Climate Change Effects on Rainfall Extremes and Implications for Highway Drainage Structures

T. T. Tanyimboh[1,*] and N. Parbhoo[1]

[1]School of Civil and Environmental Engineering, University of the Witwatersrand, Johannesburg, Private Bag 3, WITS 2050, South Africa

*Corresponding author email: tiku.tanyimboh@wits.ac.za

Highlights

- Data analysed indicate increases in intensity and frequency of extreme rainfall events.
- Resilience of drainage structures to climate variability is integral to disaster management planning.

Introduction

Research was carried out to assess changes in extreme rainfall properties over time for the area surrounding the National Route 1 Section 29 (N1-29), located in Limpopo, South Africa. The study examined the changes in return levels for 1920-1970 and 1969-2019. The analysis showed that there is substantial change in the intensity of extreme rainfall events with increases of up to 16.9% and 14.3%, for the 20-year and 50-year return levels, respectively. This indicates an increase in the depth-duration-frequency of extreme rainfall events in the area for the period considered. Furthermore, it was found that almost all the major culverts in the section were unable to accommodate the stipulated design flood, indicating that the structures are highly susceptible to the effects of extreme rainfall events.

Study area

The study area surrounds the National Route 1, Section 29 (N1-29) located in Limpopo, South Africa. This section of the N1 connects the towns of Louis Trichardt with Musina and the Beit Bridge Border Post. The N1 serves as the main trade corridor between South Africa and Zimbabwe, and thus carries a high volume of heavy truck traffic travelling between South Africa and Zimbabwe and other SADC (Southern African Development Community) countries. The road is situated in a predominantly rural setting with low roadside development. It is classified as a Class 1 road by the South African National Roads Agency (SANRAL).

The N1-29 is situated in the northern part of the Limpopo Province, with predominantly summer rainfall and the natural vegetation is classified as savanna type bushveld (Knight Piesold, 2018). The climate of the region is dry sub-humid (moderate) with a Thornthwaite moisture index of -20 (Knight Piesold, 2018). The area receives most of its precipitation during the summer months of October to April. Winters are dry and moderate with the average rainfall for the months of May to September contributing only approximately 8% of the average annual rainfall. Maximum daily temperatures in the area range between 32.7 °C in November to 33.7 °C in January. The region experiences its lowest temperatures between June and July with the average daily minimum temperature ranging between 10.0 °C and 7.7 °C (Knight Piesold, 2018).

The South African Weather Service has two main weather stations which describe the precipitation of the catchments along the route. Details of these stations are provided in Table 1. As seen in the table, the town of Louis Trichardt, located south of the N1-29, experiences significantly more rainfall than the northern section of the route going towards Musina.

Table 1. Weather stations in the catchment of the N1-29

Weather stations	Average annual rainfall	Locations
Louis Trichardt Makhado	505 mm	5 km south of Louis Trichardt
Musina Macuville	344 mm	15 km northwest of Musina

Drainage structures along the N1-29

The N1-29 includes three road bridges and seven major culverts some of which are detailed in Table 2; W and D are the width and depth, respectively. Lesser culverts that are classified as having a cross-sectional area less than 5 m^2 were excluded from the scope of the investigation. The respective catchment areas of the culverts were derived from SRTM (Shuttle Radar Topography Mission) digital elevation data in Global Mapper, a geographic information system software package, and checked against 1:50 000 topographical maps of the study area to verify the accuracy (Knight Piesold, 2018).

Table 2. Selected culverts close to the Musina Macuville Weather Station

Culvert names	Dimensions (W × D) (m)	Catchment areas (km^2)	Closest weather station	Mean annual precipitation (mm)
Mutamba Ranch Culvert	3.0 × 2.0	0.080	Musina Macuville	344
Jooste Culvert	3.1 × 1.5	3.940	Musina Macuville	344
Bloukop Culvert	3.1 × 2.4	6.930	Musina Macuville	344

Data used in the study

Rainfall data for the period of 1920 to 2019 for the area were obtained from the South African Weather Service. Data were obtained for the Louis Trichardt Makhado and Musina Macuville weather stations. These stations were identified and selected based on their close proximately to the route. The rainfall data for each station were divided into two periods of equal length (1920-1970 and 1969-2019). Any missing values from the rainfall data obtained were replaced with a value of zero to allow processing by the statistical software package used. The peaks over threshold method uses data points above a specified threshold, thus the input of zero for missing rainfall values should not influence the extreme value distribution greatly (De Waal, 2012).

The data sets were then stored in MS Excel (.xls) format and later converted to csv files to be read into the R statistical software used for subsequent analyses. As seen in Figure 1, the area receives most of its rainfall during the summer months from December to February, with very little rain in the Winter season. The overall average monthly rainfall for the data obtained was found to be 41.5 mm and 24.9 mm for the Louis Trichardt and Musina Macuville weather stations, respectively.

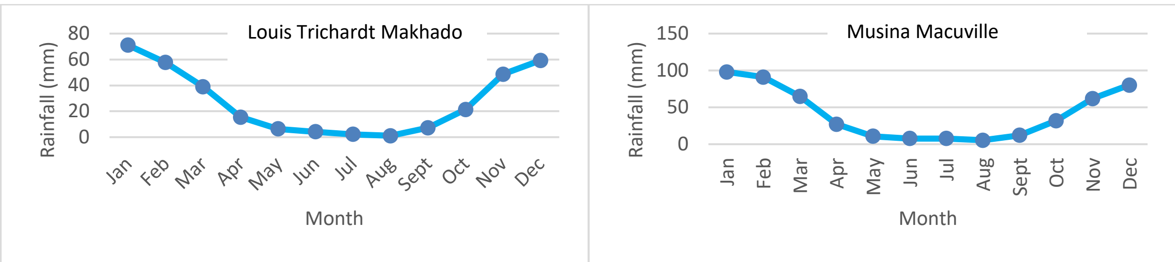

Figure 1. Mean monthly rainfall for Louis Trichardt Makhado and Musina Macuville weather stations

Methodology

Two approaches to the calculation of extremes are the block maxima and peaks over threshold methods. While the block maxima approach is commonly used, the method has a significant limitation when analysing changes in rainfall extremes over time. Katz (2010) mentioned that the block maxima method omits all extreme rainfall events occurring in a calendar year that are lower than the maximum value for that year. As a result, it is difficult to determine whether there is any significant change in the frequency of the occurrence of severe rainfall events (De Waal, 2012).

Thus, the peaks over threshold method was used herein. The method fits all data points exceeding an extreme value threshold to a Generalized Pareto Distribution (UCAR, 2010) and is better suited to the investigation of changes in return periods and levels. The 95th percentile value was taken as the threshold value for each rainfall data set due to the relative ease of computation and further supported by several studies in the literature (Karl et al., 1995). The R opensource software for statistical analysis and graphics (Venables and Smith, 2012; R Project, 2019) was used to fit the Generalized Pareto Distribution to the data sets. Recurrence intervals for the periods 1920-1970 and 1969-2019 for each rainfall station were thus obtained.

Flood peaks were determined from the return levels obtained using the Standard Design Method, the preferred method of the South African National Roads Agency (SANRAL) for sizing new hydraulic structures (SANRAL, 2013). The 1:50 year flood peaks were used to determine the hydraulic adequacy of the major culverts located on the route. River bridges were not considered as they were beyond the scope of the research. River bridges are sized for the 1:100-year flood which was not considered due to insufficient data.

Results and discussion

The results show that there is substantial change in the intensity of extreme rainfall events for the rainfall stations considered. Increases of 16.9% and 3% were found for the 20-year return level for the Louis Trichardt and Musina Macuville weather stations, respectively, and 14.3% and 10.6% increases, respectively, were observed for the 50-year return level. This indicates an increase in the depth-duration-frequency of extreme rainfall events in the area surrounding the N1-29. It also indicates that stationarity cannot be assumed for the extreme rainfall at a weather station (Milly et al., 2008). A greater return level increase was observed for the Louis Trichardt weather station than Musina Macuville station. This could possibly correspond to their associated mean annual precipitation values of 505 mm and 433 mm, respectively, as there are studies that suggest that areas of low rainfall are experiencing dry conditions.

The flood peaks calculated were used to determine whether the existing drainage structures can carry the respective design floods. Only one culvert out of seven had adequate hydraulic capacity; the rest were inadequate. The culverts were assumed to be inlet control structures when carrying out the hydraulic analysis (SANRAL, 2013; James, 2020). Although concerning, these results are not unexpected due to the age of the culverts that were built in 1970. The inadequacy of the hydraulic capacity of the structures can be attributed to their age as, previously, hydraulic structures located on National Routes in South Africa were sized according to the Rational Methods. These methods are known to result in flood peaks that are up to 60% lower than the more recently developed Standard Design Flood method (Smithers, 2012). Thus, it is expected that the existing structures would fail to meet the hydraulic capacity requirements. However, the percentage differences between the required capacities for the design floods and the existing capacities are much more than the 60% difference associated with the Standard Design Flood method, i.e., the structures were designed for a much lower flood level and thus are susceptible to the effects of any extreme rainfall events.

Conclusions and future work

Only two rainfall stations and two 50-year time periods were considered; longer rainfall records for the area were not available. The return level results revealed that extreme rainfall events are more frequent and of a greater quantum now than 50 years ago. This is important in the design of highway drainage structures. Existing structures should be examined to verify whether they require upgrading to mitigate any potential flood risk. Resilience to climate variability and extreme weather events are integral to the formulation of an adequate disaster management plan. Future work will consider infilling missing data (Nkiaka et al., 2016).

References

De Waal J. (2012). Extreme Rainfall Distributions: Analysing Change in the Western Cape. MSc dissertation, University of Stellenbosch.

James C. S. (2020). Hydraulic Structures. Springer.

Karl T. R., Derr V. E., Easterling D. R., Folland C. K., Hofmann D. J., Levitus S., Nicholls N., Parker D. E., Withee G. W. (1995). Critical issues for long-term climate monitoring. Climatic Change, 31, 185-221.

Katz R. W. (2010). Statistics of extremes in climate change. Climatic Change, 100, 71-76.

Knight Piesold (2018). Drainage Report. Knight Piesold, Johannesburg, South Africa.

Milly P., Betancourt J., Falkenmark M., Hirsch R., Kundzewicz Z., Lettenmaier D., Stouffer R. (2008). Stationarity is dead: Whither water management? Science, 319, 573-574.

R Project (2019). The R Project for Statistical Computing. https://www.r-project.org/ (accessed 15 September 2019).

SANRAL (2013). Drainage Manual, 6th edn. The South African National Roads Agency SOC Ltd., Pretoria.

Smithers J. (2012). Methods for design flood estimation in South Africa. Water SA, 38(4), 633-646.

UCAR (2010). Statistics of Weather and Climate Extremes. http://www.isse.ucar.edu/extremevalues/back.html.

Venables W. M., Smith D. N. (2012). An Introduction to R. http://cran.r-project.org/doc/manuals/R-intro.pdf. (accessed 5 October 2019). R Development Core Team.

Nkiaka E., Nawaz R. N., Lovett J. C. (2016). Using self-organizing maps to infill missing data in hydro-meteorological time series from the Logone catchment, Lake Chad basin. Environmental Monitoring and Assessment, 188, DOI: 10.1007/s10661-016-5385-1.