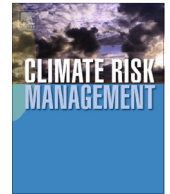




ELSEVIER

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Precipitation intensity-duration-frequency curves and their uncertainties for Ghaap plateau

C.M. Tfwala^{a,*}, L.D. van Rensburg^a, R. Schall^b, S.M. Mosia^c, P. Dlamini^a^a University of the Free State, PO Box 339, Department of Soil, Crop and Climate Sciences (54), Bloemfontein, South Africa^b University of the Free State, PO Box 339, Department of Mathematical Statistics and Actuarial Science (75), Bloemfontein, South Africa^c University of the Free State, PO Box 339, School of Mathematics Natural Science and Technology (62), Bloemfontein, South Africa

ARTICLE INFO

Article history:

Received 25 January 2017

Revised 22 April 2017

Accepted 25 April 2017

Available online 27 April 2017

Keywords:

Precipitation intensity-duration-frequency curves

Uncertainty levels

Generalized extreme value distribution function

Ghaap plateau

Ghaap plateau

ABSTRACT

Engineering infrastructures such as stormwater drains and bridges are commonly designed using the concept of Intensity-Duration-Frequency (IDF) curves, which assume that the occurrence of precipitation patterns and distributions are spatially similar within the drainage area and remain unchanged throughout the lifespan of the infrastructures (stationary). Based on the premise that climate change will alter the spatial and temporal variability of precipitation patterns, inaccuracy in the estimation of IDF curves may occur. As such, prior to developing IDF curves, it is crucial to analyse trends of annual precipitation maxima. The objective of this study was to estimate the precipitation intensities and their uncertainties (lower and upper limits) for durations of 0.125, 0.25, 0.5, 1, 2, 4, and 6 h and return periods of 2, 10, 25, 50 and 100 years in the Ghaap plateau, Northern Cape Province, South Africa using the Generalized Extreme Value (GEV) distribution. The annual precipitation maxima were extracted from long-term (1918–2014) precipitation data for four meteorological stations (Postmasburg, Douglas, Kuruman and Groblershoop) sourced from the South African Weather Services (SAWS). On average, the estimated extreme precipitation intensities for the plateau ranged from 4.2 mm/h for 6 h storm duration to 55.8 mm/h for 0.125 h at 2 years return period. At 100 year return period, the intensity ranged from 13.3 mm/h for 6 h duration to 175.5 mm/h for the duration of 0.125 h. The lower limit of uncertainty ranged from 11.7% at 2 years return period to 26% at 100 year return period, and from 12.8% to 58.4% for the upper limit for the respective return periods. This methodology can be integrated into policy formulation for the design of stormwater and flood management infrastructures in the Ghaap plateau, where mining is the main economic activity.

© 2017 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Municipal stormwater management and the design of engineering infrastructures able to withstand floods and extreme precipitation events are often based on the concept of precipitation Intensity-Duration-Frequency (IDF) curves (Jaleel and Farawn, 2013; Logah et al., 2013; Vivekanandan, 2013; Bhatt et al., 2014; Cheng and Aghakouchak, 2014; Wayal and Menon, 2014). IDF curves are commonly developed using historical annual maximum precipitation data fitted to a probability distribution to estimate the precipitation intensity for a given storm duration and return period (Overeem et al., 2008;

* Corresponding author.

E-mail addresses: cinisanitfwala@yahoo.co.uk, Tfwalacm@ufs.ac.za (C.M. Tfwala).

Cheng and Aghakouchak, 2014). The IDF curves are based on the assumptions that the occurrence of precipitation patterns and distributions are spatially similar within the drainage area and remain unchanged (stationary) throughout the lifespan of the infrastructures (Cheng and Aghakouchak, 2014). However, the occurrence of significant spatial and temporal variability in frequency and intensity of extreme precipitation events due to climate change (Prodanovic and Simonovic, 2007; Simonovic and Peck, 2009; IPCC, 2014) might invalidate these assumptions and compromise the accurate estimation of IDF curves. This in turn can have serious impacts on the design, operation and maintenance of engineering structures (Cheng et al., 2014; Yilmaz et al., 2014) making them inadequate and vulnerable to floods.

Due to rapid urbanization in many municipalities, previously pervious areas are replaced by impervious surfaces, which invariably alter the characteristics of the surface runoff hydrograph (Lee and Bang, 2000; Goonetilleke et al., 2005; Carter and Jackson, 2007). The process of urbanization involves demographic changes and increased economic activity including traffic patterns, which results in compromised air quality (Zhang et al., 2014; Fang et al., 2015). This is also accompanied by rapid increase in the demand for energy; as such a flexible and secure energy policy is required for sustainable growth to avoid environmental degradation due to energy generation (Grimm et al., 2008; Fang et al., 2015). Urbanization also comes with replacement of vegetation, which intercepts and stores sizable amounts of precipitation water. Consequently, there is an increase in runoff peaks and volumes in relatively shorter time frames (Kim et al., 2003; Goonetilleke et al., 2005; Chen et al., 2016). The frequency and severity of flooding in these areas is exacerbated by the effects of climate change, which involves occurrence of high intensity precipitation events (Dore, 2005; IPCC, 2014). Yilmaz and Perera (2014) reported a non-stationarity of extreme precipitation events for Melbourne between 1925 and 2010. In this study, 1966 was identified as the change point. For the same region, Jones (2012) reported the extreme precipitation events for the period between 1910 and 1967 to stationary and for the period between 1968 and 2010 as non-stationary.

To address the challenge of extreme precipitation events on engineering structures, an approach that allows for non-stationarity in IDF curves by incorporating a time parameter, has been proposed (Gregersen et al., 2013; Jacob, 2013; Al Saji et al., 2015; Yilmaz et al., 2014). In a non-stationarity climate, methods for assessing changes in precipitation intensity and duration, and their uncertainty are limited (Cheng and Aghakouchak, 2014). Even though Yilmaz et al. (2014, 2017) found that non-stationary models were not superior to stationary models in Melbourne and Victoria (Australia), it is still important to test non-stationary models in other locations. Owing to its flexibility and robustness in modelling maxima and uncertainty limits, the Generalized Extreme Value (GEV) distribution is used in models that allow for non-stationarity in time series (Overeem et al., 2008; Cheng and Aghakouchak, 2014; Gilleland and Katz, 2014). Furthermore, IDF curves provide a good basis for the design of stormwater and flood management infrastructures by estimating uncertainties damage risk of these structures by flooding is minimized.

In South Africa, Mason et al. (1999) analyzed 60 year (1931–1990) annual precipitation data maxima. They reported increases in intensity of extreme precipitation events between 1961 and 1990 compared to the period between 1931 and 1960. Their study covered a large part (70%) of the country, except for the north-east, north-west and the winter precipitation areas. IDF curves and their uncertainties have not been developed for most parts of the country including the study area. The increase in high intensity precipitation events is expected to continue due to climate change (IPCC, 2014) and demands that our infrastructure is able to withstand the negative impacts of these changes (Cheng and Aghakouchak, 2014). In this study, the objective was to estimate the precipitation intensities and their uncertainties (lower and upper limits) for durations of 0.125, 0.25, 0.5, 1, 2, 4 and 6 h and return periods of 2, 10, 25, 50 and 100 years in the Ghaap plateau, Northern Cape Province, South Africa using the Generalized Extreme Value (GEV) distribution.

2. Materials and methods

2.1. Site description

The Ghaap Plateau is situated between Kimberley and Upington, north of the Orange River to the Kuruman Hills, Northern Cape Province, South Africa. Its altitude varies between 900 and 1,600 m above sea level. The topography comprises undulating hills, with moderate slopes and flat plains. The mean annual precipitation ranges between 250 and 400 mm, with the majority falling between November and April. July is the driest month, often with absolutely no precipitation, while March receives the highest amount of precipitation. The average maximum temperatures are 17 °C in June and 31 °C in January, with average cold temperatures of 0 °C in June and July.

The main economic activity on the plateau is open cast mining, which depends primarily on groundwater resources. Second to mining, the economy depends on precipitation driven activities, including agriculture and nature conservation. The predominant soils in the plateau are of the Hutton form with red Aeolian sand the Kalahari group overlying the volcanic rock and sediments of the Griqualand West Supergroup, which outcrops in some places (Mucina and Rutherford, 2006). The predominant vegetation type is the Savanna Biome, which is composed of the Kuruman Mountain Bushveld and Postmasburg Thornveld.

2.2. Selection of meteorological stations and source of precipitation data

Four meteorological stations (Postmasburg, Douglas, Kuruman and Groblershoop) were selected. There are only few meteorological stations in the Northern Cape Province (Fig. 1), mainly due to the sparse population and aridity of the region

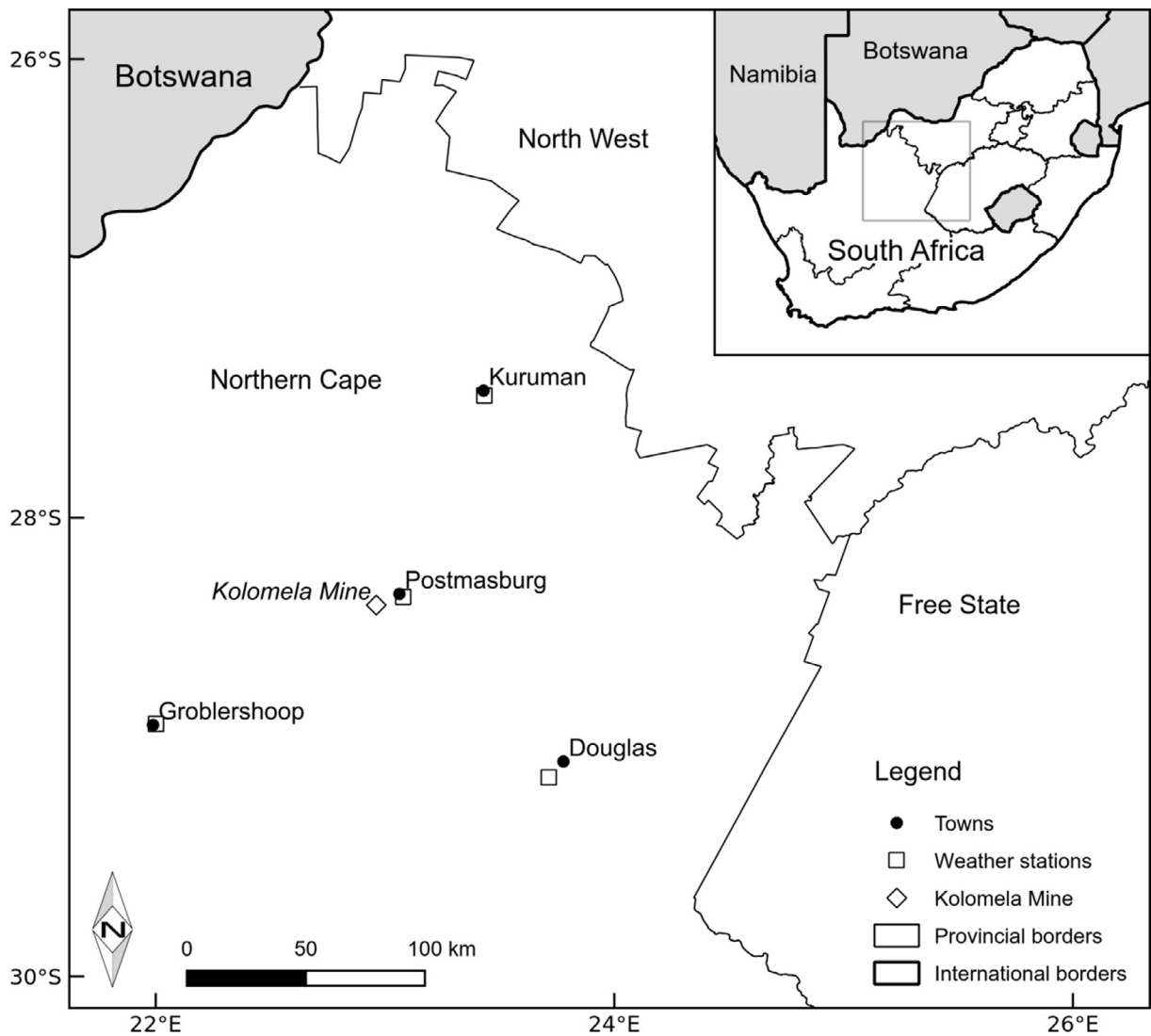


Fig. 1. Location of selected weather stations used for the development of precipitation Intensity-Duration-Frequency (IDF) curves for the Ghaap plateau in the Northern Cape Province, South Africa.

(Kruger, 2006). The stations were selected based on their proximity to the Kolomela mine, which was the main experimental site. Table 1 shows the geographical position, elevation and record length of precipitation data and average annual precipitation for the selected meteorological stations. Daily precipitation data for all four meteorological stations were obtained from the South African Weather Services (SAWS).

2.3. Developing precipitation IDF curves

Annual maxima extracted from daily precipitation records were modelled using the GEV distribution for the selected meteorological stations. Firstly, significant trends in the annual maxima were determined. Secondly, point and interval estimates of precipitation intensities were calculated at storm durations of 0.125, 0.25, 0.5, 1, 2, 4, and 6 h and for return periods of 2, 10, 25, 50 and 100 years. The cumulative distribution function of the GEV(μ, σ, ξ) distribution, for $\xi \neq 0$, is given by:

$$F(x) = \exp \left\{ - \left(1 + \xi \left(\frac{x - \mu}{\sigma} \right) \right)^{-\frac{1}{\xi}} \right\} \quad (1)$$

where μ , σ and ξ are the location, scale and shape parameter, respectively (Beirlant et al., 2004; Cheng and AghaKouchak, 2014). Here $F(x)$ is defined for $1 + \xi \left(\frac{x - \mu}{\sigma} \right) > 0$; elsewhere $F(x)$ is either 0 or 1. For $\xi = 0$, $\xi > 0$ and $\xi < 0$, the GEV leads to the Gumbel, Frechet and Max-Weibull distributions, respectively. To allow for non-stationarity and to determine if there are

Table 1

Geographical positions, elevation, data recording years and average annual rainfall for Postmasburg, Douglas, Groblershoop and Kuruman in the Ghaap plateau.

Weather station	Latitude	Longitude	Elevation (m.a.s.l)	Period record length	Years	Average rainfall (mm)
Postmasburg	–28.35	23.08	1323	1918–2014	97	317
Douglas	–29.13	23.71	1013	1960–2014	55	312
Groblershoop	–28.90	22.00	871	1939–2014	76	201
Kuruman	–27.47	23.43	1317	1960–2014	35	458

significant trends in extreme precipitation events, the location parameter of the GEV distribution was allowed to be time dependent following Cheng and AghaKouchak (2014):

$$\mu(t) = \mu_1 t + \mu_0 \quad (2)$$

where t is time, and μ_1 and μ_0 are the respective intercept and slope parameters of the linear model for the GEV location parameter as a function of time. Using SAS procedure MCMC (SAS, 2013), the annual maximum 24 h precipitation data were fitted to the GEV distribution through a Bayesian method. Specification of the data likelihood and of a prior distribution for the parameters is required (Beirlant et al., 2004) as follows:

$$x_i | \mu, \sigma, \xi \sim \text{GEV}(\mu, \sigma, \xi), i = 1, \dots, n \quad (3)$$

where x_i is the maximum precipitation for year i , and n is the number of years of data. With the parameter vector being $\theta = (\mu, \sigma, \xi)$, the prior distribution chosen for the model parameters is the Maximal Data Information (MDI) prior, namely:

$$p(\mu_0, \mu_1, \sigma, \xi) = \exp E[\log f(X|\theta)] \propto \frac{1}{\sigma} e^{-\psi(1)(1+\xi)} \quad (4)$$

where $f(X|\theta)$ denotes the probability density function of the distribution, and $\psi(1)$ is Euler's constant (Beirlant et al., 2004). The fit of the Bayesian model yields a joint posterior distribution of the model parameters. Based on this joint posterior distribution, point and interval estimates (the latter are Bayesian Credibility Intervals – BCI) for the model parameters and for suitable functions of model parameters, were calculated. The SAS code for carrying out the analysis is included as [Supplementary Material](#).

3. Results

3.1. Point and interval estimates of the GEV parameters

A summary of the point and interval estimates (BCIs) for the location (μ), scale (σ) and shape (ξ) parameters of the GEV distribution fitted to the annual maximum precipitation data for the four meteorological stations is presented in Table 2. The estimated μ for the four meteorological stations ranged between 30.9 mm for Douglas to 40.5 mm for Groblershoop. The lower limits for μ ranged between 27.6 and 34.7 and upper limits ranged between 34.4 and 46.5, also from Douglas and Groblershoop. The scale parameter σ ranged between 12.1 for Kuruman and 17.2 for Postmasburg, with lower limits ranging from 10 to 13.3 and upper limits from 14.5 to 22.1 also from the respective meteorological stations. The ξ ranged from 0 for Groblershoop to 0.2 for Kuruman. Also from the same meteorological stations, the lower limits of the shape parameter ranged from –0.2 to 0 and the upper limits ranged from 0.2 for Groblershoop to 0.4 for both Kuruman and Postmasburg. Thus, the parameters of the fitted GEV distributions for the four stations were quite similar.

3.2. Precipitation intensities and uncertainty

The precipitation intensities for Postmasburg shown in Fig. 2 (solid lines) for short duration (0.125 h) ranged from 51.9 mm/h at return period of 2 years to 161 mm/h at longer return period of 100 years. For the longer duration of 6 h the intensity was 3.9 mm/h at 2 year return period and 12.2 mm/h at 100 years return period. At Douglas (Fig. 3) the inten-

Table 2

Estimates and Bayesian Credibility Intervals (BCI); (lower and upper limits) for the location (μ), scale (σ) and shape (ξ) parameters of the GEV distribution for annual maximal rainfall data from Postmasburg (97 years), Douglas (55 years), Groblershoop (75 years) and Kuruman (35 years) in the Ghaap plateau.

Station	Location parameter (μ)			Scale parameter (σ)			Shape parameter (ξ)		
	Estimate	BCI		Estimate	BCI		Estimate	BCI	
		Lower limit	Upper limit					Lower limit	Upper limit
Postmasburg	34.6	29.5	40.2	17.2	13.3	22.1	0.1	–0.1	0.4
Douglas	30.9	27.6	34.4	13.5	11.0	16.5	0.2	0.0	0.4
Groblershoop	40.5	34.7	46.5	16.1	12.3	21.3	0.0	–0.2	0.2
Kuruman	32.9	30.2	35.7	12.1	10.0	14.5	0.2	0.0	0.3

sity for short duration (0.125 h) ranged from 56.9 mm/h to 202.3 mm/h at the 2 and 100 year return periods respectively. Six hour duration intensity was 4.3 mm/h at 2 year return period and 15.3 mm/h at the 100 year return period. At Groblershoop (Fig. 4), the intensity for 0.125 h duration was 49.9 mm/h at 2 year return period and 178.5 mm/h at the return period of 100 years. Kuruman (Fig. 5) had a precipitation intensity of 64.3 mm/h and 160.2 mm/h at the 2 and 100 year return periods respectively for short duration (0.125 h) storms. For the duration of 6 h the intensities were 3.9 mm/h at 2 years return period and 12.2 mm/h at 100 year return period. As expected, in all the meteorological stations, the intermediate storm durations (0.25, 0.5, 1, 2, and 4 h) and return periods (10, 25, and 50 years) had intensities that fall within the presented extremes at durations 0.125 and 6 h, as well as return periods of 2 and 100 years.

In Figs. 2–5, broken lines indicate the BCIs for the estimated IDF curves (solid lines), thus providing an indication of the uncertainty associated with the reported estimates. The narrowest range of uncertainty at Postmasburg (Fig. 2) was from 3.6 mm/h to 4.3 mm/h at 2 year return period and 6 h duration. The corresponding lower and upper limits of the estimated intensity (3.9 mm/h) deviated by 8.3% and 9.1%, respectively. Higher uncertainty levels at Postmasburg ranged from 123.3 mm/h to 234 mm/h at 100 year return period and 0.125 h duration. The corresponding lower and upper limits deviated by 23.4% and 45%, respectively.

At Douglas (Fig. 3), a narrow uncertainty ranged from 3.7 mm/h to 5.0 mm/h at a return period of 2 years and 6 h duration. These corresponded to respective lower and upper limit deviations of 14.4% and 15.8% from the estimated intensity of 4.3 mm/h. The widest range of uncertainty from 87.6 mm/h to 231.6 mm/h at 100 year return period and 2 h duration had a corresponding lower and upper limit deviation of 31.3% and 81.7%, respectively.

A narrow uncertainty range from 3.4 mm/h to 4.2 mm/h at Groblershoop (Fig. 4) was observed at 2 year return period and 6 h duration. These corresponded to respective lower and upper limit deviations of 10.6% and 11.7%. The highest uncertainty range from 130.4 mm/h to 273.7 mm/h was observed at 100 year return period and 2 h duration corresponding to lower and upper limit deviations of 26.9% and 53.4%, respectively.

At Kuruman a narrow range 4.2 mm/h to 5.6 mm/h was observed at return period of 2 years and duration of 6 h, corresponding to deviations of 13.4% and 14.6% for the lower and upper limits, respectively. The highest range of uncertainty for this station was from 124.3 mm/h to 245.3 mm/h at 100 year return period and 6 h duration, corresponding to deviations of 22.4% and 53.1% for the lower and upper limit, respectively.

4. Discussion

4.1. Estimated GEV parameters for meteorological stations

For all the meteorological stations used in this study, the initial fit of the GEV distribution with time-dependent location parameter ($\mu(t) = \mu_0 + \mu_1 t$) showed that there was no significant time trend (that is, stationarity can reasonably be

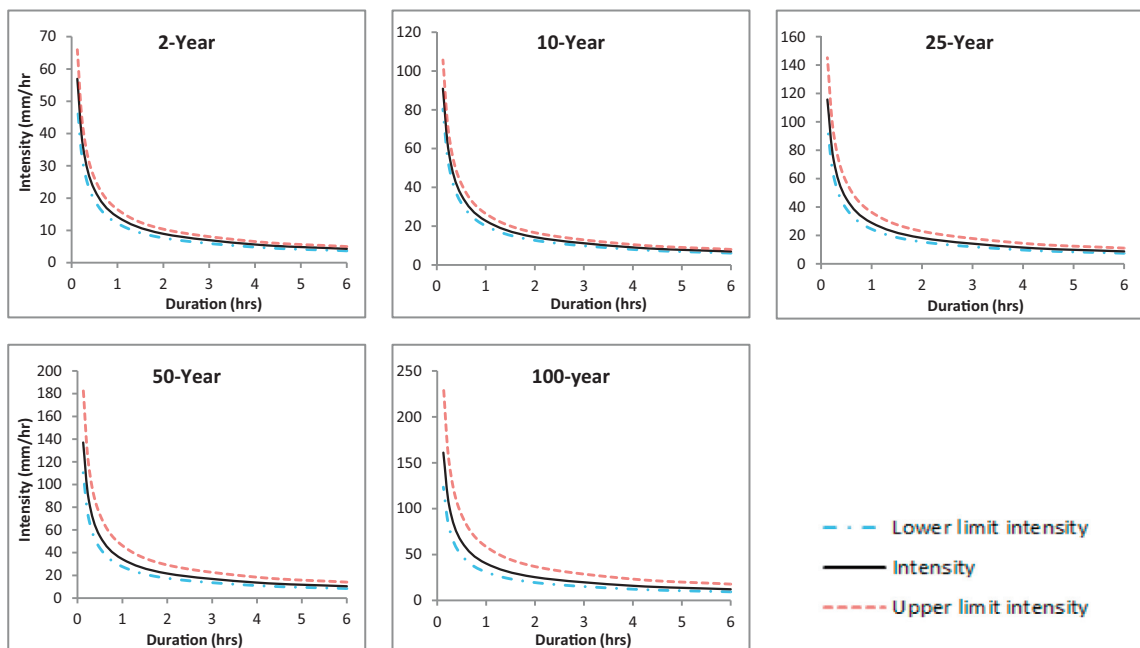


Fig. 2. Precipitation Intensity-Duration-Frequency (IDF) curves (intensity) and uncertainties (lower and upper limits) for Postmasburg, on the Ghaap plateau, given by Generalized Extreme Value (GEV) distribution for storm durations of 0.125–6 h at 2–100 year return periods.

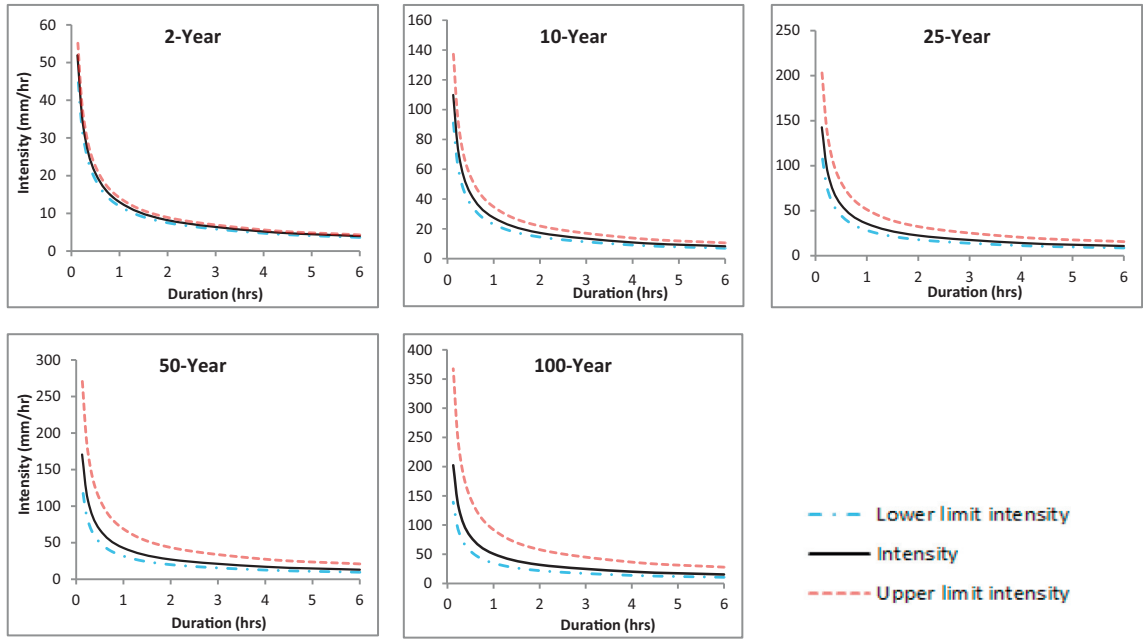


Fig. 3. Precipitation Intensity-Duration-Frequency (IDF) curves (intensity) and uncertainties (lower and upper limits) for Douglas, on the Ghaap plateau, given by Generalized Extreme Value (GEV) distribution for storm duration of 0.125–6 h at 2–100 year return periods.

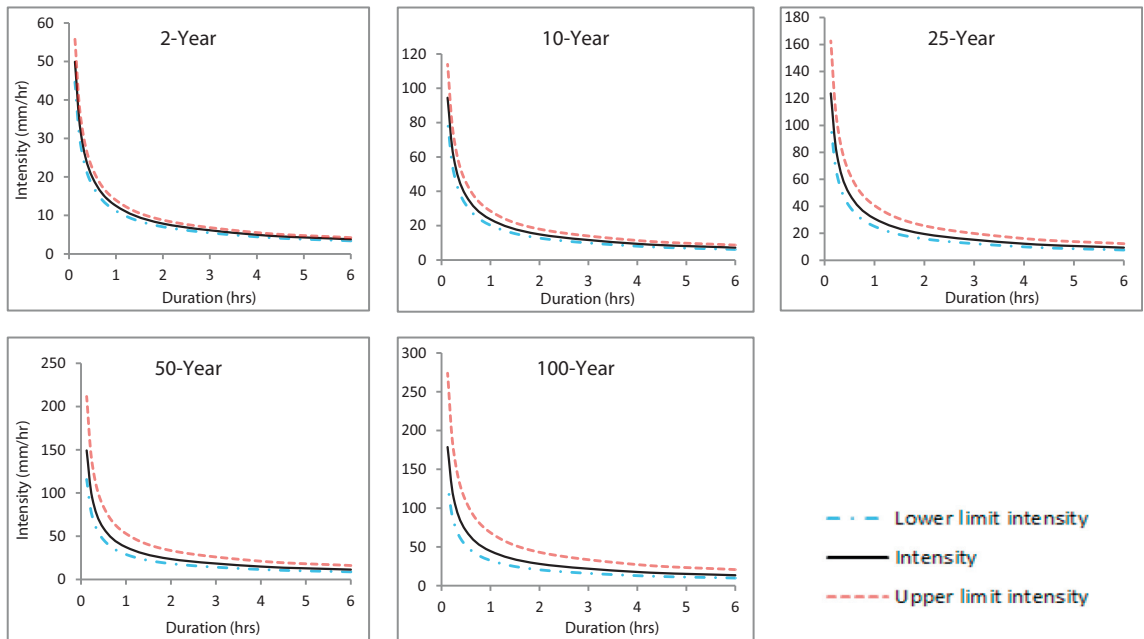


Fig. 4. Precipitation Intensity-Duration-Frequency (IDF) curves (intensity) and uncertainties (lower and upper limits) for Groblershoop, on the Ghaap plateau, given by Generalized Extreme Value (GEV) distribution for storm duration of 0.125–6 h at 2–100 year return periods.

assumed) since the estimate of the slope parameter μ_1 (0.1) was close to zero, and its BCI included the value zero. This implies that there is no evidence that the precipitation extremes on the Ghaap plateau have changed significantly over time within the data recording period. According to IPCC (2014), the impacts of climate change are not going to be similar in different regions, with some locations showing large effects, whereas in some no significant changes will be observed, as was the case in the present study area.

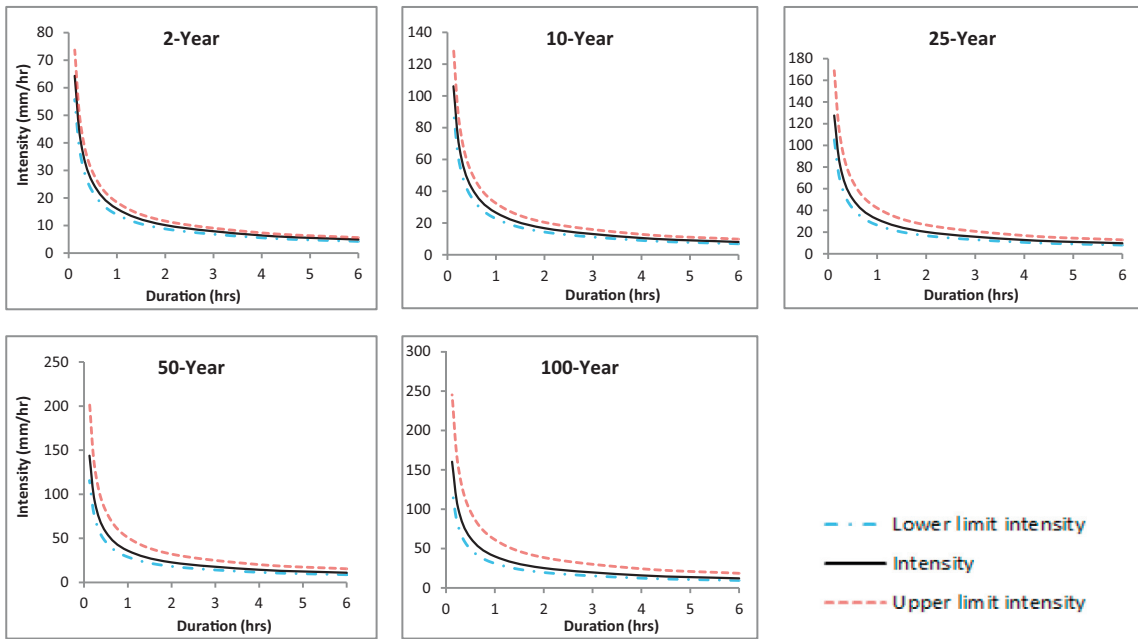


Fig. 5. Precipitation Intensity-Duration-Frequency (IDF) curves (intensity) and uncertainties (lower and upper limits) for Kuruman, on the Ghaap plateau, given by Generalized Extreme Value (GEV) distribution for storm duration of 0.125–6 h at 2–100 year return periods.

4.2. On precipitation intensities and uncertainties

On average, the estimated precipitation intensity at 2 year return period ranged from 4.2 mm/h for long duration (6 h) storms to 55.8 mm/h for short duration storms (0.125 h). For the 100 year return period, the precipitation intensity ranged from 13.3 mm/h for 6 h duration to 175.5 mm/h for the duration of 0.125 h. The range of precipitation intensity values is similar to ranges reported elsewhere under similar conditions. For instance, [Jaleel and Farawn \(2013\)](#) used the Gumbel Distribution (GD) to develop IDF curves for Basrah City in Iraq, which has a mean annual precipitation of 161 mm. Using data from 1980 to 2010 they estimated intensities of up to 55 mm/h at return periods of 2 years, and up to 170 mm/h at 100 year return period. In contrast, higher precipitation intensities were recorded from 1960 to 2005 in higher rainfall areas (up to 5000 mm/year). In Bangladesh ([Rashid et al., 2012](#)) and India ([Bhatt et al., 2014](#)) higher precipitation intensities of up to 985 mm/h for 0.167 h duration and 100 year return period were estimated using the GD. Concurring with other studies ([Bazaraa and Ahmed, 1991](#); [AlHassoun, 2011](#); [Ahmed et al., 2012](#); [Elsebaie, 2012](#)), the findings of the present study revealed that the precipitation intensity is inversely proportional to the duration and directly proportional to the return periods, implying that high intensity storms normally last for short durations. This also implies that the high intensity storms with greater potential to damage infrastructures and the environment have a lower frequency of occurrence.

On average, the lower limit of uncertainty, associated with over estimating the risk posed by high intensity precipitation events, and hence over costing infrastructures, ranged from 11.7% at 2 year return period to 26% at 100 year return period. On the other hand, the upper limit, associated with under estimating the risk of infrastructure damage by flooding was 12.8% at 2 year return period and 58.4% at 100 year return period. The uncertainty level increased with an increase in return period, meaning, the high intensity storms occurring at longer return periods have a higher risk of over or under estimation. The uncertainty in formulation of IDF curves is often disregarded, leading to over or under estimating the risks posed by high intensity precipitation events.

With high intensity precipitation events expected to be more frequent due to climate change ([IPCC, 2014](#)), it is important to have IDF curves available for specific locations. In this way municipal stormwater can be better managed and damage to engineering infrastructures by floods, minimized. The present study area is dominated by a growing mining sector, which is associated with rapid urbanization. Urbanization will induce changes such as removal of vegetation and infrastructure development. Vegetation removal intercepts and stores precipitation, whereas building and pavement infrastructure renders previously pervious areas to be impervious. The subsequent altering of the area's hydrology by reducing the infiltration area and increasing the drainage output will benefit from updated IDF curves, which include uncertainty levels. Engineers may use the IDF curves and uncertainties to properly advise administrators and policy makers on further development of the Ghaap plateau. Insight into the quantification of peak runoff outputs during extreme precipitation events can be given, and hence provide adequate information for infrastructure design.

5. Conclusions

The objective of the present study was to estimate the precipitation intensities and their uncertainties for durations of 0.125, 0.25, 0.5, 1, 2, 4, and 6 h and return periods of 2, 10, 25, 50 and 100 years in the Ghaap plateau, Northern Cape Province, South Africa. The conclusions drawn from this study were that; i) the extreme precipitation on the plateau exhibited consistent trends, ii) the high intensity storms posing higher risk of damage to infrastructure and the environment are less frequent than low intensity storms. However, of critical concern is that their probability of over or under estimation (uncertainty) is higher. In the Ghaap plateau, the development of IDF curves is crucial for stormwater management and design of engineering infrastructures. Administrators and policy makers can use the IDF curves when planning development on the plateau. Further studies should prioritise recording, storage and use of long-term precipitation data to develop IDF curves for other areas of the country, and at regional and continental levels. It is essential to understand and quantify the impacts of increased stormwater and flooding on infrastructure and even on the environment. This is especially so under the context of climate change, where high intensity precipitation events are expected to increase in frequency and magnitude. Future work must also consider assessing the trends of urbanization, particularly removal of vegetation and infrastructure development, which make pervious surfaces to be impervious and changes the surface runoff characteristics of landscapes.

Acknowledgements

The Kolomela mine is acknowledged for financial assistance for this study. The South African Weather Services for providing precipitation data.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.crm.2017.04.004>.

References

- Ahmed, Z., Rao, D.R., Reddy, K.R.M., Raj, E., 2012. Rainfall intensity variation for observed and derived data – a case study of Imphal. *APRN J. Eng. Appl. Sci.* 7 (11), 1506–1513.
- Al Saji, M., O'Sullivan, J.J., O'Connor, A., 2015. Design impact and significance of non-stationarity of variance in extreme rainfall. *Proc. IAHS* 371, 117–123.
- AlHassoun, S.A., 2011. Developing empirical formulae to estimate rainfall intensity in Riyadh region. *J. King Saud Univ.* 23, 81–88.
- Bazaraa, A.S., Ahmed, S., 1991. Rainfall characterization in an arid area. *Eng. J. Qatar Univ.* 4, 35–50.
- Beirlant, J., Goegebeur, Y., Teugels, J., Segers, J., 2004. *Statistics of Extremes. Theory and Applications*. Wiley, Chichester.
- Bhatt, J.P., Gandhi, H.M., Gohil, K.B., 2014. Generation of intensity duration frequency curves using daily rainfall data for different return periods. *J. Inter. Acad. Res. Multidiscip.* 2 (2), 717–722.
- Carter, T., Jackson, C.R., 2007. Vegetated roofs for stormwater management at multiple spatial scales. *Landscape Urban Plann.* 80, 84–94.
- Chen, Y., Samuelson, H.W., Tong, Z., 2016. Integrated design workflow and a new tool for urban rainwater management. *J. Environ. Manage.* 180, 45–51.
- Cheng, L., AghaKouchak, A., 2014. Nonstationary precipitation Intensity-duration-frequency curves for infrastructure design in a changing climate. *Sci. Rep.* 4, 1–6.
- Cheng, L., AghaKouchak, A., Gilleland, E., Katz, R.W., 2014. Non-stationary extreme value analysis in a changing climate. *Clim. Change* 127, 353–369.
- Dore, M.H., 2005. Climate change and changes in global precipitation patterns: what do we know? *Environ. Int.* 31, 1167–1181.
- Elsebaie, I.H., 2012. Developing rainfall intensity-duration-frequency relationship for two regions in Saudi Arabia. *J. King Saud Univ. Eng. Sci.* 24, 131–140.
- Fang, G.E., Liu, H., Li, G., Sun, D., Miao, Z., 2015. Estimating the impact of urbanization on air quality in China using spatial regression models. *Sustainability* 7, 15570–15592.
- Gilleland, E., Katz, R.W., 2014. New software to analyze how extremes change over time. *Eos* 92 (2), 13–14.
- Gregersen, I.B., Madsen, H., Rosbjerg, D., Arnbjerg-Nielsen, K., 2013. A spatial and nonstationary model for the frequency of extreme rainfall events. *Water Resour. Res.* 49, 127–136.
- Goonetilleke, A., Thomas, E., Ginn, S., Gilbert, D., 2005. Understanding the role of land use in urban stormwater quality management. *J. Environ. Manage.* 74, 31–42.
- Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J.G., Bai, X.M., Briggs, J.M., 2008. Global change and the ecology of cities. *Science* 319, 756–760.
- IPCC, 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, Geneva, Switzerland.
- Jacob, D., 2013. Nonstationarity in extremes and engineering design. In: AghaKouchak, A., Easterling, D., Hsu, K., Schubert, S., Sorooshian, S. (Eds.), *Extremes in a Changing Climate*. Springer, Dordrecht, pp. 363–417.
- Jaleel, L.A., Farawn, M.A., 2013. Developing rainfall intensity-duration-frequency relationship for Basrah city. *Kufa J. Eng.* 5 (1), 105–112.
- Jones, R.N., 2012. Detecting and attributing nonlinear anthropogenic regional warming in south-eastern Australia. *J. Geophys. Res.* 117, D04105. <http://dx.doi.org/10.1029/2011JD016328>.
- Kim, H., Seagren, E.A., Davis, A.P., 2003. Engineered bioretention for removal of nitrate from stormwater runoff. *Water Environ. Res.*, 355–367.
- Kruger, A.C., 2006. Observed trends in daily precipitation indices in South Africa: 1910–2004. *Int. J. Climatol.* 26, 2275–2285.
- Lee, J.H., Bang, K.W., 2000. Characterization of urban stormwater runoff. *Water Res.* 34, 1773–1780.
- Logah, F.Y., Kankam-Yeboah, K., Bekoe, E.O., 2013. Developing short duration rainfall intensity frequency curves for Accra in Ghana. *Inter. J. Lat. Res. Eng. Comp.* 1 (1), 67–73.
- Mason, S.J., Waylen, P.R., Mimmack, G.M., Rajaratnam, B., Harrison, J.M., 1999. Changes in extreme rainfall in South Africa. *Clim. Change* 41, 249–257.
- Mucina, L., Rutherford, M.C., 2006. *The Vegetation of South Africa Lesotho and Swaziland*. South African National Biodiversity Institute, Pretoria, South Africa.
- Overeem, A., Buishand, A., Holleman, I., 2008. Rainfall depth-duration-frequency curves and their uncertainties. *J. Hydrol.* 348, 124–134.
- Prodanovic, P., Simonovic, S.P., 2007. Development of rainfall intensity duration frequency curves for the city of London under changing climate. *Water Resources Research Report No: 058*, UK.
- Rashid, M.M., Faruque, S.B., Alam, J.B., 2012. Modeling of short duration rainfall intensity duration frequency (SDR-IDF) equation for Sylhet City in Bangladesh. *APRN J. Sci. Tech.* 2 (2), 92–95.

- SAS Institute Inc, 2013. SAS/STAT 13.1 User's Guide. SAS Institute Inc, Cary, NC.
- Simonovic, S.P., Peck, A., 2009. Updated rainfall intensity duration frequency curves for the city of London under changing climate. Water Resources Research Report No: 065, UK.
- Vivekanandan, N., 2013. Development of intensity-duration-frequency relationships using OSA estimators of probability distributions. *J. Res. Archit. Civil Eng.* 1 (2), 1–7.
- Wayal, A.S., Menon, K., 2014. Intensity-duration-frequency curves and regionalization. *Inter. J. Innovative Res. Adv. Eng.* 1 (6), 28–32.
- Yilmaz, A., Hossain, I., Perera, B., 2014. Effect of climate change and variability on extreme rainfall intensity-frequency-duration relationships: a case study of Melbourne. *Hydrol. Earth Syst. Sci.* 18, 4065–4076.
- Yilmaz, A., Perera, B., 2014. Extreme rainfall nonstationarity investigation and intensity-frequency-duration relationship. *J. Hydrol. Eng.* 19, 1160–1172.
- Yilmaz, A.G., Imteaz, M.A., Perera, B.J.C., 2017. Investigation of non-stationarity of extreme rainfalls and spatial variability of rainfall intensity-frequency-duration relationships: a case study of Victoria, Australia. *Int. J. Climatol.* 37 (1), 430–442.
- Zhang, D., Liu, J., Li, B., 2014. Tackling air pollution in China – what do we learn from the great smog of 1950s in London. *Sustainability* 6, 5322–5338.