A review of methods to account for impacts of non-stationary climate data on extreme rainfalls for design rainfall estimation in South Africa

K A Johnson, J C Smithers, R E Schulze

Frequency analysis of extreme rainfall and flood events are used to determine design rainfalls and design floods which are needed to design hydraulic structures such as dams, spillways and culverts. Standard methods for frequency analysis of extreme events are based on the assumption of a stationary climate. However, this assumption in rainfall and flood frequency analysis is being challenged with growing evidence of climate change. As a consequence of a changing climate, the frequency and magnitude of extreme rainfall events are reported to have increased in parts of South Africa, and these and other changes in extreme rainfall occurrences are expected to continue into the future. The possible non-stationarity in climate resulting in changes in rainfall may impact on the accuracy of the estimation of extreme rainfall quantities and design rainfall estimations. This may have significant consequences for the design of new hydraulic infrastructure, as well as for the rehabilitation of existing infrastructure. Hence, methods that account for non-stationary data, such as caused by climate change, need to be developed. This may be achieved by using data from downscaled global circulation models in order to identify non-stationary climate variables which affect rainfall, and which can then be incorporated into extreme value analysis of a non-stationary data series.

INTRODUCTION

Rainfall frequency analysis is used to construct Depth-Duration-Frequency (DDF) curves, which are needed for the estimation of design floods in order to design and construct hydraulic structures, including dam walls, spillways, culverts and stormwater drains. Extreme rainfall quantities are of particular interest for this purpose (Hao & Singh 2013). Standard methods for frequency analysis of extreme events are based on the assumption of a stationary climate (Prosdocimi *et al* 2014). However, anthropogenically induced climate change has resulted in changes in extreme weather events, thus questioning the assumption of stationarity (Serinaldi & Kilsby 2015). As a consequence of a changing climate, the frequency and magnitude of extreme rainfall events may increase (Bates *et al* 2008). The possible non-stationarity in climate is projected to result in changes in rainfall and runoff, with potential impacts on the accuracy of design rainfall estimations and the estimation of extreme rainfall quantities such as the Probable Maximum Precipitation (PMP). This may have significant consequences for the design of hydraulic infrastructure, and consequently also for the South African economy (Cullis *et al* 2015). This concept has triggered the need to account for uncertainty due to non-stationary data in the analysis of extreme rainfall events (Yilmaz *et al* 2014).

This paper contains a review of the potential impacts of climate change on extreme rainfall in South Africa, and methods for incorporating non-stationary data in extreme design rainfall estimates.

CLIMATE CHANGE AND NON-STATIONARY DATA

Climate change

A significant amount of current scientific evidence suggests that increasing

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greenhouse gas emissions have resulted in an increase in the global mean temperatures (IPCC 2007; 2014). This trend in climate change is expected to continue into the future with an overall warming of the planet expected. Higher global temperatures are linked to significant changes in precipitation, storm occurrences, sea level rise, and extreme weather events (Bates *et al* 2008; Easterling & Kunkel 2011; Cullis *et al* 2015). A major concern associated with higher temperatures is increased evaporation rates, thus resulting in increased total global precipitation (Trzaska & Schnarr 2014). Studies have shown that it is possible that climate change processes will intensify the hydrological cycle, thus resulting in more frequent and intense climatological events. It is thus very likely that the frequency of extreme temperatures and extreme precipitation events will not only increase, but that the patterns of extreme precipitation will become more erratic (Westra 2011; Madsen *et al* 2013; WRF 2014). At a global scale, broad trends in precipitation may not necessarily be linked to the same trends in runoff, and some areas may experience increased runoff whilst others may experience less (Bates *et al* 2008).

Climate change impacts in South Africa

The impact of changing climate has become a key concern in South Africa (Department of Environmental Affairs 2014a; 2014b; 2017). In South Africa, over the past five decades, the mean annual temperatures have increased more than 1.5 times the observed global average (Ziervogel *et al* 2014), and the Department of Environmental Affairs (2017) noted that the highest recorded temperatures since 1951 occurred in 2015. The Intergovernmental Panel on Climate Change (IPCC) notes that severe and widespread impacts associated with such temperature increases are attributable to climate change (IPCC 2018). Changes in temperature have a significant impact on extreme weather events (Pfahl *et al* 2017; IPCC 2018), and generally warmer atmospheric conditions are more conducive to heavy rainfall (IPCC 2017; Pfahl *et al* 2017). Over parts of South Africa, it has been noted that the frequency of extreme rainfall events has increased (Ziervogel *et al* 2014).

The estimation of design floods is impacted upon by changes in rainfall and runoff distribution characteristics (Smithers 2012). Numerous studies have indicated that the changing climate has impacted both rainfall and associated flooding in South Africa. Studies have proven that the annual maximum rainfall in South Africa has been increasing (Ndiritu 2005) and that seasonal patterns of rainfall have also shifted, proving that patterns of rainfall are becoming more variable (Knight & Fitchett 2019; Schulze & Schütte 2019). Alexander (2006) demonstrated, with a high degree of confidence, that climate change in South Africa has resulted in a discernible increase in average rainfall over parts of the country, as well as increased occurrences of heavy rainfall events. This is supported by results of studies by De Waal *et al* (2017) that display a general increase in the frequency of intense rainfall events, which further challenges the assumptions of stationary climatic conditions in design rainfall estimation. Trend analysis of almost 100 years of daily precipitation records by Kruger (2006) showed some significant changes in precipitation in the country, although annual precipitation increased and decreased for different areas in the country, with some areas showing increased occurrences of more extreme precipitation events. Although the total annual precipitation may be fairly constant over time in certain parts of South Africa, the number of rainfall events has decreased in parts, thus indicating that rainfall intensities have increased in these parts of the country (Van Wageningen & Du Plessis 2007; Kruger & Nxumalo 2017; Pohl *et al* 2017). Despite no consistent evidence of clear trends in changes of rainfall intensities in the western parts of the country, future climate conditions for rainfall are projected to intensify and become more extreme for the wider South African region (Du Plessis & Burger 2015). Consequently, design rainfalls are projected to increase in some areas due to climate change, thus impacting on future designs of hydraulic structures (Knoesen *et al* 2011; Schulze *et al* 2011; Schulze & Schütte 2019).

Climate change impacts on the Probable Maximum Precipitation (PMP)

The PMP is an extreme rainfall quantity applied by hydrologists and engineers to determine the Probable Maximum Flood, an extreme flood quantity used in the design of high-hazard hydrological structures (Wang 1984). Many observations of global climate trends have raised an increasing concern that the PMP will change due to the influence of a changing climate (Rouhani 2016). The potential influences of climate change on key variables for PMP estimation, such as maximum moisture and precipitation efficiency, have been studied (Clark 1987; Rastogi *et al* 2017). Results of this research suggest that changes in both atmospheric temperature and the maximum atmospheric moisture that can be held may increase PMP estimates by around 20% due to climate change (Clark 1987; Rastogi *et al* 2017). In South Africa, Johnson & Smithers (2020) revised the PMPs using an updated rainfall database and a modernised methodology. Many of the extreme events noted in the study occurred after the previously estimated PMPs published by the Hydrological Research Unit at the University of the Witwatersrand (HRU (1972). Approximately 80% of the new PMPs are greater than the corresponding HRU (1972) estimates, with some new estimates shown to be greater than five times the previous estimates. This indicates that there has been an increase in extreme rainfall events and that the PMP estimates are influenced by the length of rainfall records. As such, Johnson & Smithers (2020) recommend that a database of extreme rainfalls should be continually updated and used to revise the PMP following the occurrence of new extreme rainfall events.

Several non-stationary statistical analyses of extreme rainfalls indicate that it is likely that the PMP will change into the future (Cheng *et al* 2014; Gao *et al* 2016; Wi *et al* 2016). Studies of the impact of climate change on PMP estimates on a global scale conclude that, as future atmospheric water vapour concentrations increase due to climate change, the PMP values for future climate conditions should increase as well (Kunkel *et al* 2013). Such increases would consequently have severe implications for the design of new large hydraulic infrastructure, as well as of existing infrastructure (Clark 1987; Stratz & Hossain 2014; Clavet-Gaumont *et al* 2017). The following factors should be considered when assessing the possible impacts of climate change on PMP: moisture availability, depth–area curves, storm types, storm efficiency and generalised rainfall depths. Moreover, changes in observed and projected extreme rainfall should both be taken into account (WMO 2009b).

Modelling the impacts of climate change

Climate change scenarios can be constructed in many ways. The most widely applied method to project climate is the use of outputs from Global Circulation Models (GCMs). GCMs can simulate the key features of the global climate relatively reliably at a large scale. However, these models often cannot characterise impacts at a local scale due to their low spatial resolution and limited description of sub-grid processes (Bergant *et al* 2006). For the assessment of potential climate change impacts on local vulnerabilities, managers and decision-makers may require information to be at a refined local scale. Thus, climate change impact analyses are dependent on GCM outputs that are downscaled to a local scale by linking them to regional or local climate characteristics (Schulze *et al* 2011; WRF 2014).

Global circulation models

The earth's climate is governed by the interactions between many extensive and complex processes. Consequently, the impacts of increasing greenhouse gas concentrations on climate cannot be quantitatively predicted by intuitive reasoning. Thus, GCMs, which represent the planet's system mathematically, have been developed (Jacob & Van den Hurk 2009). In order to simulate the earth's climate system realistically, various physical processes of the global climate system are defined numerically in these computer models. Scenarios of greenhouse gas emissions to the atmosphere are used as inputs for GCMs. The GCM outputs are then used to generate climate change scenarios which are in turn used to model impacts of climate change on human and natural systems (Trzaska & Schnarr 2014). There have been numerous improvements in climate change research over the past three decades, which have strengthened the confidence in the predictive capabilities of climate models (Halmstad *et al* 2012). However, there is still significant uncertainty involved in estimating future extreme events when using such models, and it must be noted that it is impossible to predict future climate scenarios with any degree of accuracy (Das & Simonovic 2012; Delgado *et al* 2014).

Regional climate downscaling

GCMs can be made relevant to local impact assessments by the use of downscaling techniques and bias correction. There are two principal approaches used to downscale large-scale climate projections to a more local scale, namely dynamical downscaling and statistical downscaling (Trzaska & Schnarr 2014).

Dynamical downscaling

Dynamical downscaling is used to generate climate change scenarios at a higher spatial resolution (about 30 to 50 km) and higher temporal resolution (time-step of six hours) and is achieved by the explicit inclusion of additional data and physical processes in higher resolution Regional Climate Models (RCMs) covering selected portions of the globe (Willows & Connell 2003; Trzaska & Schnarr 2014). Although this method has many advantages, it requires large volumes of data and is computationally intensive. Moreover, in order to implement and interpret results, a high level of expertise is needed (Trzaska & Schnarr 2014). Despite limitations of RCMs, the use of these models is becoming increasingly popular (Halmstad *et al* 2012; Lawrence *et al* 2012; Willems *et al* 2012; Cullis *et al* 2015; Maraun & Widman 2015; Shongwe *et al* 2015; Rouhani 2016).

Statistical downscaling

Statistical downscaling involves the establishment of statistical relationships between large-scale climate variables and local-scale variables at a daily timescale (Willows & Connell 2003, Trzaska & Schanrr 2014). These relationships are applied to the GCM outputs to obtain future local climate change projections. Statistical methods require minimal computing and are simple to implement and interpret. The use of statistical techniques is advantageous, as the GCM can be downscaled to a particular point, which can be used to obtain selected projections at a particular site, e.g. rainfall projections to be used as input for hydrological models (Willows & Connell 2003). These methods rely on historical climate observations of large-scale atmospheric circulation and the assumption that the current observed relationships will continue into the future (Zorita & Von Storch 1999).

Climate model downscaling in South Africa

In South Africa there are two main centres for climate modelling: the University of Cape Town Climate System Analysis Group (CSAG) and the Council for Scientific and Industrial Research (CSIR). The CSAG focuses on climate change projections (*inter alia*) and in the past has often made use of the statistical downscaling process to derive regional climate change scenarios from global scenarios produced by GCMs (Schulze *et al* 2011). The CSIR focuses on the use of a variable-resolution Conformal-Cubic Atmospheric Model (CCAM) which is dynamically downscaled and runs globally at higher resolutions (Engelbrecht *et al* 2011).

Climate futures for South Africa and recommendations

Based on climate modelling studies, an increase in heavy precipitation is likely, defined as a likelihood of at least 90%, throughout the world in the 21st century (Field *et al* 2012). In South Africa, the Long-Term Adaption Scenarios (LTAS) project used CSAG and CSIR downscaled projections from two recent generations of GCMs, namely Coupled Model Intercomparison Project Phase 3 and Phase 5 (CMIP3 and CMIP5) and emission scenarios that were used in the Fourth and Fifth IPCC assessments. The CSIR downscaled the CMIP3 for emission scenario A2 and CMIP5 for Representative Concentration Pathways RCP4.5 and RCP8.5. The CSAG downscaled the CMIP3 for emission scenarios A2 and B1, and Representative Concentration Pathways RCP4.5 and RCP8.5. Table 1 summarises the mean projected changes in precipitation for these different emission scenarios for the different downscaling methods. The South African LTAS and the Intergovernmental Panel on Climate Change (IPCC) indicate that increases in temperature and the frequency of extreme rainfall occurrences are likely to continue in future (IPCC 2014; Ziervogel *et al* 2014; IPCC 2017). In South Africa, based on various temperature projections for future periods (2081–2100), temperatures are expected to increase by 3–6ºC when compared to a reference period (1986–2005). However, changes in magnitudes of precipitation are less certain.

Climate models project changes in precipitation that are more temporally uneven than present-day precipitation, indicating that most of the annual rainfall is likely to occur over a shorter period than in the past. This suggests that the intensity of heavy rainfalls is likely to increase (Pendergrass & Knutti 2018). It is anticipated that most of southern Africa will experience warming trends

Table 1 **Summary of the ensemble mean projected changes in precipitation into the 2080s for different emissions scenarios and different downscaling methods (Ziervogel *et al* 2014 – reproduced here under a Creative Commons open-access agreement)**

			Summer Rainfall Region			Winter Rainfall Region		
			SON	DJF	MAM	MAM	JJA	SON
CSAG	CMIP5	RCP8.5	**↑**	**↑**	**↓**	**↓**	**↑**	**↑↓**
		RCP4.5	**↑**	**↑**	**↓**	**↓**	**↑**	↑
	CMIP3	A2	**↑**	**↓**	**↑**	**↑**	**↑**↓	**↑↓**
		B1	**↑↓**	**↑**	↓	↑	↑	**↑**↓
CSIR	CMIP5	RCP8.5	**↓**↑	**↑**↓	**↓**	**↓**	**↓**	**↓**
		RCP4.5	**↑↓**	**↑↓**	**↑↓**	↓	↓	↓
	CMIP3	A2	↑↓	↑↓	↑↓	↑↓	↓	↓

SON: September, October, November **DJF:** December, January, February
MAM: March, April, May **JJA:** June, July, August

Single arrow implies consistent direction of change across the summer or winter rainfall region respectively, with upward and downward arrows indicating increases and decreases respectively; large and small arrows indicating strong and weak responses, and upward and downward arrows together indicating areas of both increase and decrease in the rainfall region.

Source: Extracted via analysis of the projection maps within South African LTAS.

and increased rainfall variability, with increased heavy rainfall events and associated flooding (Midgley *et al* 2011). Analysis of downscaled climate models has shown that climate change impacts may result in increased precipitation in parts of the country and increased drying trends in others (Cullis *et al* 2015; Schulze & Schütte 2019). Furthermore, changes in extreme rainfalls affect estimates of design rainfalls. Although design rainfalls may be projected to decrease in parts of the country, projected increases of long duration design rainfalls in South Africa are generally in the range of 10–20% (Schulze *et al* 2011) and could be up to 40% in some parts (Schulze & Schütte 2019). Potential future flood risks due to increased extreme rainfall events have increased across most of the country, which may further impact existing structures (Department of Environmental Affairs 2014a).

Most studies on extreme rainfall are based on frequency analysis assuming stationary conditions (Serinaldi & Kilsby 2015). Previous studies in South Africa have assumed a stationary climate. However, as the climate is ever-changing, the assumption of stationarity of annual maxima may not be reasonable for deriving design rainfalls (Ndiritu 2005; De Waal *et al* 2017). In addition, the frequency of extreme rainfall events has been changing and this is likely to continue in future (IPCC 2007; Field *et al* 2012). Hence, methods to account for trends in extreme rainfall events in a changing environment need to be developed (Smithers *et al* 2014). The need for concepts and models that account for non-stationary analysis of climatic and hydrologic extremes has been highlighted frequently in recent literature (Smithers 2012; Madsen *et al* 2013; Cheng *et al* 2014; Salas & Obeysekera 2014; Yilmaz *et al* 2014; Hounkpè *et al* 2015; De Waal *et al* 2017; Tan & Gan 2017; Mo *et al* 2018). Smithers (2012) suggested that dealing with non-stationary data, such as the projected impacts of climate change, should be taken into account for the development of new methods for design flood estimation in South Africa.

NON-STATIONARY ANALYSIS OF EXTREME RAINFALL

There are two main methods for analysing the frequency and severity of extreme events: Cumulative Frequency Analysis (CFA) or Extreme Value Analysis (EVA). For CFA the data, such as daily rainfall measurements, are used to construct a cumulative frequency distribution from which an extreme event with a defined frequency of exceedance with the data set can be defined. This approach has numerous limitations. It is not possible to estimate the probability of an extreme event that is larger than the maximum value in the data series. Furthermore, the threshold used for the identification of extreme events is objectively random and, consequently, it is likely that the frequency and quantity of extreme events obtained by CFA will be strongly dependent on the threshold chosen. EVA, however, is less constrained by these limitations (Francis 2011).

Extreme value analysis (EVA)

EVA is a statistical method of analysis. Using EVA, it is possible to estimate the probability and magnitude of events that exceed those in a given data series. EVA allows the estimation of the probability and magnitude of future events to be made based on limited historical data, e.g. a 30-year record of observed events can be used in the estimation of the risk/exceedance probability of extreme events beyond the 1 in 30-year recurrence interval. However, it must be noted that the degree of uncertainty in the projected risk of extremes increases as the return period reaches the length of available data, and the uncertainty increases even further when the return period exceeds the length of the data series (Coles 2001).

There are numerous frequency distributions, or statistical models, which can be used in EVA. Commonly, two general methods can be used: (1) the "Peak-over-threshold" (POT) method, and (2) the "block maxima" or Annual Maximum Series (AMS) method. The POT method is used to represent the behaviour of exceedances above a high threshold and the extreme values are analysed using a Generalised Pareto (GP) distribution (Coles 2001; Klein Tank *et al* 2009). The block maximum method considers the sample of extreme values by selecting the maximum value observed in each block. Generally, blocks are one hydrological year in length, but they can be one season in length. The Generalised Extreme Value (GEV) distribution is a frequently used distribution to analyse the block maxima (Klein Tank *et al* 2009). The GEV distribution is flexible for exhibiting the behaviour of extremes with three distribution parameters: location, scale and shape (Coles 2001). Other distribution methods used for EVA of rainfall include the Gumbel's Extreme Value Type 1 (EV1) distribution, the Log-normal distribution and the Log-Pearson Type III (LP3) distribution (WMO 2009a).

Accounting for non-stationarity in extreme value analysis

As stationarity is defined as the time invariance of the properties of extremes, for non-stationary processes the parameters of the underlying distribution are time-dependent (Katz 2010). Thus, the properties of the distribution vary with time (Francis 2011). EVA distributions can be used with non-stationary data by allowing for at least one of the parameters (e.g. location, scale or shape) to depend on a climate variable which varies over time (Kharin & Zwiers 2005). Climate variables which change with time are known as covariates, which can be defined to suit the user. As an example for local scale applications, it is known that precipitation may increase as temperature rises, hence an appropriate choice of covariate for accounting for non-stationarity due to climate change may be mean temperature (Francis 2011; Roth *et al* 2014). Accounting for non-stationary data in EVA using covariates has been successfully undertaken in numerous studies. Hounkpè *et al* (2015) tested the assumption of stationarity in estimating flood events, employing a statistical model which uses a time-dependent and/or covariate dependent GEV distribution to fit the annual max discharge, and found that the non-stationary model more adequately explains variation in the data in flood frequency analysis. In Denmark, a spatio-temporal model of extreme rainfall for short durations was developed using a non-stationary POT approach. The model was determined to be highly qualified to model spatio-temporal variability in the parameters of the GP distribution (Gregersen *et al* 2017). Tramblay *et al* (2011) and Tramblay *et al* (2013) used a non-stationary POT model with climatic covariates for heavy rainfalls in France. The covariates investigated included humidity fluxes, monthly air temperature and seasonal occurrence of southern circulation patterns. The studies determined that the non-stationary model provides a better fit to the data compared to the standard stationary model. Models that incorporate climatic covariates allow for the re-evaluation of the risk of extreme precipitation scenarios and can be useful for evaluating possible future changes (Tramblay *et al* 2013). In Finland, a non-stationary POT analysis method for extreme precipitation was developed incorporating covariates such as temperature and atmospheric circulation patterns. The results indicate that the non-stationary analysis of extreme precipitation is statistically valid for most of the observations and is independent of location or seasonality (Pedretti & Irannezhad 2019). A time-varying GEV distribution which incorporates the impacts of different non-stationary climatic conditions on extreme rainfall occurrences was developed for application in parts of North America. The results of that study show that extreme precipitation can be underestimated using the assumption of stationarity, thus highlighting the importance of updating design strategies for hydraulic infrastructure in changing climatic conditions (Sarhadi & Soulis 2017).

DISCUSSION AND CONCLUSION

Evidence that increases in greenhouse gas emissions due to anthropogenic activities have resulted in climate change has been widely documented. Increases in these gases have resulted in increased global temperatures. Higher temperatures are linked to significant changes in the magnitudes and frequencies of extreme precipitation events, and thus to increased flood risks. Numerous studies have shown that the changing climate has impacted rainfall in South Africa. In the past 15 years, many studies indicate that changing climatic conditions have resulted in variations in the occurrence of extreme precipitation events, and overall trends show that rainfall intensities have increased in many parts of the country, while few studies note a decrease in precipitation intensities. Changes in climate impact on the estimation of design rainfalls and extreme rainfall quantities such as PMP, which could potentially be up to five times greater at certain locations when compared to past estimates. Consequently, these changes may impact the future design of hydraulic structures. Moreover, the consequences of the changing climate may also impact on existing infrastructure (Department of Environmental Affairs 2014a). The impacts of climate change can be modelled using GCMs. These models can be used at a global scale or can be downscaled and bias-corrected for application at local scales. Data from downscaled GCMs can be analysed using EVA, which takes into account non-stationarity by means of covariates. Results of numerous studies indicate that the inclusion of climatic covariates in such analyses could improve the statistical modelling of extreme events.

Most previous studies of design rainfall and PMP estimation have been based on what has now been found to be the unrealistic assumption of a stationary climate. As such, methods that account for non-stationary data, such as climate change impacts, need to be developed. The impacts of the changing climate need to be considered in the estimation of design rainfall and PMP estimates to allow for the characteristics of the non-stationarity of the climate to be modelled into the design life of hydraulic structures. Internationally new approaches have been developed to account for the impact of climate change in extreme rainfalls for design flood estimation; however, in South Africa there has been relatively little research in this regard. For South Africa, the need to identify trends in extreme rainfall events due to a changing climate and the need to account for non-stationary data in the development of new methods for design flood estimation have been highlighted by Smithers (2012) and by Smithers *et al* (2014). Given the importance of flood risk management, the shortcomings of the methods currently used by practitioners and the potential impact of climate change, dealing with a non-stationary climate data series currently requires urgent attention in South Africa.

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