainfalls
rainfall intensity
return periods
cloudburst
South Africa

INTRODUCTION

Extreme very short-term or hourly rainfall events mostly cause damage to infrastructure, property, the loss of livestock and even the loss of lives from the resulting flash floods and mass wasting (Wu and Lin, 2017; Thayyen et al., 2013; Zeng and Wang, 2022; Woolley et al., 1946). Extreme rainfall events are categorised in decreasing magnitude from cloudbursts to downpours to showers. Woolley et al. (1946, p. ii) introduced the term 'cloudburst' as "...a torrential downpour of rain which by its spottiness and relatively high intensity suggests the bursting and discharge of the whole cloud at once". Although, most of the events studied by Woolley et al. (1946) are now considered as downpours, this study led to the recognition that such extreme rainfall events, together with specific hydrological conditions, can lead to flash floods (Doswell et al., 1996; Knös et al., 2022). For example, in South Africa (SA), a downpour from a severe thunderstorm at Linksfield, Johannesburg, on 9 November 2016 caused extensive damage to roads and hundreds of vehicles with the tragic loss of 7 lives (SAWS, 2017). The City of Johannesburg Metropolitan Municipality reports that this event also severely impacted 862 people from 373 households in the Setswetla informal settlement, next to the Jukskei River and downstream from Linksfield (Mvulane, 2020). Measured at the OR Tambo International Airport (ORTIA), which is 11 km to the east of the Linksfield disruptive rainfall event, the downpour produced 83 mm in the preceding hour ending at 18:10, with the highest 5-min rainfall amount of 17.2 mm recorded at 17:35.

The Glossary of Meteorology of the American Meteorological Society (AMS, 2015) uses a threshold of 100 mm/h rainfall intensity to identify a cloudburst event. Importantly, this definition is based on the rainfall total for the period of 1 hour. Very few rainfall events in SA exceed the threshold set by the AMS but some local events nevertheless cause significant amounts of damage, which makes it difficult to implement disaster risk reduction (DRR) strategies. Thus, the aim of this study was to define local rainfall intensity categories and to calculate percentiles and return periods of daily, hourly and 5-min rainfall storms to forecast them more accurately in the context of DRR for SA. The 99.9th and 99.99th percentiles are proposed as thresholds for forecasting extreme hourly and 5-min rainfall, respectively, for local municipalities, provinces and SA. In addition, the study addresses extreme rainfall events in SA in relation to current predictions for regional climate change, which suggest that extreme events will increase in both frequency and intensity (Seneviratne et al., 2021; Lehman et al., 2015).

DATA AND METHODS

In SA, the measurement of 5-min rainfall intervals became widespread by the South African Weather Service (SAWS) from 1994, as autographic gauges were replaced with electronic gauges. Currently, SAWS have 246 automatic weather stations (AWS) and 170 automatic rainfall stations (ARS) across the country. The Campbell-Scientific CR1000X data logger of the AWS is connected to a 0.2 mm

resolution TB4MM tipping bucket gauge made in the USA that has the following specifications (Campbell Scientific Inc., 2024):

- Measurement range: Max. rainfall intensity = 700 mm/h (58.3 mm/5 min)
- Accuracy: ± 2% inaccurate at 250 mm/h (20.8 mm/5 min) and ± 3% inaccurate at 500 mm/h (41.7 mm/5 min)

In other words, the 5-min rainfall of 66.2 mm measured at 23:20 on 4 April 2000 at Hoedspruit, Limpopo (see Table A2, Appendix) could have been anything between 64.2 and 68.2 mm using a 3% inaccuracy. This illustrates the uncertainties in the measurement of extreme or highest 5-min rainfall events.

For this study, recorded 5-min, hourly and daily rainfall data from AWSs (see Table A1, Appendix) were quality controlled to find those stations with ≥ 21 years continuous data. Since weather forecasting in SAWS is done provincially by 5 regional offices (ROs); the combining of the stations was done provincially and not according to climatic regions. In addition, to obtain a good spatial representation across SA, a weighted approach based on the area of the provinces was adopted. Based on these criteria, 64 AWSs were selected across SA with the following numbers per province: Northern Cape (NC) – 15, Eastern Cape (EC) – 8, Free State (FS) – 7, Western Cape (WC) – 7, Limpopo (LP) – 7, North West (NW) – 7, KwaZulu-Natal (KZN) – 6, Mpumalanga (MP) – 5 and Gauteng (GP) – 2 (Table 1). The provinces of Mpumalanga and Gauteng, the two smallest provinces and conveniently co-located, are combined for averaging purposes (Fig. 1). Combining the provinces of Mpumalanga and Gauteng as a spatial unit facilitates the comparison of thresholds with the other provinces, because the average of just two stations for Gauteng does not compare well with the approximate average of seven stations for the other provinces. The combined spatial unit termed 'MG' places it in the same size category as the other provinces, apart from the Northern Cape, which covers approximately 30% of SA.

The 90th, 99th, 99.9th and 99.99th percentiles and highest rainfall values for each of the 64 selected stations from 1 July 1994 to 30 June 2021 were determined for the daily, hourly and 5-min datasets as follows: The rainfall datasets were sorted in descending order to link the date and time with the rainfall event. Highest daily, hourly and 5-min rainfalls were then checked for consistency, and faulty records were removed for each station. The highest values as well as 90th, 99th, 99.9th and 99.99th percentiles for the

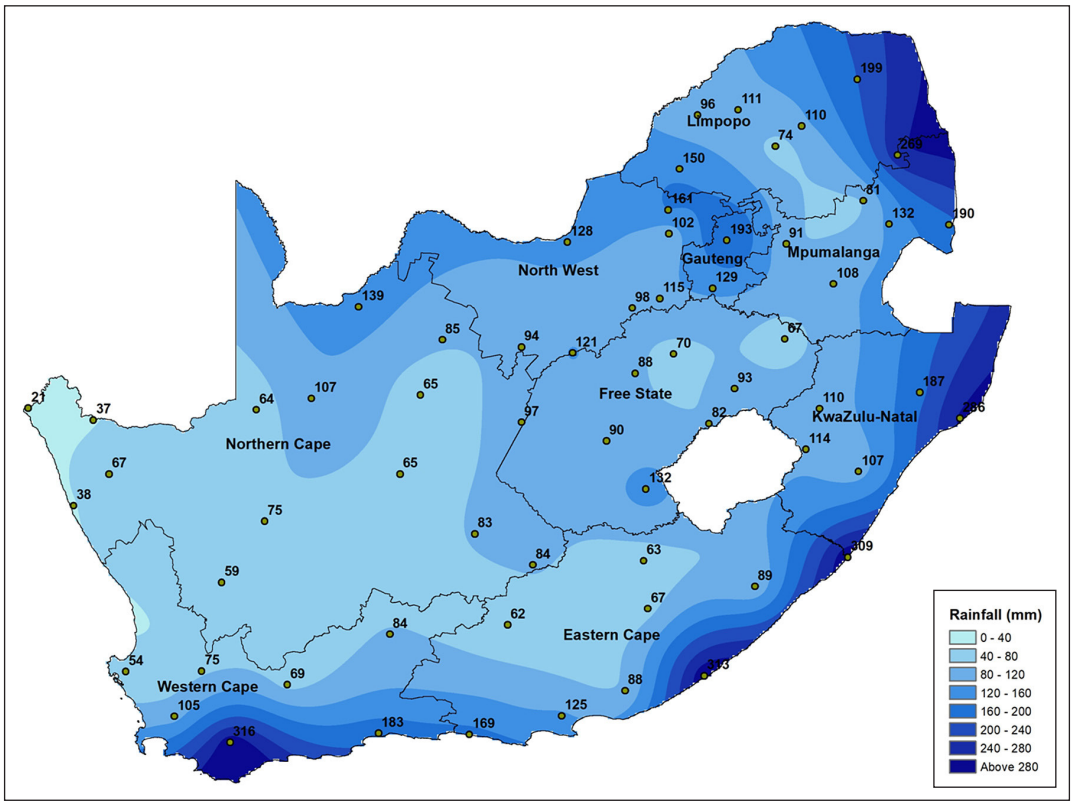

Figure 1. Highest daily rainfall amounts (mm) for SA

Table 1. Averages of the highest (mm) and percentile (mm) rainfall amounts for the 9 SA provinces for daily, hourly and 5-min rainfall

Province	Number of stations	Daily highest	Percentiles			Hourly highest	Percentiles			5-min highest	Percentiles			
			90	99	99.9		90	99	99.9		90	99	99.9	99.99
Northern Cape	15	72.3	12.8	35.0		42.1	3.4	11.8	24.2	12.5	0.8	3.1	6.7	
Eastern Cape	8	121.9	15.4	45.1	81.8	54.4	3.1	10.4	22.6	15.8	0.7	2.6	6.2	11.3
Free State	7	89.0	17.7	44.2	70.5	50.2	4.1	13.4	28.6	14.4	0.9	3.4	7.5	12.1
Western Cape	7	126.7	14.2	40.4	84.2	40.2	2.9	9.0	20.7	11.3	0.6	2.2	5.1	8.5
Limpopo	7	144.0	21.0	58.2	129.4	66.2	4.9	19.3	41.2	22.0	1.1	4.5	8.7	18.8
North-West	7	116.9	19.1	51.5	94.4	59.8	4.8	17.1	34.8	17.2	1.1	4.2	8.3	13.1
KwaZulu-Natal	6	185.3	20.2	61.7	120.0	64.1	3.6	15.3	38.1	17.4	0.8	3.7	8.2	13.0
Mpumalanga & Gauteng	7	131.9	19.8	54.1	108.6	69.5	4.6	18.2	38.0	16.6	1.0	4.5	8.9	14.3
Total stations	64													
Weighted average		116.1	16.9	46.8		53.9	3.9	13.9	29.9	15.5	0.9	3.5	7.3	13.0

64 stations were grouped by province and for MG (see Table A2, Appendix). The stations presented in Table 2 exclude the station at Rustenburg because its 5-min data were missing for its highest hourly rainfall storm. Table 2 summarises the maximum 5-min accumulated rainfall over an hour (M) for 63 stations and includes the following variables: date and time, M, highest 5-min rain rate, cloudburst classification, downpour minutes, daily rainfall total and percentage rainfall contributions of (i) hourly to daily, (ii) 5-min to hourly and (iii) 5-min to daily.

The American Meteorological Society's Glossary of Meteorology (AMS, 2015) uses a threshold of 100 mm/h rainfall or 8.33 mm/5 min rainfall intensity to identify a cloudburst. For this study, if the highest 5-min rainfall is less than or equal to 8.33 mm, it is regarded as a shower and when the highest 5-min rainfall is greater than 8.33 mm but is less than or equal to 25.0 mm, it is considered a downpour. When the highest 5-min rainfall is greater than 25.0 mm, it is considered a SA-cloudburst. Downpour minutes of a storm are the period for which the rainfall exceeds the downpour rainfall rate (8.33 mm/5 min). In addition, the expected maximum rainfall amounts in return periods of 10, 25, 50 and 100 years for 5-min, hourly and daily rainfalls were calculated based on annual maximums from 1995 to 2021 for the 64 stations (Table A3, Appendix). The Fisher-Tippett Type I statistical or Gumbel distribution for extreme values was used following similar short-duration rainfall analysis studies (see WB, 1983; Reich, 1961; Gumbel, 1967). During the quality control process, the years 2000 and 2010 were removed for Komatidraai's return period calculations because of missing data. Estimates for parameters of the Gumbel distribution are calculated using the method of moments approach (Kruger, 2022). The formulae use the average (x) and population standard deviation (s) of the rainfall extremes (r) for each of the daily, hourly and 5-min datasets for each station. The cumulative density function (Gumbel) is:

$$F(r) = \frac{1}{e^{-\frac{r}{b}} \cdot e^{\frac{z}{b}}} \text{ with the dispersion}$$

$$b = (\tfrac{s}{\pi})\sqrt{6} \text{ and mode } z = x - b(0.57721)$$

The Gumbel function F when calculated with an Excel spreadsheet gives the return period in years for rainfall in mm. The cumulative density function can be written such that estimated extreme rainfall (r) is calculated for a given return period (F), namely: $r(F) = z - b\ln(\frac{1}{F})$. The return periods presented in Table A3 (Appendix) are the first published for 5-min rainfall observations in SA.

RESULTS

The discussion of the highest rainfall and percentile values presented in Table 1 follows for daily, hourly and 5-min rainfall and the investigation of rainfall forecasting thresholds.

Daily data

Normal annual rainfall across SA varies from below 200 mm in the west to above 1 000 mm along the east coast (Kruger, 2007). This increasing trend in rainfall amount and intensity from west to east is confirmed by the trend in the average highest and average 99th percentile of daily rainfall amounts for provinces presented in Table 1. The weighted average for the 99th percentile of daily rainfall is 46.8 mm which is close to the 50 mm criterion that is conventionally used to issue a warning for disruptive rainfall in SA, although, the 50 mm threshold for heavy or extreme daily rainfall is an over-estimation for the Cape provinces (Northern, Western and Eastern) and the Free State, but an under-estimation for the remaining provinces in SA. Nevertheless, the 50 mm or slightly lower 47 mm is a reasonable indicator of heavy or extreme daily rainfall for SA. The 99th percentile values for daily rainfall amounts (Table 1) indicate that more extreme rainfall events occur in the east and north-east of SA while less extreme rainfall events occur in the southern interior and western parts of the country (see Fig. 2). The average of the 99.9th percentile of daily rainfall totals for SA is 92.6 mm. It is important to note that the stations at Vioolsdrif and Augrabies Falls in the NC did not receive enough rainfall to calculate the 99.9th percentile of daily rainfall for these stations (see Table A2, Appendix) and were thus

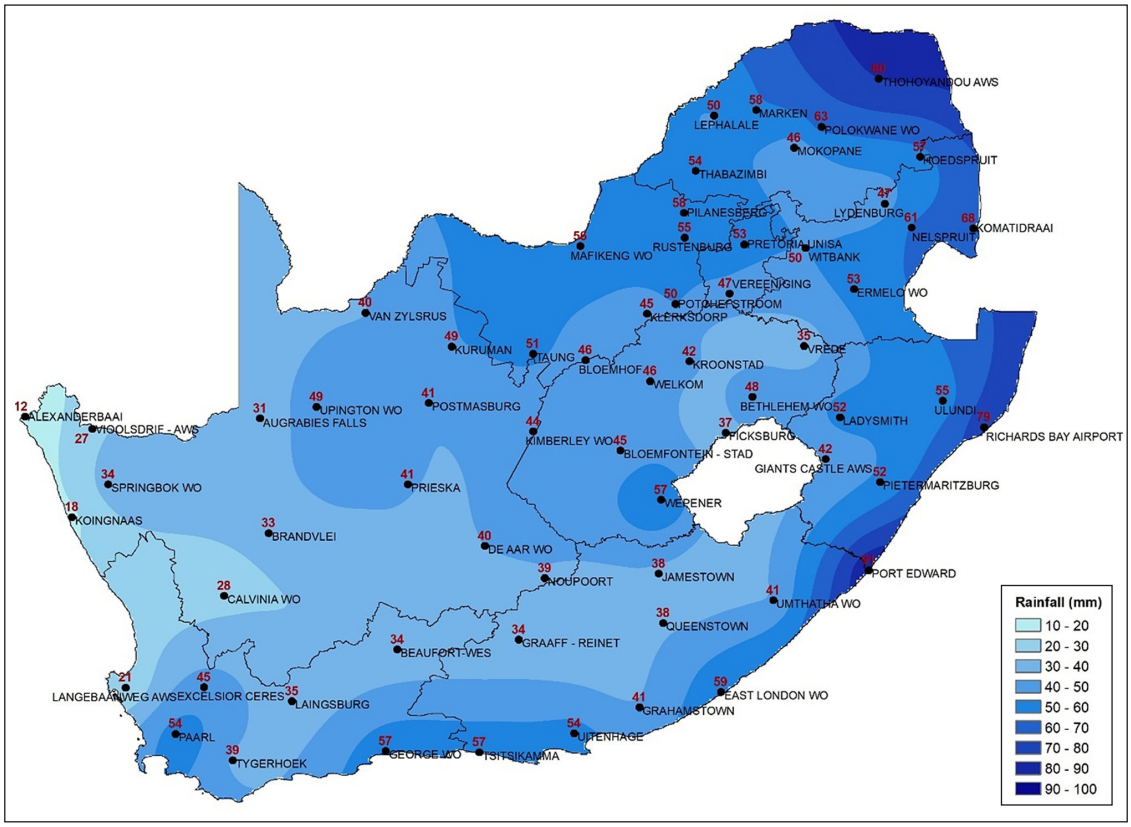

Figure 2. Daily rainfall amounts (mm) for South Africa: 99th percentile values

Table 2. The date and time (hour:min) of maximum 5-min accumulated hourly rainfall (*M*), clock hourly rainfall (*H*), highest 5-min rainfall (*F*), classification (class), downpour minutes (min), daily rainfall (*D*), percentage (*P*) contributions (*C*) of *M* to *D* (PCM2D), –F to M (PCF2M) and –F to D (PCF2D) for 63 stations and sorted largest to smallest for *M*. The differently dated storms are indicated in bold and the *M* and *H* are equal for the four underlined storms.

Stations	Date & hour:min	*M* (mm)	*H* (mm)	*F* (mm)	Class	Min (min)	*D* (mm)	PCM2D (%)	PCF2M (%)	PCF2D (%)
Hoedspruit	2000/04/04 23:40	157.8	132.2	66.2	Cloudburst	50	193.2	81.7	42.0	34.3
Pretoria	1996/01/19 1:20	133.8	102.2	13.4	Downpour	110	193.4	69.2	10.0	6.9
Port Edward	**1997/01/03 22:25**	115.0	77.2	13.4	Downpour	75	308.8	37.2	11.7	4.3
Bloemhof	2007/12/08 9:45	101.2	97.2	22.0	Downpour	60	120.6	83.9	21.7	18.2
Marken	1996/03/04 3:10	94.8	75.0	15.8	Downpour	50	107.4	88.3	16.7	14.7
East London	2002/08/16 0:45	93.2	84.0	11.8	Downpour	40	312.8	29.8	12.7	3.8
Ulundi	2011/01/02 21:35	91.8	62.8	12.6	Downpour	40	186.8	49.1	13.7	6.7
Komatidraai	2002/04/10 23:25	91.4	75.6	15.2	Downpour	50	100.2	91.2	16.6	15.2
Grahamstown	2014/11/23 22:55	83.4	80.6	11.4	Downpour	45	87.6	95.2	13.7	13.0
Mafikeng	2003/01/05 22:35	83.2	61.2	17.4	Downpour	45	87.0	95.6	20.9	20.0
Wepener	2021/02/14 20:10	81.6	79.4	12.4	Downpour	45	90.6	90.1	15.2	13.7
Vereeniging	1995/01/27 17:25	78.4	63.8	19.0	Downpour	40	83.2	94.2	24.2	22.8
Ermelo	2017/04/10 18:00	78.2	78.2	12.4	Downpour	40	89.8	87.1	15.9	13.8
Noupoort	1997/03/13 18:05	77.8	77.4	19.8	Downpour	45	83.6	93.1	25.4	23.7
Tsitsikamma	2005/02/20 0:30	76.6	54.8	11.6	Downpour	30	103.4	74.1	15.1	11.2
Pilanesberg	2014/03/13 17:50	74.6	72.8	11.2	Downpour	35	160.6	46.5	15.0	7.0
Polokwane	1996/12/09 16:45	74.4	59.4	13.0	Downpour	40	85.0	87.5	17.5	15.3
Uitenhage	2010/03/26 18:25	74.4	56.8	20.0	Downpour	40	86.0	86.5	26.9	23.3
Tygerhoek	2021/05/05 17:05	69.8	69.2	8.4	Downpour	5	315.8	22.1	12.0	2.7
Thabazimbi	2006/02/27 14:45	69.6	57.4	11.0	Downpour	25	149.6	46.5	15.8	7.4
Pietermaritzburg	**2004/02/21 16:45**	68.6	53.6	9.4	Downpour	5	84.0	81.7	13.7	11.2
Richards Bay	2005/01/03 20:55	67.6	67.0	12.4	Downpour	35	73.4	92.1	18.3	16.9
Nelspruit	**2000/04/04 17:40**	67.6	38.0	11.4	Downpour	20	96.0	70.4	16.9	11.9
Kuruman	2001/11/12 18:45	63.8	47.8	30.2	Cloudburst	35	66.4	96.1	47.3	45.5
Taung	**2000/12/10 16:25**	63.2	37.4	10.2	Downpour	10	74.2	85.2	16.1	13.7
Witbank	**1999/01/21 9:15**	63.0	48.8	10.0	Downpour	5	82.2	76.6	15.9	12.2
Potchefstroom	2013/10/28 15:20	62.8	51.8	16.2	Downpour	30	66.0	95.2	25.8	24.5
De Aar	2018/10/13 18:20	62.2	54.8	13.6	Downpour	25	78.0	79.7	21.9	17.4
Upington	**2011/03/16 1:40**	62.0	40.0	8.6	Downpour	10	107.0	57.9	13.9	8.0
Excelsior Ceres	2007/04/24 6:20	62.0	39.8	22.0	Downpour	30	69.6	89.1	35.5	31.6
Klerksdorp	**2006/11/13 12:40**	61.2	42.4	8.0	Shower	0	98.4	62.2	13.1	8.1
Beaufort-Wes	**2007/04/01 20:25**	60.6	47.0	8.6	Downpour	5	62.8	96.5	14.2	13.7
Lephalale	**1997/01/15 22:35**	59.6	32.2	8.8	Downpour	5	61.6	96.8	14.8	14.3
Ladysmith	**2012/12/10 18:15**	58.4	49.6	9.8	Downpour	15	86.6	67.4	16.8	11.3
Giants Castle	2016/01/13 17:00	58.2	58.2	15.2	Downpour	30	66.6	87.4	26.1	22.8
Calvinia	2017/04/08 19:10	57.8	57.2	18.4	Downpour	30	57.8	100.0	31.8	31.8
Kroonstad	2006/02/19 14:00	57.8	57.8	10.6	Downpour	30	58.6	98.6	18.3	18.1
Kimberley	2015/02/24 16:55	57.8	54.0	8.8	Downpour	10	75.2	76.9	15.2	11.7
Lydenburg	**2015/01/28 14:45**	55.8	43.2	6.6	Shower	0	60.2	92.7	11.8	11.0
Welkom	2021/02/06 23:05	54.0	53.6	7.8	Shower	0	60.4	89.4	14.4	12.9
Vrede	**2007/01/30 16:35**	53.4	31.0	15.0	Downpour	15	67.2	79.5	28.1	22.3
Bethlehem	2004/02/13 2:50	52.6	43.8	9.0	Downpour	15	68.2	77.1	17.1	13.2
Thohoyandou	**2021/01/06 21:30**	52.4	33.4	7.6	Shower	0	72.8	72.0	14.5	10.4
Van Zylsrus	2017/02/19 21:05	51.2	50.6	7.2	Shower	0	138.6	36.9	14.1	5.2
Brandvlei	2018/02/14 15:00	48.0	48.0	11.6	Downpour	20	51.0	94.1	24.2	22.7
Prieska	**1998/02/16 20:45**	47.4	31.2	10.8	Downpour	20	61.6	76.9	22.8	17.5
Jamestown	2000/11/28 14:45	46.6	46.2	12.4	Downpour	15	53.0	87.9	26.6	23.4
Graaff – Reinet	2016/12/14 19:20	46.6	39.8	7.6	Shower	0	47.0	99.1	16.3	16.2
Postmasburg	2000/02/21 19:55	45.6	42.6	8.2	Shower	0	57.6	79.2	18.0	14.2
Mokopane	1996/03/04 17:10	45.4	44.0	13.2	Downpour	15	74.0	61.4	29.1	17.8
Bloemfontein	**1996/01/24 18:35**	45.0	29.6	11.0	Downpour	25	64.4	69.9	24.4	17.1
Springbok	1998/03/27 17:45	44.2	42.4	8.8	Downpour	5	67.0	66.0	19.9	13.1
George	2006/08/01 16:55	42.6	42.0	5.4	Shower	0	174.6	24.4	12.7	3.1
Ficksburg	**2013/12/02 19:35**	40.4	31.8	5.0	Shower	0	60.6	66.7	12.4	8.3
Umthatha	2012/01/23 17:55	39.6	37.6	7.0	Shower	0	51.0	77.6	17.7	13.7
Queenstown	**2006/01/06 17:50**	38.4	31.4	6.2	Shower	0	47.2	81.4	16.1	13.1
Paarl	2004/06/14 9:40	34.4	30.6	6.8	Shower	0	46.8	73.5	19.8	14.5
Augrabies Falls	**2012/12/19 17:20**	32.2	19.2	8.8	Downpour	10	32.4	99.4	27.3	27.2
Laingsburg	**2009/04/23 14:10**	27.8	23.4	4.2	Shower	0	54.6	50.9	15.1	7.7
Langebaanweg	1999/06/18 13:10	20.0	19.6	8.4	Downpour	5	28.2	70.9	42.0	29.8
Vioolsdrif	**2008/03/06 20:10**	17.0	14.4	3.2	Shower	0	27.4	62.0	18.8	11.7
Koingnaas	**2003/08/24 3:20**	14.0	10.8	4.8	Shower	0	17.6	79.5	34.3	27.3
Alexanderbaai	**2011/05/05 2:45**	9.4	6.8	3.4	Shower	0	14.0	67.1	36.2	24.3
Averages		62.2	51.5	12.2		22.0	92.2	76.1	20.2	15.9

excluded from this calculation for SA. Fortunately, the highest recorded rainfall totals for storms at Vioolsdrif and Augrabies Falls are available (see Table A2, Appendix). These highest rainfall totals are regarded as extreme rainfall indicators.

Hourly data

The largest value for the average highest hourly rainfall of 69.5 mm for Mpumalanga and Gauteng (MG) demonstrates that these provinces experience the most convective rainfall (see Fig. 3). The 40.2 mm calculated for the Western Cape, representing the smallest average highest, demonstrates that it experiences the least convective and more stratiform rainfall (see Fig. 3). There is a 29.3 mm increase in average highest hourly rainfall from the south-west (WC) to north-east (MG) over SA, indicating the contrast between summer convective and winter stratiform rainfall. The average highest hourly rainfall of 53.9 mm for all provinces indicates that hourly rainfall greater than 53.9 mm should be considered an exceptional event, especially for drier provinces.

The weighted average for the 99th percentiles of the data is 13.9 mm/h, which is close to the criterion of ≥ 12.6 mm/h for a heavy rainfall rate or intensity used by WB (1982). A rainfall intensity between 2.5 and 12.5 mm/h is regarded as moderate and less than 2.5 mm/h is a slight rain intensity (WB, 1982). Figure 4 indicates the scarcity of heavy (≥ 12.6 mm/h) rainfall events over the western, southern and south-eastern parts of SA. The 29.9 mm/h value, which is the weighted average for the 99.9th percentile, is a useful indicator of extreme hourly rainfall intensity, but it is important to recognise the spatial variation between the provinces, i.e. 20.7 mm/h in the WC to 41.2 mm/h in LP. The 99.9th percentile values indicate that rainfall of above 30 mm/h occurs for most of the north-eastern part of SA, with below 30 mm/h typically occurring over most of the central, western and southern parts (Fig. 5).

Five-minute data

The value of 22.0 mm/5 min recorded in the LP is the largest average highest value and indicates that the LP experiences the most intense convective rainfall. Conversely, the WC is shown to experience the least intense rainfall with the smallest average highest value of only 11.3 mm/5 min, which again demonstrates that it experiences mostly stratiform rainfall. The weighted average of the highest values for all provinces is 15.5 mm/5 min. Figure 6 indicates a trend with the largest values in the northern and eastern provinces and the smallest in the southern and western provinces of SA. This same trend is observed for highest hourly rainfall values over SA (see Fig. 3 for comparison).

The 99.9th percentiles for the 5-min data indicate that 8.9 mm and 5.1 mm are the largest and smallest average highest values for MG and WC, respectively. The 99.9th percentiles of 5-min data that are > 8.0 mm occur in LP, NW, KZN and MG and are comparable to ≥ 8.33 mm/5 min, which is equivalent to the 100 mm/h definition of a cloudburst by the American Meteorological Society's Glossary of Meteorology (AMS, 2015). Thus, the rates of 8.0 mm/5 min or 96 mm/h are equivalent to the 1.6 mm/min threshold which was used to identify an extreme precipitation event over Southern China on 7 May 2017 (see Zeng et al., 2021). Figure 7 indicates that 5-min values > 8 mm occur over most of the central, northern and eastern parts of SA, with < 5 mm in places over the extreme western and southern parts of the country. This observation illustrates the scarceness of these intense events in the stratiform rainfall region of SA.

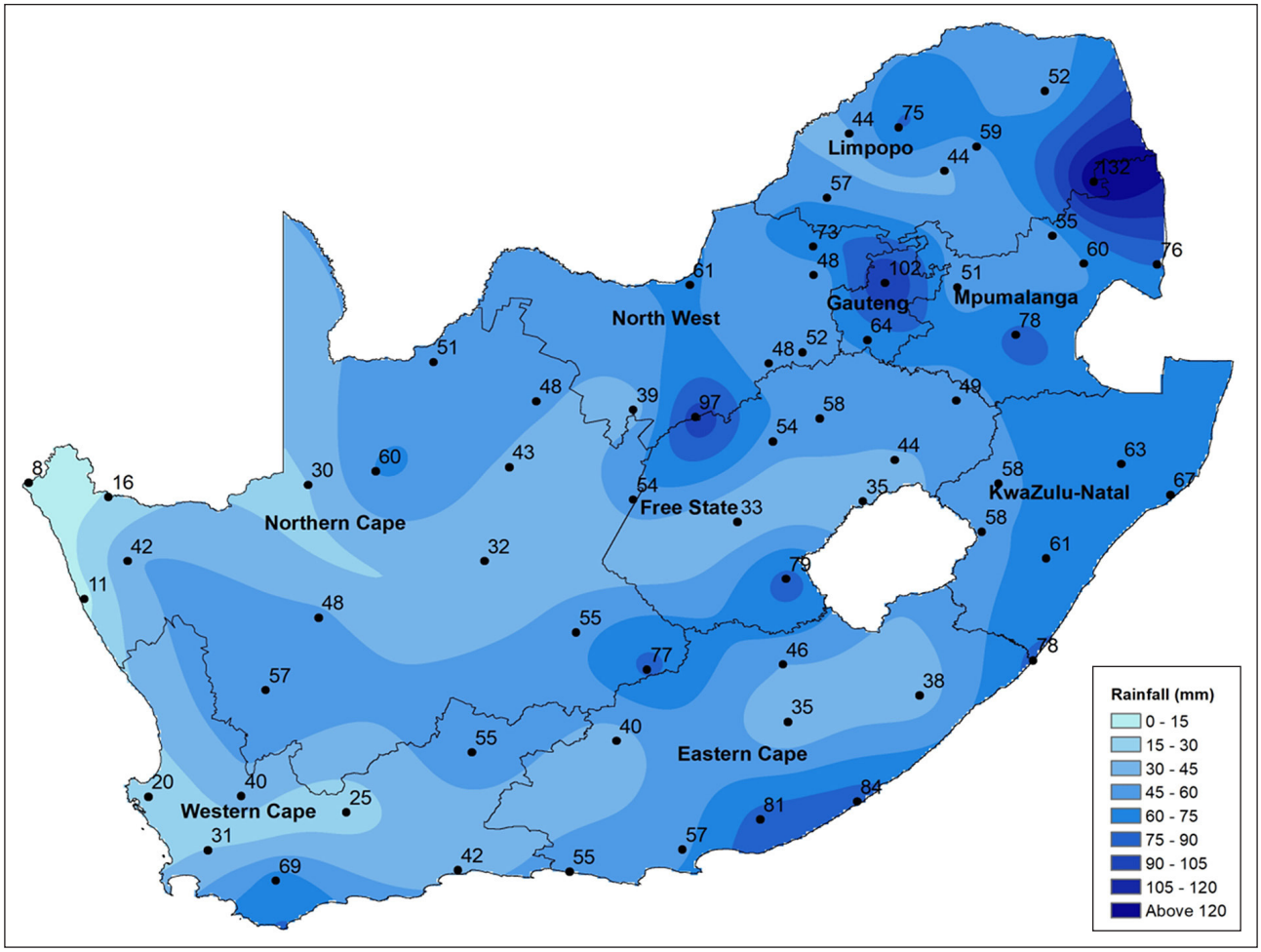

Figure 3. Highest hourly rainfall totals (mm) for SA

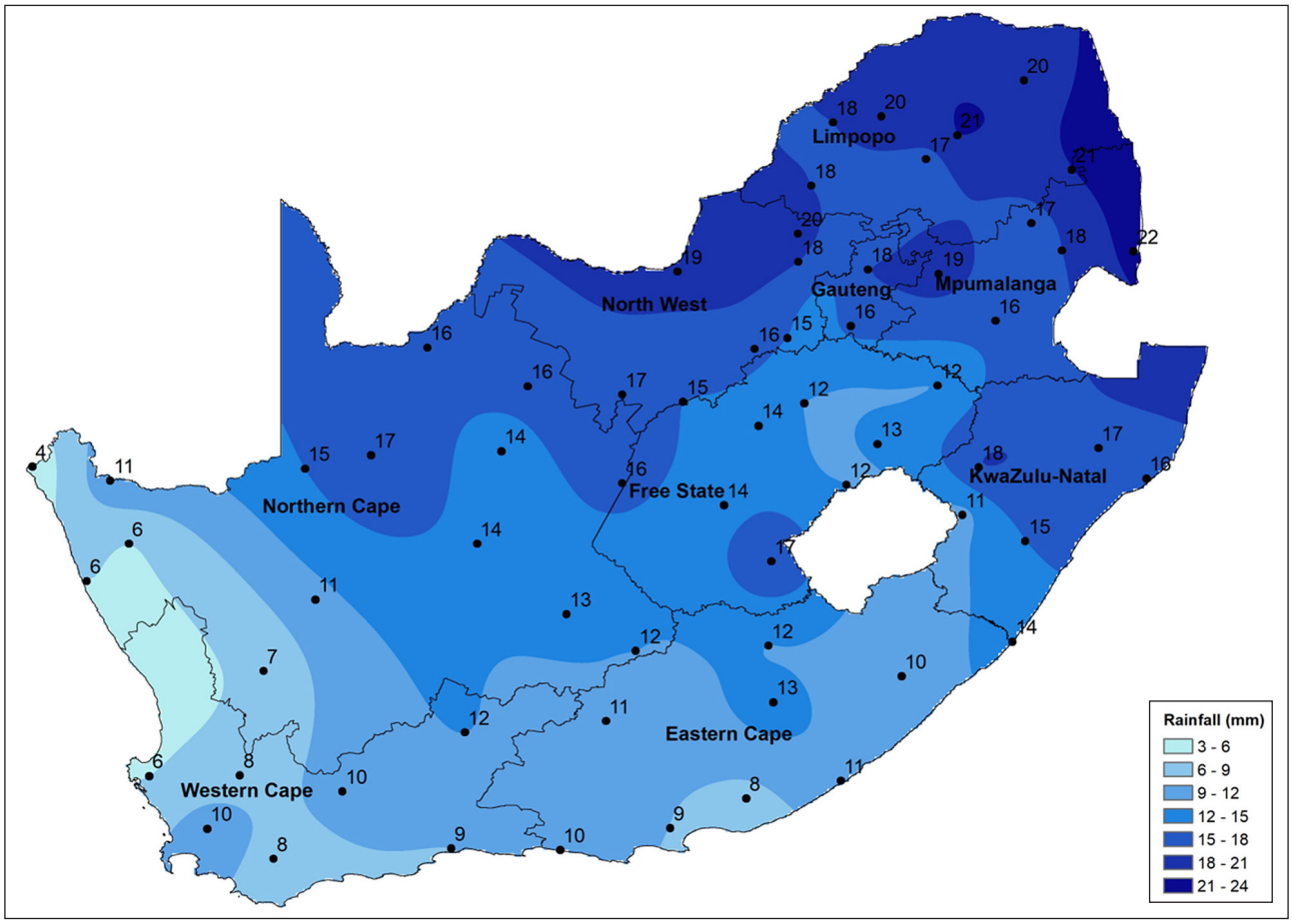

Figure 4. Hourly rainfall amounts (mm) for SA: 99th percentile values

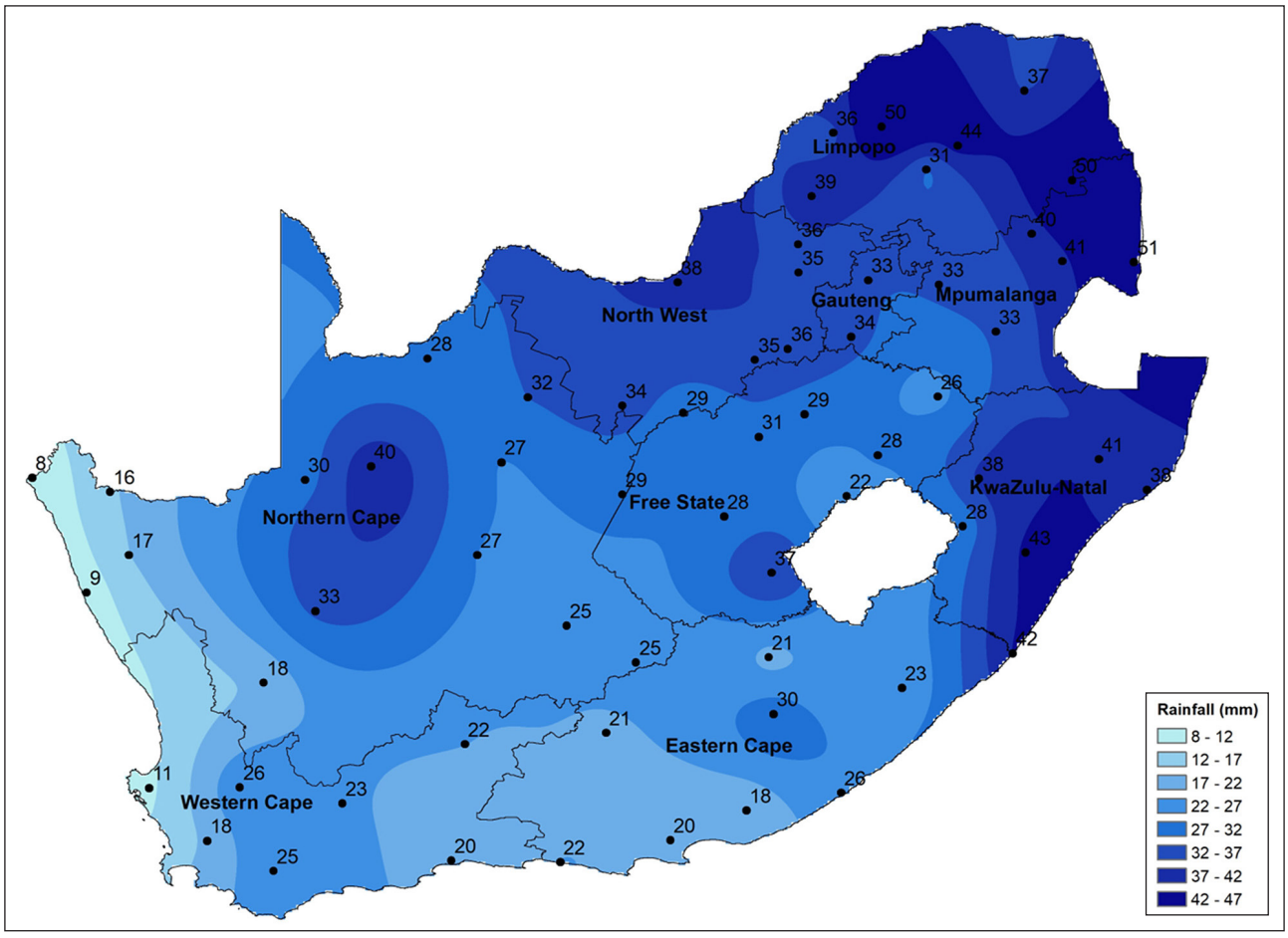

Figure 5. Hourly rainfall amounts (mm) for SA: 99.9th percentile values

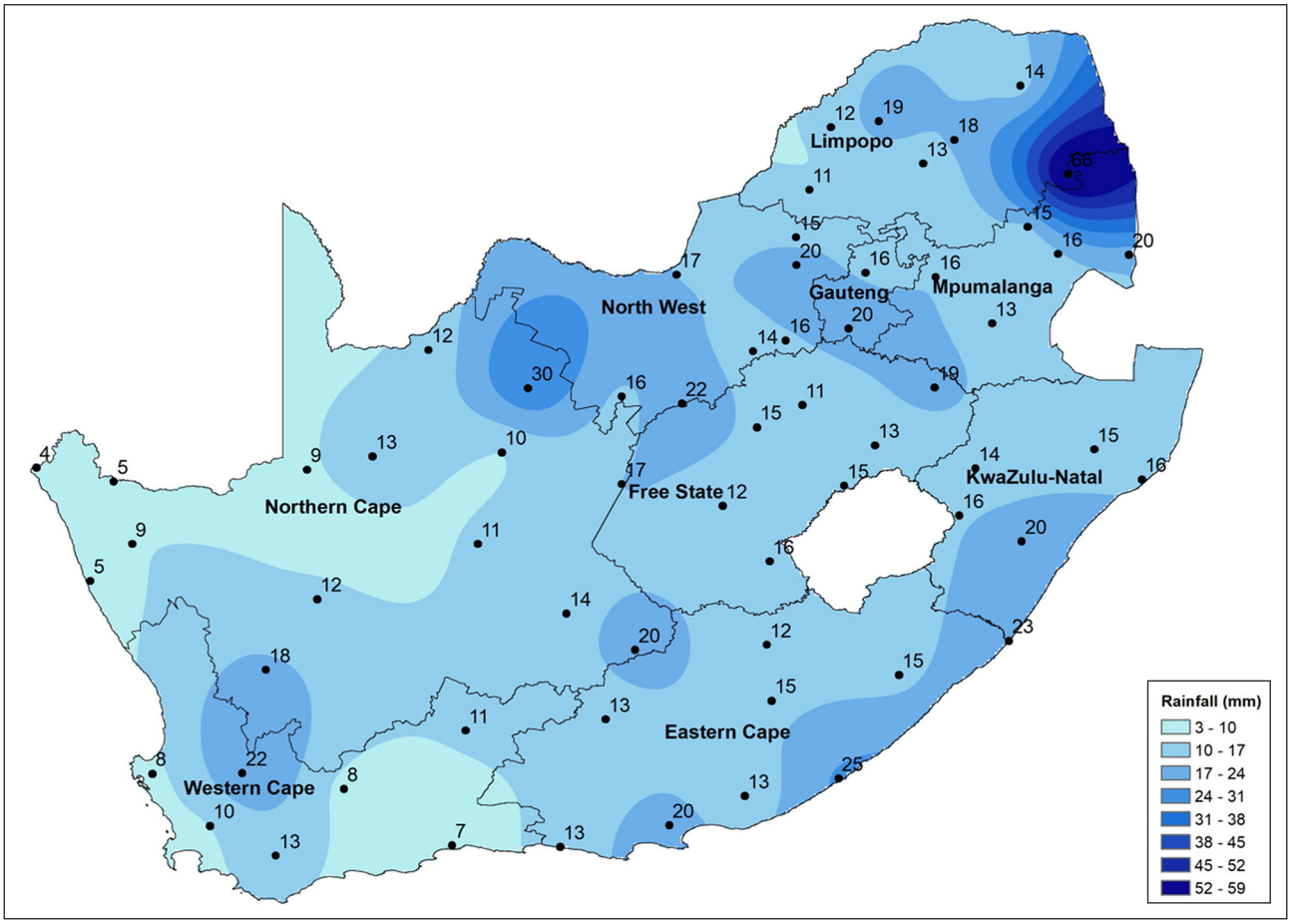

Figure 6. Highest 5-min rainfall amounts (mm) for SA

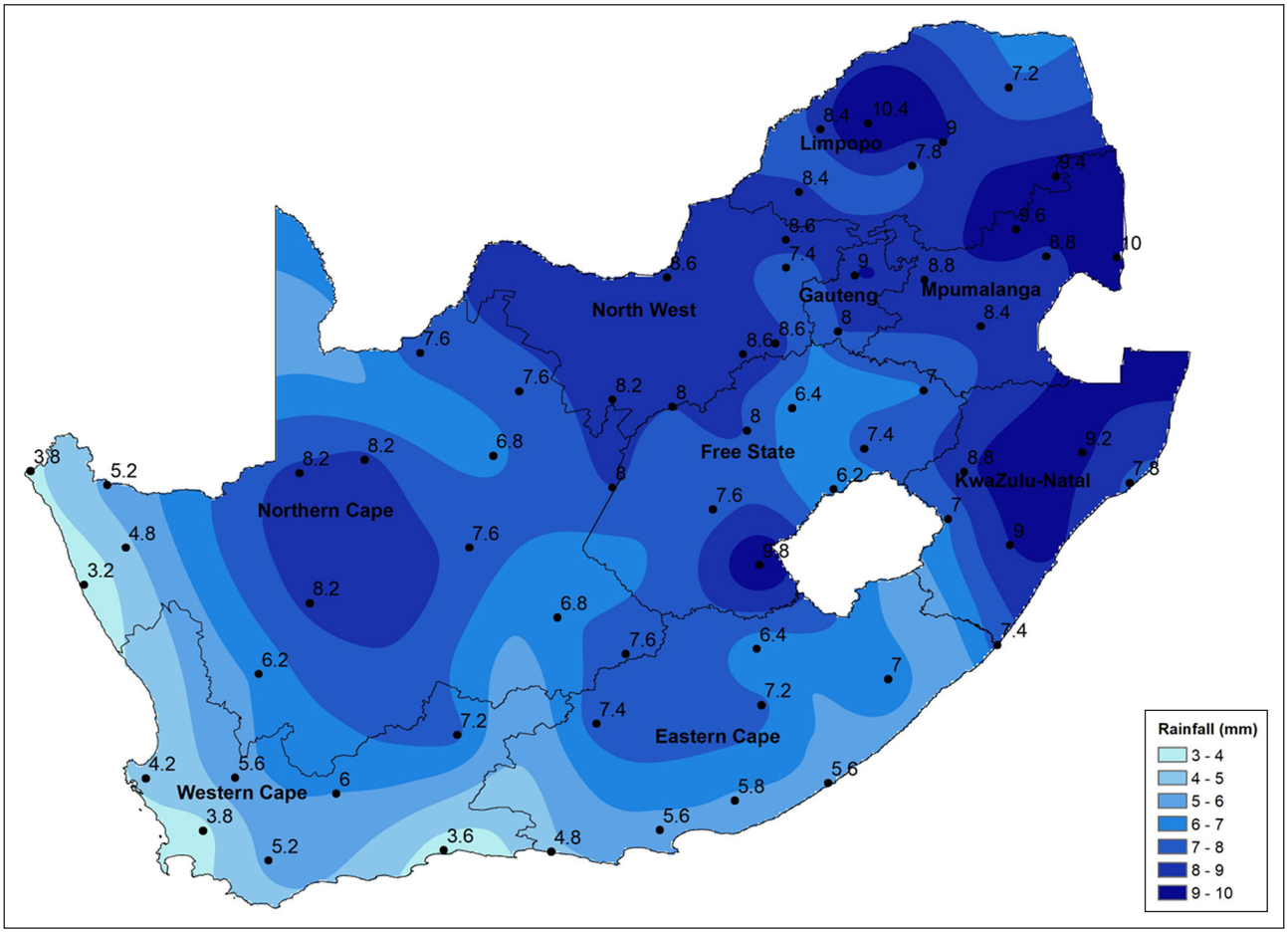

Figure 7. Five-minute rainfall amounts (mm) for SA: 99.9th percentile values

The 99.99th percentile values are an indicator of the most extreme or highest rainfall events. The calculated 18.8 and 8.5 mm represent the largest and smallest averages for the LP and WC provinces, respectively. The weighted average of 13.0 mm for the 99.99th percentiles is observed for all provinces, apart for the NC. The NC is not included in Table 1 because it has an average of only 12.1 mm for the 12 stations with sufficient rainfall data to calculate the 99.99th percentile. For instance, Alexander Bay, Vioolsdrif and Augrabies Falls, all bordering Namibia, have insufficient rainfall to calculate the 99.99th percentile for these locations. Thus, the average 99.99th percentile for rainfall over 5 min for the remaining 61 stations across SA is 12.8 mm, which is rounded up to 13 mm. The 99.99th percentiles' weighted average of 13.0 mm/5 min is equivalent to the extrapolated threshold of 2.6 mm/min for extreme precipitation presented by Zeng et al. (2021). The 99.99th percentile values that are ≥ 13.0 mm for LP, NW, KZN and MG provinces indicate that these provinces experience the most extreme 5-min rainfall events.

Comparison of *M* with clock hourly rainfalls and classification of *M*'s storms

For 34.9% of the 63 stations (see Table 2), the date of the maximum 5-min accumulated hourly rainfall (*M*) amount is different to the date of the highest hourly rainfall amount that is listed in Table A2 (Appendix). These 22 differently dated events or storms are indicated in bold in Table 2. In other words, 65.1% of the clock hourly events are also the *M* events for a station. The *M* value is on average 8.2 mm larger than the highest hourly rainfall for the 63 stations considered. The difference between the maximum accumulated and highest hourly rainfall totals varies from 0 to 36.8 mm. The 36.8 mm difference for Port Edward is for two different events, but it can be higher for an individual event; for example, the storm on 3 January 1997 at Port Edward had an hourly rainfall amount of 77.2 mm at 22:00, resulting in a difference of 37.8 mm. The *M* value is on average 10.8 mm larger than the highest hourly rainfall for each of the storm events for the 63 stations. The highest hourly rainfall for a station is only equal to *M* for 6.4% of the time, namely for the four underlined stations in Table 2. The highest hourly rainfall totals, dates and hours for the remaining 59 stations are shown in Table A2 (Appendix).

Table 2 shows that two storm events are classified as SA-cloudbursts, namely:

- The severe thunderstorm of 4 April 2000 at Hoedspruit that produced 132.2 mm in 25 min from an intense upper-air trough system (NOAA PSL, 2000). It follows from the cloudburst definition (> 25 mm/5 min) that the storm is a 25-min cloudburst because 132 > 125 mm over 25 min. The storm could also be regarded as a 50-min downpour of 157.8 mm. According to WMO-cloudburst definition (> 100 mm/h), this storm, as well as the Pretoria Unisa, Port Edward and Bloemhof storms, are classified as WMO-cloudbursts, although in the context of SA, the latter three events are classified as downpours because their highest 5-min rainfalls ≤ 25 mm (Table 2). The intense upper trough system that resulted in the Hoedspruit cloudburst also caused an *M* of 67.6 mm at Nelspruit 6 h earlier, from a thunderstorm (see Table 2). The Nelspruit 20-min downpour of 33.6 mm was confirmed by the Ermelo radar system.
- The severe thunderstorm of 12 November 2001 at Kuruman, NC, that produced 30.2 mm in 5 min, due to an upper air perturbation system (NOAA PSL, 2001), is the other event which can be considered a SA-cloudburst. The storm is a 5-min cloudburst because 30 > 25 mm, and a 35-min downpour of 62.0 mm that caused flooding in the town.

The maximum hourly rainfall amount of 133.8 mm recorded at the Unisa weather station in Pretoria overnight on 18 to 19 January 1996 is the largest storm classified as a downpour (see Table 2). This severe storm, which produced 185.8 mm in 110 min, caused serious flooding damage in Pretoria (SAWS, 1996). The storm was caused by a high-pressure system ridging to the south of SA with an associated upper air trough (DEAT, 1996). The afternoon radiosonde ascent at Irene, 15 km south of Pretoria, on 18 January 1996 indicated a precipitable water (PW) content of 27.4 mm. A PW > 25 mm means high energy air availability and downpours or cloudbursts can be expected. High energy air is moist warm air usually from a tropical origin and these conditions typically arise over SA in summer (Tyson, 1986). A map of the maximum 5-min accumulated hourly rainfall amounts (see Fig. 8)

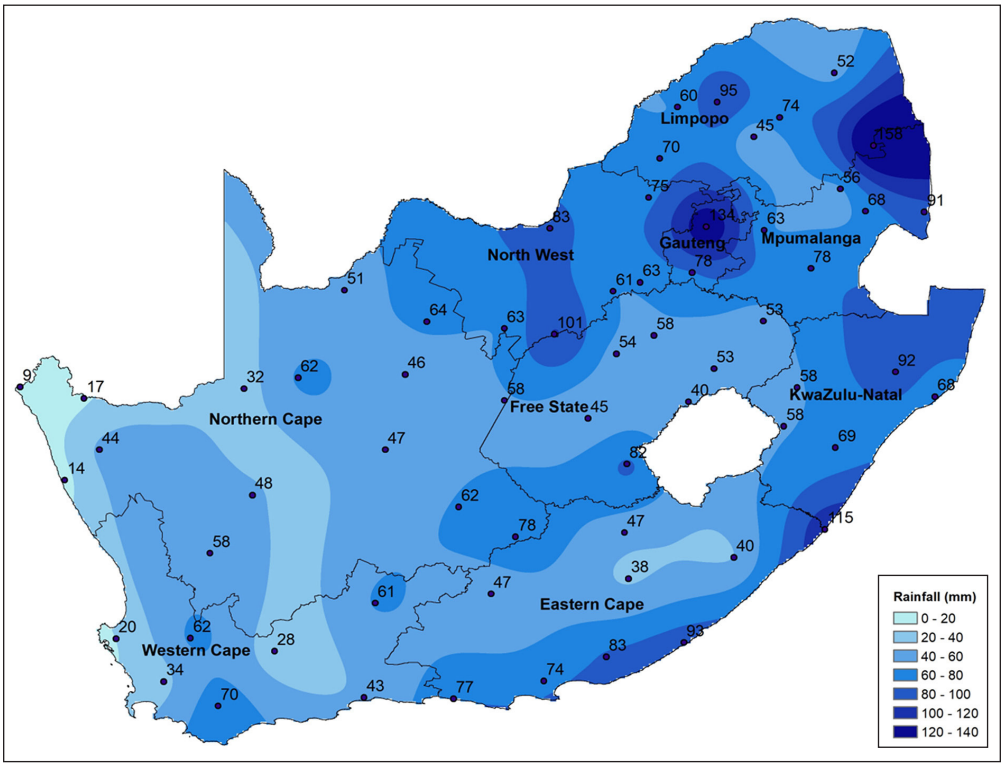

Figure 8. Maximum 5-min accumulated hourly rainfall amounts (mm) for SA

depicts downpours > 80 mm in places over the northern and eastern provinces of SA. The map further shows downpours with < 30 mm in places over the western and south-western parts of the country. Figure 8 compares well with the map of highest hourly rainfalls (see Fig. 3).

The Hoedspruit cloudburst of 66.2 mm in 5 min on 4 April 2000 is the all-time highest 5-min rainfall recorded until 30 June 2023 for SA. Associated with this event, the 10-, 15- and 30-min rainfall totals of 121.0, 128.8 and 132.2 mm, respectively, are also the all-time highest records for SA. Furthermore, the recorded 66.2 mm in 5 min is greater than the 63.0 mm recorded at Porto Bello, Panama, on 29 November 1911 – the current all-time global 5-min rainfall record according to literature (Burt, 2007; Cornthwaite, 1919). Although, the 66.2 mm recorded is less than the estimated 129.5 mm for the global maximum 5-min rainfall total given by a regression equation developed by Ramage (1995).

Return periods

Table A3 (Appendix) indicates that for GP, the expected maximum rainfall for a 10-year return period is 12.7 and 50.9 mm for 5-min and hourly rainfall events, respectively. These values compare well with the highest 5-min and hourly rainfalls of 11.0 and 50.6 mm, respectively, at Bolepi House in Erasmusrand, Tshwane, GP, that has a 15-year climate record (Vermeulen, 2022). Table A3 (Appendix) further indicates that every 100 years one can expect hourly rainfall storms for Pretoria (GP) and George (WC) that produce 79.6 and 39.6 mm, respectively. The more than double calculated value for Pretoria versus George illustrates the difference between the summer convective rainfall regime of the GP and the winter stratiform rainfall regime of the WC. The return periods calculated from the Gumbel distribution for the Hoedspruit and Kuruman SA-cloudbursts as well as for the Pretoria, Port Edward and Bloemhof downpours are presented in Table 3.

The SA-cloudbursts at Hoedspruit and Kuruman are 1-in-900- and 1-in-300-year events, respectively, based on their *F* rainfall amounts. Hoedspruit became a WMO-cloudburst in 10 min with its 121.0 mm for the highest 10-min rainfall total. Kuruman never became a WMO-cloudburst because its *M* is < 100 mm/h. However, the three downpours are all WMO-cloudbursts. The rarity of the Pretoria downpour lies in its hourly rain that is a 1-in-1 000-year event, while its highest 5-min rainfall is only a 1-in-14-year event. The downpours at Port Edward and Bloemhof are 1-in-200- and 1-in-600-year events, respectively, based on their *M* values. The average return periods for the two SA-cloudbursts based on 5-min and hourly data are 647 and 1 092 years, respectively. The average return periods for the three downpours based on 5-min and hourly data are 65 and 2 923 years, respectively. The hourly events are the rarest for both SA-cloudburst and downpour groups. The average return period of the 5-min events of the SA-cloudbursts is an order of magnitude larger than the value of the downpours. Thus, the rarity of a SA-cloudburst lies in its extremely high rainfall intensity, namely *F* > 25.0 mm. The average *F* of 48.2 mm for the two SA-cloudbursts is much larger than the 16.3 mm average *F* for the three downpours.

DISCUSSION

Currently, rainfall above 50 mm/day is regarded as the 99th percentile threshold to identify heavy or extreme daily rainfall in SA and the world (Goswami et al., 2010; Hitchens et al., 2012). However, the weighted average of the 99th percentile of values for daily rainfall across SA is 46.8 mm and is a more appropriate threshold for extreme daily rainfall in the South African context, although it must be noted that there is significant spatial variation of daily rainfall across SA. For example, the average of 99th percentile values for KZN is 61.7 mm/day, which is significantly greater than the suggested value of 46.8 mm/day to delimit extreme rainfall in SA. Consequently, the suggested extreme rainfall criteria for SA underestimates heavy rainfall in the eastern parts of South Africa such as KZN, and 62 mm would be a more appropriate criterion to classify extreme rainfall for this province. Similarly, the average of 35.0 mm/day for the 99th percentile of recorded values for the NC is considerably less than 46.8 mm/day. Therefore, rainfall from a storm in NC should only exceed 35 mm/day to be regarded as extreme. Consequently, regional statistics should be adopted to classify extreme rainfall events across SA to better prepare strategies for DRR.

Some countries, such as China, use the 99.9th percentile value of hourly rainfall as the threshold to identify extreme hourly rainfall (Luo et al., 2016). Even though there is spatial variation in the average of 99.9th percentile values for hourly rainfall across SA, from 20.7 mm in the WC to 41.2 mm in the LP, the average value of 29.9 mm/h (rounded to 30 mm/h) is an appropriate criterion for extreme hourly rainfall and a useful threshold for forecasting flash floods in SA. The calculated averages of the 99.9th percentile values and 99th percentile values for 5-min rainfall across SA are 7.3 mm and 3.5 mm, respectively. The spatial variation of average 99.9th percentile values ranges from 5.1 mm/5 min in the WC to 8.9 mm/5 min in the provinces of Mpumalanga and Gauteng. The average 99.99th percentile value for 5-min rainfall is 12.8 mm (rounded to 13 mm/5 min). The average values of the 99.99th percentile range from 8.5 mm in the WC to 18.8 mm in LP. Thus, if the average rate of 13 mm/5 min of rainfall is sustained over an hour, it would result in a rainfall event of 156 mm/h. The maximum hourly rainfall amount of 133.8 mm recorded at Pretoria (see Table 2) is the largest downpour and has a highest 5-min rainfall rate of 13.4 mm. The 13 mm/5 min indicator of extreme 5-min rainfall events is also the extrapolated equivalent of 2.6 mm/min – the threshold for extreme sub-hourly rainfall used by Zeng et al. (2021). Thus, there is a 1 in 10 000 probability (0.01% chance) that a daily rainfall event will be a cloudburst (Bharti et al., 2016), meaning a 99.99th percentile event. Therefore, the calculated value of 12.8 mm, representing the 99.99th percentile of 5-min rainfall, gives an indication of a possible cloudburst event in SA.

The classification in Table 2 indicates that the Hoedspruit and Kuruman storms of 4 April 2000 and 12 November 2001, respectively, should be regarded as cloudbursts because their highest 5-min rainfall amounts exceed 25 mm. According to the

Table 3. Expected return period in years of the *M* and highest 5-min (*F*) rainfalls (mm) for the two SA-cloudbursts and three downpour storms

Station name	Date & hour:min	*M*	Return period	*F*	Return period
Hoedspruit, Limpopo	04-Apr-2000 23:40	157.8	1 840	66.2	969
Kuruman, Northern Cape	12-Nov-2001 18:45	63.8	343	30.2	324
Pretoria, Gauteng	19-Jan-1996 1:20	133.8	7 850	13.4	14
Port Edward, KwaZulu-Natal	03-Jan-1997 22:25	115.0	280	13.4	5
Bloemhof, North West	08-Dec-2007 9:45	101.2	640	22.0	177

WMO cloudburst definition (> 100 mm/h) there are 4 cloudbursts in Table 2, namely: Bloemhof, Port Edward, Pretoria and Hoedspruit. The Bloemhof, Port Edward and Pretoria storms are re-classified as downpours because their highest 5-min rainfalls ≤ 25 mm. According to the WMO definition, the Kuruman event is not a cloudburst, but is a SA-cloudburst because the highest 5-min rainfall amount > 25 mm. Dimri (2017) proposes > 100 mm/15 min for a Himalayan cloudburst. Therefore, only the event recorded in Hoedspruit with 128.8 mm/15-min qualifies as a cloudburst according to the criterion used by Dimri (2017). The 132.2 mm for the 25 min duration of the Hoedspruit storm is interpolated to 5.3 mm/min which exceeds the 2.6 mm/min threshold for the extreme sub-hourly rainfall rate used by Zeng et al. (2021) to indicate possible flash flooding.

Using the data for the 64 stations across SA from July 1994 to June 2021, the median value of the return periods for WMO-defined cloudbursts, SA-defined cloudbursts and downpours are 38 000, 16 000 and 2 years, respectively. Meaning that WMO- and SA-defined cloudbursts are extremely rare, while a downpour event can be expected once every 2 years across the whole of SA. The minimum value for a return period is 0.5 years at Pietermaritzburg in KZN while Tshwane in GP, experienced 14 downpour events over a 15-year period at Bolepi House in Erasmusrand (Vermeulen, 2022).

According to Dimri (2017), an hourly rainfall > 70 mm is indicative of a possible WMO-cloudburst. The highest hourly rainfalls of the 64 AWSs in Table A2 (Appendix) was compared with 57 autographic rainfall stations of WB36 (WB, 1983) for the average period from 1954 to 1972. Subsequently, the frequency of stations which met the following criteria was calculated:

- Highest rainfall > 70 mm/h: 14 and 12 stations for the WB36 and this study, respectively. The two differences between the frequencies of the two climate periods compared is statistically insignificant according to Wilcoxon's sum of ranks test (Langley, 1968). Importantly, the Wilcoxon's test shows a less than 90% chance of a significant difference.
- Highest rainfall > 100 mm/h: 1 and 2 stations for the WB36 and this study, respectively. The 1 September 1968 COL-storm (Hayward and Van den Berg, 1968) at Gqeberha, formerly known as Port Elizabeth, had a highest intensity of 112 mm/h, while the Hoedspruit and Pretoria Unisa storms have highest intensities of 132 and 102 mm/h, respectively. The average highest intensity of 117.2 mm/h for the last two mentioned events compares well with Gqeberha at 112.4 mm/h. The WMO-cloudburst index cannot be considered for the Wilcoxon's sum of ranks test because there are not enough cases. Therefore, this study shows no statistically significant change from 1954 to 2021 in the intensity and frequency of cloudburst storms. It needs to be noted that the change in the rainfall recording instrumentation from autographic to electronic instruments during 1994 may affect the homogeneity of the datasets being compared.

The percentage rainfall contributions of *M* to daily (PCM2D), 5-min to *M* (PCF2M) and 5-min to daily (PCF2D) are presented in Table 2. On average, 76% and 16% of the daily rainfall occurs over 1 h and 5 min, respectively, for the 63 stations considered. Therefore, for a 50 mm/day forecast, maximums of 38 mm/h and 8 mm/5 min, respectively, can be expected for the storm events. On average 20% of the hourly rainfall in SA occurs in just 5 min. Therefore, for a 50 mm/h forecast, a maximum of 10 mm/5 min can be expected for the storm event. These calculations have implications for (i) planning DRR strategies, and (ii) evaluating severe storms. For example, in the early morning hours of 9 December 2022 a severe thunderstorm produced 176.7 mm rainfall in 5 hours at Florida in Johannesburg, GP. The resulting flash floods from this storm caused damage to roads and houses and cars were washed away. The averages of both PCM2D and PCF2D, when applied, give estimates of 134 mm/h and 28.3 mm/5 min for *M* and *F*, respectively.

Comparison with international downpours

The maximum 5-min accumulated hourly values for SA compare well with international events (see Table 4). The *M* values for Port Elizabeth and India indicated in bold italics are estimates calculated by adding 10.8 mm to their clock hourly values. The average difference between the maximum 5-min accumulated and clock hourly rainfall is 10.8 mm for the 63 stations across SA. The difference of 32.9 mm between maximum minute accumulated and clock hourly rainfall for the South China station compares well with the 37.8 largest difference of SA's Port Edward. The 'daily' and 'highest 5-min' values, when available for international stations, compare well with SA stations (see Table 4), except for the 66.2 mm/5 min of Hoedspruit that is classified as a once-in-900-years storm (see Table 3). Application of the 20.2% for the average PCF2M of the 63 stations (see Table 2) to the 30 October 2015 storm in Texas, USA, gives estimates of *F* (see bold in Table 4).

Table 4. Date and time of both highest hourly (mm) and maximum hourly (mm) rainfall events for 5 SA downpour events compared to 7 international downpour events. Daily and highest 5-min rainfalls are also presented. Bold values are estimates of either *M* or *F*.

Station name	Date & hour	Hour	Date & hour:min	*M*	*F*	Daily	Reference
Hoedspruit, Limpopo, SA	05-Apr-2000 0:00	132.2	04-Apr-2000 23:40	157.8	66.2	193.2	
Bisho, Eastern Cape, SA	05-Mar-1997 19:00	125.0	05-Mar-1997 19:15	127.8	30.0	129.4	Climate Service, SAWS
Mapumulo Prison, KwaZulu-Natal, SA	27-Jan-2017 16:00	123.0	27-Jan-2017 16:15	138.2	28.8	186.6	Climate Service, SAWS
Port Edward, KwaZulu-Natal, SA	03-Jan-1997 22:00	77.2	03-Jan-1997 22:25	115,0	13,4	308.8	
Port Elizabeth, Eastern Cape, SA	01-Sep-1968 11:00	112.4		**123.2**		428.8	Hayward and Van den Berg, 1968
Dehradun, India	14-Jun-1970 10:00	101.1		**111.9**		289.2	Dimri et al., 2017
Dharamshala, India	26-Jul-1983 10:00	191.2		**202.0**		354.5	Dimri et al., 2017
G3322, South China*	07-May-2017 6:00	184.4	07-May-2017 6:23	217.3	24.0	435.4	Zeng and Wang, 2022
LCRA-Gauge, Texas, USA#			30-Oct-2015	177.0	**35.8**		Nielsen and Schumacher, 2018
Austin-Bergstrom IA, Texas, USA			30-Oct-2015	146.3	**29.6**		Nielsen and Schumacher, 2018
Dallas, Texas, USA**			06-May-1995	117.0	16.7		Smith et al., 2001
Bulawayo, Zimbabwe##			19-Jan-1952	101.6	25.4	132.3	Sellick, 1961

Notes: *24 mm/5-min extrapolated from 4.8 mm/min rain rate peak and 435.4 mm is 16-h accumulated rainfall; #LCRA = Lower Colorado River Authority; **117.0 mm rainfall in 40 min; ##25.4 mm highest 6-min rainfall

The *F* values of 35.8 and 29.6 mm for LCRA-Gauge and Austin-Bergstrom, respectively, show that this WMO-cloudburst storm is possibly a SA-cloudburst storm.

CONCLUSION

The rainfall rates of 46.8 mm/day and 13.9 mm/h, based on the 99th percentile values, are suggested as more appropriate values to classify heavy or extreme rainfall across SA. In addition, the 99.9th percentile values of 30 mm/h and 7.3 mm/5 min, which are representative of a 1-in-1 000 event provide useful thresholds for the forecasting of flash floods, and to develop appropriate DDR strategies in SA. Furthermore, the 99.99th percentile value of 13 mm/5-min, which is representative of a 1-in-10 000 event is an indicator of a possible cloudburst storm in SA. The study also demonstrates the vast spatial variability observed in extreme rainfall rates across various temporal scales, specifically between the eastern and western parts of SA.

Importantly, a SA-cloudburst is defined as an hourly rainfall storm with a sub-hourly rainfall rate of > 25 mm/5 min. It is noteworthy that the 66.2 mm recorded in 5 min during a cloudburst at Hoedspruit on 4 April 2000 is the new all-time 5-min rainfall recordholder of the world. The calculated expected maximums of 5 min, hourly and daily rainfall totals in SA for return periods of 10, 25, 50 and 100 years presented here are a first for SA and will be useful for local hydrological modelling in the context of DRR, and specifically for flooding. The study also demonstrates the usefulness of recording 5-min data across SA to assess the maximum 5-min accumulated hourly rainfall (M) which can be used to evaluate hourly rainfall derived from numerical weather prediction (NWP) models. Lastly, evaluation of extreme rainfall events across SA is crucial to provide a better understanding of regional climate, particularly within the context of climate change which predicts increases in the intensity and frequency of extreme events (Seneviratne et al., 2021). However, comparison between the periods of 1995 to 2021 and 1954 to 1972 (WB36: WB, 1983) does not indicate a statistically significant change in the frequency and intensity of extreme rainfall events across SA.

AUTHOR CONTRIBUTIONS

Jan H Vermeulen – conceptualisation and methodology of the study, data collection and fieldwork, sample/data analysis, interpretation of results, writing of the initial draft, revision after review ; David W. Hedding – methodology of the study, sample/data analysis, interpretation of results, revision of the initial draft, revision after review; Nthabiseng Letsatsi – generating the rainfall maps and field work.

ACKNOWLEDGEMENTS

The following people are gratefully acknowledged: Mr Ishaam Abader, CEO of SAWS, Dr Jonas Mphepya, Executive: Weather and Climate, Ms Vanetia Phakula, Acting Senior Manager Disaster Risk Reduction and Mr Ezekiel Sebego for the sabbatical leave to do the research work, Karin Oxley and Anastasia Demertzis, SAWS Library, Lucky Dlamini, SAWS Climate Service, for supplying the 5-min, hourly and daily rainfall data, Dr Andries Kruger for return period formulas and quality control of storm events, Charlotte McBride and the team within Climate Service who discovered the world record holder, at 66.2 mm, for highest 5-min rainfall.

REFERENCES

AMS (American Meteorological Society) (2015) AMS Glossary of Meteorology. URL: http://glossary.ametsoc.org/wiki/Main_Page (Accessed November 2022).

BURT CC (2007) *Extreme Weather – A Guide and Record Book*. W. W. Norton & Company, New York.

BHARTI V, SINGH C, ETTEMA J and TURKINGTON TAR (2016) Spatiotemporal characteristics of extreme rainfall events over the Northwest Himalaya using satellite data. *Int. J. Climatol.* **36** 3949–3962. https://doi.org/10.1002/joc.4605

CAMPBELL SCIENTIFIC INC. (2024) Product manual. Tipping bucket rain gages. Revision 2/2024, Campbell Scientific Inc, USA, Logan UT. 7 pp.

CORNTHWAITE HG (1919) Panama rainfall. *Mon. Weather Rev.* **47** (5) 298–302. https://doi.org/10.1175/1520-0493(1919)47<298:PR>2.0.CO;2

DEAT (Department of Environmental Affairs and Tourism, South Africa) (1996) *Weather Bulletin January 1996*. Department of Environmental Affairs and Tourism, Pretoria.

DIMRI AP, CHEVUTURI A, NIYOGI D, THAYYEN RG, RAY K, TRIPATHI SN, PANDEY AK and MOHANTY UC (2017) Cloudbursts in Indian Himalayas: A review, *Earth-Sci. Rev.* **168** 1–23. https://doi.org/10.1016/j.earscirev.2017.03.006

DOSWELL CA III, BROOKS HE and MADDOX RA (1996) Flash flood forecasting: An ingredients-based methodology. *Weather Forecast.* **11** 560–581. https://doi.org/10.1175/1520-0434(1996)011<0560:FFFAIB>2.0.CO;2

GOSWAMI B, MUKHOPADHYAY P, MAHANTA R and GOSWAMI BN (2010) Multiscale interaction with topography and extreme rainfall events in the northeast India region. *J. Geophys. Res. Atmos.* **115** D12114. https://doi.org/10.1029/2009JD012275

GUMBEL EJ (1967) *Statistics of Extremes*. Columbia University Press, USA. 375 pp.

HAYWARD QL and VAN DEN BERG HJC (1968) Die Port Elizabeth-stortreëns van 1 September 1968, *Weather Bureau News Letter No. 234*. Weather Bureau, Pretoria.

HITCHENS NM, BALDWIN ME and TRAPP RJ (2012) An object-oriented characterization of extreme precipitation-producing convective systems in the Midwestern United States. *Mon. Weather Rev.* **4** 1356–1366. https://doi.org/10.1175/MWR-D-11-00153.1

KRUGER AC (2007) Climate of South Africa – Precipitation, WS47. SAWS, Pretoria. p. 4, p. 29.

KRUGER AC (2022) Statistics in Climatology WKD711. BSc. (Hons) Meteorology, University of Pretoria, p. 47 pp.

LANGLEY R (1968) *Practical Statistics*. Pan Books Ltd., London, 399 pp.

LEHMAN J, COUMON D and FRIELER K (2015) Increased record-breaking precipitation events under global warming. *Clim. Change* **132** 501–515. https://doi.org/10.1007/s10584-015-1434-y

LUO Y, WU M, REN F, LI J and WONG W (2016) Synoptic situations of extreme hourly precipitation over China. *J. Clim.* **29** (24) 8703–8719. https://doi.org/10.1175/JCLI-D-16-0057.1

MVULANE P (2020) Settling on water pathways: A case study of Setswetla vulnerability to flash floods. Unpublished MSc. dissertation, University of the Witwatersrand. 155 pp.

NIELSEN ER and SCHUMACHER RS (2018) Dynamical insights into extreme short-term precipitation associated with supercells and mesovortices. *J. Atmos. Sci.* **75** 2983–3009. https://doi.org/10.1175/JAS-D-17-0385.1

NOAA PSL (National Oceanic and Atmospheric Administration – Physical Sciences Laboratory, USA) (2000) NCEP/DOE Reanalysis II. URL: https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html (Accessed August 2022).

NOAA PSL (National Oceanic and Atmospheric Administration - Physical Sciences Laboratory, USA) NCEP (2001) NCEP/DOE Reanalysis II. URL: https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html (Accessed August 2022).

RAMAGE CS (1995) Forecasters guide to tropical meteorology (AWS TR 240 updated), AWS/TR-95/001. Air Weather Service, U.S. Air Force, AWSTL. 392 pp.

REICH BM (1961) Short duration rainfall intensity in South Africa. *S. Afr. J. Agric. Sci.* **4** (4) 589–614.

SAWS (South African Weather Service) (1996) Climate summaries of South Africa, January. South African Weather Service, Centurion.

SAWS (South African Weather Service) (2016) Climate summaries of South Africa, November. South African Weather Service, Centurion.

SAWS (South African Weather Service) (2017) Caelum – 1991 to 2016 (unpublished). Climate Service, South African Weather Service, Pretoria.

SELLICK NP (1961) Intensity duration curves for rainfall in Rhodesia. *Bibliography of Regional Meteorological Literature, Vol. II Southern Africa, 1948-1960*. Rhodesia Nyasaland Meteorological Service, Salisbury. 1 224 pp.

SENEVIRATNE SI, ZHANG X, ADNAN M, BADI W, DERECZYNSKI C, DI LUCA A, GHOSH S, ISKANDAR I, KOSSIN J, LEWIS S and co-authors (2021) Weather and climate extreme events in a changing climate. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI and co-authors (eds)*Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*]. Cambridge University Press, Cambridge. 1513–1766.

SMITH JA, BAECK ML, ZHANG Y and DOSWELL CA III (2001) Extreme rainfall and flooding from supercell thunderstorms. *J. Hydrometeorol*. **2** 469–489. https://doi.org/10.1175/1525-7541(2001)002<0469:ERAFFS>2.0.CO;2

THAYYEN RJ, DIMRI AP, KUMAR P and AGNIHOTRI G (2013) Study of downpour and flash floods around Leh, India during August 4-6, 2010. *Nat. Hazards* **65** (3) 2175–2220. https://doi.org/10.1007/s11069-012-0464-2

TYSON PD (1986) *Climate Change and Variability in Southern Africa*. Oxford University Press, Cape Town. 220 pp.

VERMEULEN JH (2022) An investigation of extreme very short-term rainfall at Bolepi House in Erasmusrand, Tshwane from May 2003 to April 2018: Implications for disaster risk reduction assessments in South Africa. *SAWS Weather-Smart Newsletter, October*. 21–26.

WB (Weather Bureau) (1982) Weather codes for land stations (surface observations). Weather Bureau, Department of Transport, South Africa.

WB (Weather Bureau) (1983) WB36. Part II. Extremes of rainfall, temperature and wind. Weather Bureau, Department of Transport, South Africa.

WU M and LIN G (2017) The very short-term rainfall forecast for a mountainous watershed by means of an ensemble weather prediction system in Taiwan. *J. Hydrol*. **546** 60–70. https://doi.org/10.1016/j.jhydrol.2017.01.012

WOOLLEY RR, MARSELL RE and GROVER NC (1946) Cloudburst floods in Utah, 1850–1938, Geological Survey, Water Supply Paper 994. Government Printing Office, Washington DC. 128 pp.

ZENG Z and WANG D (2022) On the local rain-rate extreme associated with a mesovortex over South China: Observational structures, characteristics and evolution. *Mon. Weather Rev*. **150** 1075–1096. https://doi.org/10.1175/MWR-D-21-0033.1

ZENG Z, WANG D and CHEN Y (2021) An investigation of convective features and Z-R relationships for a local extreme precipitation event. *Atmos. Res*. **250** 105372. https://doi.org/10.1016/j.atmosres.2020.105372

APPENDIX

Table A1. Recorded 5-min, hourly and daily data from SAWS automatic weather stations

Climate No.	Station name	Latitude (°)	Longitude (°)	Height amsl (m)	Start of hourly data	End of hourly data
0184491 4	Koingnaas	–30.20	17.29	95	23-Jul-1994 23:00	12-Feb-2022 16:00
0190868 1	Brandvlei	–30.46	20.48	923	24-Jul-1994 9:00	01-Mar-2022 12:00
0321110 7	Postmasburg	–28.35	23.08	1 321	24-Jul-1994 18:00	07-Mar-2022 11:00
0427083B8	Van Zylsrus	–26.88	22.05	938	24-Jul-1994 19:00	03-Mar-2022 21:00
0169880 1	De Aar WO	–30.67	23.99	1 286	24-Jul-1994 15:00	08-Mar-2022 12:00
0144791 2	Noupoort	–31.19	24.96	1 495	24-Jul-1994 22:00	08-Mar-2022 2:00
0134479A3	Calvinia WO	–31.48	19.76	975	30-Jun-1994 5:00	15-Feb-2022 14:00
0214700B2	Springbok WO	–29.67	17.88	1 006	23-Jul-1994 23:00	13-Feb-2022 16:00
0317475A8	Upington WO	–28.41	21.26	835	24-Jul-1994 14:00	07-Mar-2022 14:00
0224400 8	Prieska	–29.67	22.74	949	24-Jul-1994 15:00	08-Mar-2022 21:00
0393806 4	Kuruman	–27.43	23.45	1 323	30-Jun-1994 12:00	09-Mar-2022 23:00
0274034A4	Alexanderbaai	-28.57	16.53	24	24-Jul-1994 3:00	27-Feb-2022 7:00
0276162 9	Vioolsdrif	–28.70	17.60	167	24-Jul-1994 5:00	31-Jul-2002 23:00
0276196 8	Vioolsdrif – AWS*	–28.77	17.62	178	01-Aug-2002 0:00	23-Jan-2022 0:00
0290468A9	Kimberley WO	–28.81	24.77	1 196	25-Jul-1994 13:00	09-Jun-2021 10:00
0281606A5	Augrabies Falls	–28.60	20.34	635	27-Apr-2001 8:00	06-Mar-2022 23:00
0059572B8	East London WO	–33.04	27.82	134	07-Feb-1997 13:00	24-Jun-2021 20:00
0056917 8	Grahamstown	–33.29	26.50	642	10-Jul-1994 6:00	30-Jun-2021 6:00
0096072 5	Graaff-Reinet	–32.19	24.54	792	24-Jul-1994 17:00	03-Jun-2021 9:00
0123685 X	Queenstown	–31.92	26.88	1 108	25-Jul-1994 0:00	03-Jun-2021 12:00
0127272A4	Umthatha WO	–31.55	28.67	745	02-Dec-1996 15:00	24-Jun-2021 3:00
0034763 X	Uitenhage	–33.71	25.44	156	10-Jul-1994 9:00	30-Jun-2021 5:00
0015692A4	Tsitsikamma	-34.02	23.90	7	30-Jun-1994 7:00	29-Jun-2021 13:00
0148517A9	Jamestown	–31.12	26.81	1 615	25-Jul-1994 5:00	20-May-2021 13:00
0261307A4	Bloemfontein – Stad	–29.12	26.19	1 406	25-Jul-1994 15:00	20-May-2021 18:00
0331585 9	Bethlehem WO	–28.25	28.33	1 689	26-Jul-1994 10:00	22-Jun-2021 13:00
0364300 1	Welkom	–27.99	26.67	1 344	28-Oct-1994 17:00	30-Jun-2021 14:00
0296709AX	Ficksburg	–28.83	27.90	1 628	25-Jul-1994 18:00	08-May-2021 6:00
0365398 8	Kroonstad	–27.67	27.31	1 440	25-Jul-1994 18:00	08-May-2021 8:00
0405326A9	Vrede	–27.42	29.17	1 674	05-Aug-1994 16:00	23-Feb-2021 0:00
0232654 4	Wepener	–29.92	26.85	1 414	01-May-1999 7:00	20-May-2021 18:00
0007699A0	Tygerhoek	–34.15	19.90	157	30-Jun-1994 2:00	05-Jun-2021 5:00
0012661 7	George WO	–34.00	22.38	197	30-Jun-1994 4:00	30-Jun-2021 4:00
0021823 0	Paarl	–33.72	18.97	106	30-Jun-1994 1:00	01-Jul-2021 0:00
0063807 2	Excelsior Ceres	–32.96	19.43	958	30-Jun-1994 0:00	01-Jul-2021 0:00
0092081 5	Beaufort-Wes	–32.35	22.57	899	25-Jul-1994 0:00	30-Jun-2021 3:00
0045642 0	Laingsburg	–33.19	20.86	656	19-Oct-1995 17:00	30-Jun-2021 2:00
0061298 8	Langebaanweg AWS	–32.97	18.16	31	30-Jun-1994 0:00	01-Jul-2021 0:00
0674341 8	Lephalale	–23.68	27.71	839	30-Sep-1994 3:00	24-Jun-2021 15:00
0677802BX	Polokwane WO	–23.86	29.45	1 226	05-Aug-1994 16:00	30-Apr-2021 14:00
0587725CX	Thabazimbi	–24.58	27.41	977	23-Oct-1994 17:30	25-Jun-2021 15:50
0638081 1	Hoedspruit*	–24.35	31.05	524	02-Jun-1996 6:00	18-May-2014 1:00
0638051 X	Hoedspruit Air Force Base	–24.35	31.05	518	18-Jul-2014 0:00	06-Jun-2021 0:00
0723664 6	Thohoyandou AWS	–23.08	30.38	614	07-Dec-1996 23:00	28-Jun-2021 13:00
0675666 2	Marken	–23.59	28.39	1 001	14-Oct-1994 2:00	19-Jun-2021 14:00
0633882 7	Mokopane	–24.20	29.01	1 107	20-Sep-1995 2:00	20-Jun-2021 12:00
0437104A4	Potchefstroom	–26.74	27.08	1 351	23-May-1997 17:00	10-Jun-2021 8:00
0511399 X	Rustenburg	–25.66	27.23	1 150	28-Sep-1994 15:00	10-Jun-2021 16:00
0548375A4	Pilanesberg	–25.26	27.22	1 085	17-Aug-1995 2:00	10-Jun-2021 2:00
0508047 0	Mafikeng WO	–25.80	25.54	1 281	23-Oct-1994 16:00	10-Jun-2021 15:00
0436204 1	Klerksdorp	–26.90	26.62	1 329	25-Jul-1994 15:00	09-Jun-2021 21:00
0360453A0	Taung	–27.55	24.77	1 115	05-Oct-1994 21:00	10-Jun-2021 16:00
0362189 7	Bloemhof	–27.65	25.62	1 225	26-Sep-1994 18:00	10-Jun-2021 7:00
0155394A5	Port Edward	–31.06	30.22	14	30-Jun-1994 19:00	24-Jun-2021 17:00
0305017 9	Richards Bay	–28.78	32.02	7	30-Jun-1994 0:00	28-Dec-2002 0:00
0305134 6	Richards Bay Airport*	–28.74	32.09	36	08-Jan-2003 22:00	18-Jun-2021 12:00
0239698 5	Pietermaritzburg	–29.63	30.40	673	25-Jul-1994 19:00	03-Jun-2021 12:00
0300454 3	Ladysmith	–28.58	29.75	1 069	25-Jul-1994 17:00	03-Jun-2021 5:00
0268016AX	Giants Castle AWS	–29.26	29.52	1 759	25-Jul-1994 16:00	03-Jun-2021 1:00
0337738 2	Ulundi	–28.31	31.42	524	01-Mar-1997 20:00	14-Jun-2021 21:00
0554816A7	Lydenburg	–25.11	30.48	1 439	22-Aug-1994 9:00	04-Jun-2021 4:00
0515320 8	Witbank	–25.83	29.19	1 555	05-Aug-1994 20:00	02-Jun-2021 8:00
0520691 2	Komatidraai	–25.51	31.91	188	30-Jul-1994 9:00	20-Jun-2021 13:00
0479870 X	Ermelo WO	–26.50	29.98	1 774	05-Aug-1994 19:00	12-Jun-2021 12:00
0555750 9	Nelspruit	–25.50	30.91	883	20-Aug-1994 18:00	20-Jun-2021 7:00
0513346 0	Pretoria Unisa	–25.77	28.20	1 439	05-Aug-1994 17:00	08-May-2021 15:00
0438784 3	Vereeniging	–26.57	27.96	1 481	25-Jul-1994 19:00	10-Jun-2021 0:00

*indicates climate stations combined

Table A2. Dates (and time), highest (mm) and percentiles (mm) for daily, hourly and 5-min rainfalls for the stations of all 9 provinces

Station name	Daily				Hourly				5 min				
	Date	Highest	Percentiles		Date & hour	Highest	Percentiles		Date & hour:min	Highest	Percentiles		
			99	99.9			99	99.9			99	99.9	99.99
Northern Cape													
Koingnaas	25-May-1997	38.0	17.9	38.0	23-Jun-2009 1:00	11.4	5.9	9.4	24-Aug-2003 3:20	4.8	1.4	3.2	4.8
Brandvlei	03-Apr-1996	74.6	33.4	74.6	14-Feb-2018 15:00	48.0	10.6	32.6	14-Feb-2018 14:35	11.6	3.4	8.2	11.6
Postmasburg	18-Jan-2010	65.2	41.2	64.6	21-Feb-2000 20:00	42.6	13.6	26.8	21-Apr-2019 16:30	9.6	3.6	6.8	9.2
Van Zylsrus	19-Feb-2017	138.6	39.9	138.6	19-Feb-2017 21:00	50.6	16.2	28.2	29-Mar-1995 18:55	11.6	4.0	7.6	11.6
De Aar	25-Jan-2010	83.0	39.5	78.0	13-Oct-2018 18:00	54.8	13.2	25.4	13-Oct-2018 17:35	13.6	3.6	6.8	12.0
Noupoort	13-Mar-1997	83.6	39.4	72.0	13-Mar-1997 18:00	77.4	12.0	25.0	13-Mar-1997 17:15	19.8	3.2	7.6	19.8
Calvinia	15-Dec-2010	58.5	28.4	58.5	08-Apr-2017 19:00	57.2	7.4	18.2	08-Apr-2017 18:55	18.4	2.0	6.2	12.0
Springbok	27-Mar-1998	67.0	33.7	67.0	27-Mar-1998 18:00	42.4	6.0	16.6	27-Mar-1998 17:40	8.8	1.4	4.8	8.6
Upington	15-Mar-2011	107.0	49.3	107.0	15-Feb-2011 18:00	60.4	17.0	39.8	15-Feb-2011 17:10	12.6	4.6	8.2	12.6
Prieska	18-Sep-2001	65.4	40.6	65.4	10-Feb-2017 14:00	32.2	14.0	27.2	09-Nov-2001 12:15	11.0	3.6	7.6	11.0
Kuruman	26-Jan-2021	85.2	49.1	85.2	12-Nov-2001 18:00	47.8	15.5	31.8	12-Nov-2001 17:55	30.2	3.8	7.6	17.0
Alexanderbaai	16-Apr-2006	20.8	11.6	20.8	22-Nov-2016 18:00	8.0	4.1	8.0	27-Aug-1996 3:50	4.2	1.4	3.8	-
Vioolsdrif	04-Jan-2021	37.2	26.8	-	05-Apr-2005 15:00	15.6	11.0	15.6	28-Feb-2000 14:20	5.4	2.6	5.2	-
Kimberley	11-Mar-2019	96.6	43.9	88.6	24-Feb-2015 17:00	54.0	15.8	29.4	04-Nov-2009 15:10	16.8	4.2	8.0	15.2
Augrabies Falls	24-Mar-2014	64.0	31.1	-	08-Feb-2019 16:00	29.6	15.4	29.6	29-Mar-2011 0:30	9.2	3.6	8.2	-
Eastern Cape													
East London	15-Aug-2002	312.8	58.5	121.0	16-Aug-2002 1:00	84.0	10.6	25.6	19-Nov-2020 8:55	24.8	2.2	5.6	12.6
Grahamstown	23-Nov-2014	87.6	40.9	74.4	23-Nov-2014 23:00	80.6	8.2	18.2	09-Apr-2002 14:25	13.4	2.0	5.8	10.6
Graaff – Reinet	02-Aug-2006	62.2	34.3	53.8	14-Dec-2016 19:00	39.8	10.8	21.2	20-Oct-2015 15:20	13.0	3.2	7.4	11.6
Queenstown	04-Mar-2007	66.6	38.1	64.6	09-Jan-2012 18:00	35.4	13.2	29.6	22-Dec-2004 19:45	15.0	3.6	7.2	9.8
Umthatha	25-Jan-2010	89.1	40.7	88.5	23-Jan-2012 18:00	37.6	10.0	23.2	03-Feb-2016 17:15	14.8	2.8	7.0	13.0
Uitenhage	07-May-2011	125.0	53.8	87.0	26-Mar-2010 18:00	56.8	8.9	20.2	26-Mar-2010 17:55	20.0	2.0	5.6	13.8
Tsitsikamma	07-Sep-2018	168.6	56.6	105.2	20-Feb-2005 0:00	54.8	10.0	21.6	05-May-2021 18:45	12.6	2.2	4.8	8.4
Jamestown	18-Jan-2006	63.4	37.8	60.0	28-Nov-2000 15:00	46.2	11.7	21.0	28-Nov-2000 14:15	12.4	3.0	6.4	10.8
Free State													
Bloemfontein	16-Feb-1998	89.6	45.1	69.0	02-Jan-2009 15:00	33.0	14.0	28.2	13-Feb-1996 20:05	12.2	3.4	7.6	11.2
Bethlehem	01-Jan-1998	92.8	47.8	70.6	13-Feb-2004 3:00	43.8	13.4	28.0	22-Jan-2012 17:45	13.0	3.2	7.4	12.0
Welkom	03-Mar-1996	88.4	46.0	68.2	06-Feb-2021 23:00	53.6	13.9	31.2	18-Dec-1998 7:25	14.8	3.4	8.0	14.0
Ficksburg	22-Dec-2020	82.4	36.5	60.8	06-Apr-2017 15:00	35.0	11.6	21.6	09-Jul-2004 11:35	15.2	3.0	6.2	9.8
Kroonstad	20-Feb-2017	70.2	42.2	70.0	19-Feb-2006 14:00	57.8	11.8	28.6	24-Nov-2010 17:15	10.8	3.2	6.4	10.0
Vrede	30-Jan-2007	67.2	35.0	55.6	27-Nov-2016 18:00	48.6	12.3	25.8	06-Apr-2004 17:30	19.4	3.0	7.0	13.4
Wepener	20-Feb-2017	132.2	56.7	99.0	14-Feb-2021 20:00	79.4	16.8	36.6	23-Nov-2016 18:40	15.6	4.6	9.8	14.6
Western Cape													
Tygerhoek	05-May-2021	315.8	38.5	123.0	05-May-2021 17:00	69.2	7.7	24.6	24-Dec-1995 11:45	13.0	1.8	5.2	9.8
George	21-Nov-2007	183.4	56.5	114.6	01-Aug-2006 17:00	42.0	8.6	19.6	26-Oct-1997 4:30	7.4	1.8	3.6	6.2
Paarl	14-Jun-1996	104.8	53.6	84.0	14-Jun-2004 10:00	30.6	9.6	17.8	08-May-1998 18:05	10.2	2.0	3.8	6.8
Excelsior Ceres	14-Jun-2016	75.2	45.1	69.6	24-Apr-2007 6:00	39.8	7.7	26.0	24-Apr-2007 5:55	22.0	1.6	5.6	12.4
Beaufort-Wes	21-Dec-2002	84.4	33.5	84.4	21-Dec-2002 23:00	55.4	12.4	22.2	29-Jan-1999 18:45	10.6	3.6	7.2	10.2
Laingsburg	02-Mar-2000	69.0	34.7	69.0	26-Oct-2009 5:00	24.6	10.4	23.4	11-Mar-2020 22:45	7.8	2.8	6.0	7.8
Langebaanweg	06-Jun-2007	54.0	21.2	45.0	18-Jun-1999 13:00	19.6	6.4	11.2	18-Jun-1999 12:20	8.4	2.0	4.2	6.0
Limpopo													
Lephalale	04-Mar-2014	95.8	49.9	95.8	04-Feb-1996 17:00	43.6	18.0	36.4	28-Oct-2011 23:10	12.2	4.2	8.4	11.6
Polokwane	19-Feb-2018	109.5	62.7	95.6	09-Dec-1996 17:00	59.4	20.7	44.4	21-Mar-1995 14:50	17.8	5.0	9.0	14.2
Thabazimbi	27-Feb-2006	149.6	54.1	149.6	27-Feb-2006 15:00	57.4	17.9	39.4	27-Feb-2006 14:10	11.0	4.6	8.4	10.6
Hoedspruit	17-Jan-2012	268.8	57.0	193.2	05-Apr-2000 0:00	132.2	21.4	50.0	04-Apr-2000 23:20	66.2	5.0	9.4	54.8
Thohoyandou	23-Feb-2000	199.0	79.9	188.5	10-Feb-2000 1:00	51.8	20.2	37.2	24-Dec-2016 13:40	14.4	3.8	7.2	11.0
Marken	06-Apr-2010	111.2	57.5	111.2	04-Mar-1996 3:00	75.0	20.0	49.8	23-Mar-1995 23:15	19.2	4.6	10.4	18.0
Mokopane	04-Mar-1996	74.0	46.3	72.0	04-Mar-1996 17:00	44.0	16.8	31.2	04-Mar-1996 16:30	13.2	4.4	7.8	11.4
North West													
Potchefstroom	02-Mar-2000	115.0	49.8	102.6	28-Oct-2013 15:00	51.8	15.4	36.4	01-Nov-2020 11:20	16.4	4.0	8.6	13.2
Rustenburg	17-Nov-1995	102.4	54.9	90.8	03-Mar-2000 4:00	47.8	17.8	34.6	06-Oct-1998 19:35	19.8	4.1	7.4	12.0
Pilanesberg	13-Mar-2014	160.8	58.2	121.0	13-Mar-2014 18:00	72.8	19.8	36.4	08-Nov-2012 15:20	15.2	4.6	8.6	12.8
Mafikeng Wo	18-Nov-1995	127.6	55.8	87.0	05-Jan-2003 22:00	61.2	18.8	38.0	05-Jan-2003 22:00	17.4	4.8	8.6	12.8
Klerksdorp	13-Nov-2006	98.4	45.0	79.0	14-Jan-2021 15:00	48.4	16.3	35.4	01-Feb-2007 9:20	14.0	4.2	8.6	13.0
Taung	04-Jan-2017	93.6	51.4	93.6	11-Jan-2012 17:00	39.4	16.6	34.0	01-Nov-2020 5:20	15.6	4.2	8.2	13.0
Bloemhof	08-Dec-2007	120.6	45.6	86.8	08-Dec-2007 10:00	97.2	15.2	28.6	08-Dec-2007 9:30	22.0	3.7	8.0	15.2
KwaZulu-Natal													
Port Edward	03-Jan-1997	308.8	90.8	176.6	06-Dec-2012 23:00	78.2	14.4	42.0	30-Apr-2006 20:10	23.2	3.0	7.4	14.8
Richards Bay	19-Nov-2000	285.8	79.2	147.8	03-Jan-2005 21:00	67.0	16.2	37.6	26-Feb-2005 0:35	15.8	3.6	7.8	11.4
Pietermaritzburg	04-Mar-2007	107.0	51.9	84.4	25-Dec-1995 19:00	60.6	14.7	42.6	04-Apr-2010 17:25	20.4	4.0	9.0	14.6
Ladysmith	06-Sep-2012	110.0	51.7	87.6	12-Jan-2010 21:00	58.0	17.7	37.6	25-Jan-1996 18:15	13.8	4.4	8.8	11.6
Giants Castle	06-Sep-2012	113.6	42.0	77.5	13-Jan-2016 17:00	58.2	11.4	28.0	19-Dec-2014 13:10	16.2	3.2	7.0	12.0
Ulundi	02-Jan-2011	186.8	54.8	145.8	02-Jan-2011 22:00	62.8	17.3	40.8	16-Mar-2012 21:40	15.0	4.2	9.2	13.6
Mpumalanga & Gauteng													
Lydenburg	25-Dec-2012	80.6	47.2	78.8	23-Dec-1995 0:00	55.2	17.4	40.2	22-Dec-1995 23:10	15.2	4.6	9.6	13.8
Witbank	11-Feb-1996	91.0	50.0	82.2	09-Mar-1997 14:00	51.0	18.5	33.4	07-Nov-2008 3:40	15.6	4.4	8.8	13.6
Komatidraai	22-Jan-2004	189.6	67.5	189.6	10-Apr-2002 23:00	75.6	22.2	51.2	05-Apr-2019 19:00	20.2	5.4	10.0	16.0
Ermelo	17-Jan-2003	107.6	52.6	89.8	10-Apr-2017 18:00	78.2	16.4	33.2	27-Nov-2016 19:20	12.8	4.2	8.4	11.8
Nelspruit	04-Mar-2014	132.0	61.2	106.2	07-Mar-2013 18:00	60.2	18.4	40.6	07-Mar-2013 17:35	15.8	4.6	8.8	14.4
Pretoria Unisa	18-Jan-1996	193.4	53.1	121.0	19-Jan-1996 1:00	102.2	18.4	33.0	24-Feb-2014 13:55	16.0	4.4	9.0	13.4
Vereeniging	15-Dec-2010	129.0	47.4	92.4	27-Jan-1995 18:00	63.8	16.0	34.4	19-Nov-1994 4:45	20.4	4.0	8.0	17.4

Table A3. Expected maximum amounts of rainfall in return periods of 10, 25, 50 and 100 years based on annual extremes for the 9 provinces (stations ordered alphabetically)

Station name	Rainfall (mm)											
	Daily				Hourly				5-min			
	10	25	50	100	10	25	50	100	10	25	50	100
Northern Cape												
Alexander Bay	14.0	16.9	19.0	21.2	6.5	7.8	8.8	9.7	3.1	3.8	4.4	4.9
Augrabies Falls	42.2	52.2	59.7	67.3	22.8	27.8	31.5	35.3	8.4	10.2	11.5	12.9
Brandvlei	48.2	58.8	66.9	75.0	30.6	38.2	43.9	49.7	8.4	10.2	11.5	12.9
Calvinia	46.7	56.1	63.2	70.2	29.2	37.1	43.1	49.1	9.8	12.0	13.8	15.5
De Aar	61.3	72.1	80.3	88.5	33.9	40.6	45.7	50.7	9.5	11.0	12.1	13.2
Kimberley	74.7	88.8	99.4	110.1	36.7	43.5	48.7	53.9	12.2	14.3	15.8	17.4
Koingnaas	27.8	32.8	36.6	40.4	9.7	11.2	12.4	13.6	3.6	4.2	4.7	5.2
Kuruman	67.7	80.2	89.6	99.0	36.5	43.5	48.9	54.3	15.5	19.4	22.3	25.2
Noupoort	64.2	76.6	85.9	95.3	42.8	53.0	60.7	68.5	12.6	15.1	17.0	18.9
Postmasburg	56.3	65.6	72.6	79.7	28.9	34.5	38.7	43.0	8.6	10.0	11.1	12.1
Prieska	54.1	63.9	71.3	78.7	27.3	32.2	35.9	39.6	9.6	11.2	12.4	13.7
Springbok	51.2	60.6	67.7	74.8	23.7	29.8	34.5	39.2	6.4	7.9	9.1	10.2
Upington	68.8	82.9	93.6	104.2	36.5	43.3	48.5	53.7	10.3	11.8	12.9	14.0
Van Zylsrus	67.1	84.2	97.1	110.1	30.7	37.1	42.0	46.9	9.6	11.3	12.6	13.9
Vioolsdrif	25.4	32.1	37.1	42.2	12.7	15.7	17.9	20.2	4.8	5.9	6.7	7.5
Eastern Cape												
East London	158.2	198.7	229.3	260.0	45.2	55.5	63.2	71.0	15.4	19.2	22.0	24.8
Graaff Reinet	49.9	57.6	63.4	69.3	27.2	32.2	36.0	39.8	10.6	12.3	13.6	15.0
Grahamstown	71.2	83.5	92.8	102.2	37.8	47.2	54.3	61.4	10.2	11.9	13.2	14.4
Jamestown	56.2	64.5	70.8	77.1	27.4	32.6	36.6	40.6	10.2	12.0	13.4	14.7
Queenstown	53.6	60.8	66.3	71.7	31.2	36.2	40.0	43.8	10.3	11.8	12.9	14.1
Tsitsikamma	109.1	129.1	144.2	159.3	36.8	44.7	50.7	56.7	9.0	10.7	11.9	13.1
Uitenhage	84.7	102.9	116.7	130.5	32.2	39.8	45.6	51.3	10.2	12.6	14.5	16.3
Umthatha	74.6	86.9	96.3	105.6	31.3	36.1	39.8	43.5	12.1	13.9	15.3	16.7
Free State												
Bethlehem	73.6	84.2	92.1	100.1	35.0	40.3	44.3	48.2	10.8	12.2	13.2	14.2
Bloemfontein	68.1	79.0	87.2	95.5	29.8	33.9	37.0	40.1	10.9	12.2	13.2	14.2
Ficksburg	58.5	68.2	75.6	82.9	27.8	32.2	35.5	38.8	10.1	11.6	12.8	14.0
Kroonstad	64.5	76.2	85.0	93.8	34.0	41.0	46.4	51.7	8.7	9.9	10.9	11.8
Vrede	54.3	62.4	68.6	74.7	32.0	37.6	41.9	46.2	12.5	15.0	17.0	18.9
Welkom	66.5	76.8	84.7	92.6	39.6	47.1	52.8	58.5	12.3	14.2	15.6	17.0
Wepener	96.0	115.5	130.3	145.1	49.9	60.4	68.2	76.1	14.0	16.1	17.7	19.4
Western Cape												
Beaufort - Wes	57.8	70.3	79.8	89.3	31.8	39.4	45.2	50.9	9.4	10.7	11.8	12.8
Excelsior Ceres	60.7	68.9	75.2	81.4	33.4	40.9	46.5	52.1	12.1	15.2	17.5	19.8
George	123.7	150.6	170.8	191.1	26.5	31.7	35.7	39.6	6.3	7.2	7.9	8.5
Laingsburg	45.3	55.5	63.3	71.0	18.9	22.6	25.4	28.2	7.3	8.6	9.6	10.6
Langebaanweg	35.6	42.1	47.0	51.9	13.8	16.2	18.0	19.7	5.8	6.7	7.4	8.1
Paarl	79.3	91.5	100.7	109.9	22.2	26.0	28.8	31.6	7.1	8.4	9.4	10.4
Tygerhoek	145.3	187.2	218.9	250.7	42.1	53.3	61.7	70.2	9.1	11.1	12.6	14.1
Limpopo												
Hoedspruit	138.6	176.1	204.4	232.8	66.7	82.7	94.8	106.9	25.6	33.7	39.9	46.0
Lephalale	80.3	95.2	106.4	117.7	38.6	44.3	48.6	52.9	10.9	12.6	13.8	15.1
Marken	89.3	106.9	120.2	133.5	53.1	64.4	72.9	81.3	14.6	17.4	19.5	21.6
Mokopane	59.4	69.3	76.8	84.3	35.6	41.4	45.8	50.1	10.4	11.8	12.9	14.0
Polokwane	84.2	98.3	109.0	119.7	47.6	56.1	62.5	69.0	12.3	14.2	15.6	17.1
Thabazimbi	95.1	118.3	135.8	153.4	41.0	49.6	56.1	62.6	9.2	10.6	11.7	12.7
Thohoyandou	149.3	180.0	203.2	226.5	43.5	49.1	53.4	57.6	11.3	13.0	14.2	15.5
North-West												
Bloemhof	76.3	91.6	103.2	114.7	48.1	59.8	68.7	77.6	13.5	16.2	18.3	20.3
Klerksdorp	71.2	82.9	91.8	100.6	40.3	46.6	51.3	56.0	11.7	13.3	14.4	15.6
Mafikeng	84.8	99.6	110.9	122.1	42.7	49.7	55.0	60.3	12.2	13.9	15.2	16.5
Pilanesberg	101.4	122.3	138.1	153.9	48.6	57.2	63.8	70.3	12.7	14.4	15.8	17.1
Potchefstroom	86.4	103.3	116.1	128.9	42.0	49.2	54.6	60.0	13.1	15.3	16.9	18.6
Rustenburg	82.2	98.2	110.2	122.2	40.4	48.0	53.7	59.5	12.6	14.6	16.2	17.8
Taung	74.6	88.9	99.8	110.6	36.0	42.6	47.5	52.4	11.8	13.9	15.6	17.2
KwaZulu-Natal												
Giants Castle	79.4	93.9	104.8	115.8	41.6	49.8	56.0	62.2	12.5	14.6	16.2	17.8
Ladysmith	76.0	87.0	95.2	103.5	44.1	50.3	55.0	59.7	11.9	13.2	14.2	15.2
Pietermaritzburg	88.1	101.6	111.8	122.0	54.3	62.8	69.3	75.8	15.6	17.8	19.5	21.2
Port Edward	208.4	253.5	287.6	321.7	65.0	78.8	89.2	99.6	16.1	19.3	21.7	24.1
Richards Bay	169.4	204.4	230.9	257.3	57.2	67.5	75.3	83.2	12.8	14.6	16.0	17.3
Ulundi	117.8	144.2	164.3	184.3	49.3	58.2	64.9	71.5	13.3	15.0	16.4	17.7
Mpumalanga												
Ermelo	85.5	99.2	109.6	120.0	48.2	57.0	63.8	70.5	11.7	13.0	14.0	14.9
Komatidraai	132.5	162.2	184.6	207.1	61.1	73.1	82.1	91.2	15.1	17.7	19.6	21.5
Lydenburg	66.7	78.0	86.5	95.0	44.2	52.3	58.4	64.5	13.0	15.3	17.0	18.8
Nelspruit	102.9	121.9	136.3	150.6	52.8	61.8	68.6	75.4	13.2	14.9	16.1	17.4
Witbank	75.1	85.9	94.0	102.2	41.6	47.5	52.0	56.5	12.8	14.7	16.0	17.4
Gauteng												
Pretoria	110.2	135.7	155.1	174.4	50.9	62.3	70.9	79.6	12.7	14.7	16.2	17.7
Vereeniging	84.0	99.2	110.7	122.2	41.5	48.8	54.4	59.9	13.2	15.6	17.4	19.2