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Long-term trends of heavy rainfall in South Africa

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Abstract The long-term trends of heavy rainfall in South Africa were analysed using the annual maximum rainfalls of 1–7 days duration of 786 representative rainfall series. Using the Mann-Kendall indicator-of-trend test, 42.1% of the series gave significant increases of the annual maxima at the 90% significance level while only 9.5% indicated a significant reduction. The Mann-Kendall magnitude-of-trend test identified overall average increases of annual maxima ranging from 0.087 to 0.126 mm year^{-1}. A comparison of the mean of the first and the second half of each series obtained average increases varying from 13.0 to 15.2 % over durations that averaged to 58 years. This study reveals that annual maxima of 1–7 day duration have been increasing in South Africa and it may not be justified to ignore these trends without verifying their insignificance.
Key words annual maxima; heavy rainfall; long-term trends; Mann-Kendall test; South Africa

INTRODUCTION

The realistic estimation of high intensity rainfall is invaluable for the estimation of design floods required in the design of flood damage mitigation structures including bridges, channels and flood storage reservoirs. The effectiveness of non-structural flood damage mitigation measures such as flood plain zoning also depends on the realistic estimation of the design rainfall. Estimates of high intensity rainfall are also used to estimate soil loss and vegetation damage from high intensity storms (Smithers & Schulze, 2000a). Typically, depth–duration–frequency and intensity–duration–frequency relationships are obtained from analysis of the available rainfall data—a process that does not allow for trends in rainfall. If significant trends in heavy rainfall exist, designs based on these relationships may lead to underdesign or overdesign. This study makes use of a comprehensive database of daily rainfalls in South Africa (Lynch, 2002) to find out whether there are detectable trends in the annual maximum rainfalls of medium to long duration (1, 3, 5 and 7 days), estimate their magnitude, and explore their spatial distribution. Autographic rainfall data in South Africa is of short duration with only 12 stations of length greater than 40 years (Smithers & Schulze, 2000b) and is therefore inadequate for analysis of long-term trends.

METHODOLOGY

The database applied (Lynch, 2002) consists of historical daily rainfalls from 11 705 rainfall stations. Representative stations were obtained for each square grid of 0.25° × 0.25° throughout South Africa. The series of longest duration within each and with 60 or more years of complete observed daily data was selected as the representative. Grids without stations with at least 60 years of data were unrepresented. This process gave a total of 786 stations for analysis. Changes in a series could occur in many ways including a gradual trend, a sudden (step) change over a small proportion of the period that data is available, or a combination of several changes (Kundzewicz & Robson, 2004). The analysis here was confined to the detection of gradual trends. The tests carried out were: Mann-Kendall's trend detection test, Mann-Kendall's magnitude-of-trend estimator, and the comparison of the mean and the standard deviation of the annual maxima of the first and the second half of each series. No step change tests were carried out.

Mann-Kendall's trend detection test

Mann-Kendall's trend detection test is non-parametric and has the advantage of not requiring a continuous series and was therefore appropriate for the analysis here as all the series had discontinuities. The test has been used to detect hydro-climatological trends (Lettenmaier *et al.*, 1994; Ndiritu, 2003) and to analyse trends of water quality data (Yu *et al.*, 1993; Hirsh *et al.*, 1982). If r_i represents the annual maxima for year i ($1 \le i \le n$), the statistic S for was computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(r_i - r_j) \tag{1}$$

where

$$\operatorname{sgn}(x) = \begin{cases} 1 & \text{if} \quad x > 0 \\ 0 & \text{if} \quad x = 0 \\ -1 & \text{if} \quad x < 0 \end{cases} \tag{2}$$

The variance of S was computed as:

$$\operatorname{var}(S) = \frac{n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)}{18} \tag{3}$$

where t was the extent of any given tie (the number of annual maxima in a given tie).

Both Mann and Kendall showed that for even small lengths of data (e.g. $n = 10$), the distribution of S closely approximates the normal distribution if the standard normal variate Z is computed as:

$$Z = \begin{cases} \dfrac{S-1}{\operatorname{var}(S)^{\frac{1}{2}}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{S+1}{\operatorname{var}(S)^{\frac{1}{2}}} & \text{if} \quad S < 0 \end{cases} \tag{4}$$

Hirsh *et al.* (1982) showed that the normal approximation works quite well even for records as short as three years. Once Z has been obtained, the presence or absence of a trend at specified significance levels can be determined.

Mann-Kendall magnitude of trend test

By this method, an estimate of the trend magnitude is taken as median of the set of the slopes obtained from all possible pairs of the data points in the series. The magnitude denoted as M_1 was obtained as

$$M_1 = \text{median}(D_{i,j}) \quad \text{where} \quad D_{i,j} = \frac{r_i - r_j}{(i-j)} \quad \text{for all pairs} \quad 1 \le i \le j \le n \tag{5}$$

with the same notation as the trend detection test.

Comparison of the mean and standard deviation of sub-series

To quantify the change in mean and standard deviation of the annual maxima, each series was divided into two, with each sub-series having an equal number of years with complete data ($n/2 \ge 30$). If n was odd, then the middle value in the series was not used in the computation.

RESULTS

Table 1 presents a summary of the analysis of trend detection and estimation of the magnitude of trend by the Mann-Kendall method. The second column gives the average of the standard normal variates obtained for all the 786 series. Columns 3 to 8 show the percentage of the stations that gave significant increasing and decreasing trends at 90, 95 and 99% significance levels. Column 9 shows the average magnitude of trend and column 10 the percentage of stations that indicated a positive magnitude of trend. These results clearly indicate that on the average, there has been an increase in the annual maxima for all the durations in the region covered by the analysis which covers more than 90% of South Africa.

Table 1 Results of Mann-Kendall analysis.

Length of maxima (days)	Mean Z	Percentage of stations indicating significant trend: Increase			Decrease			Mean M_1 (mm year^{-1})	% of $M_1 > 0$
		90%	95%	99%	90%	95%	99%		
1	1.342	42.1	36.0	27.1	9.5	6.6	3.1	0.087	69.2
3	1.300	45.2	38.4	26.5	8.9	5.7	2.9	0.115	70.0
5	1.218	44.3	36.0	27.1	9.0	6.2	2.7	0.120	69.2
7	1.169	43.9	35.1	26.2	9.2	6.1	3.1	0.126	69.6

Table 2 Comparison of mean and standard deviation of first and second half of annual rainfall maxima series.

Length of maxima (days)	Mean				Standard deviation		
	First half (mm)	Second half (mm)	% increase	M_2 (mm year^{-1})	First half (mm)	Second half (mm)	% increase
1	45.2	50.4	15.2	0.087	21.6	23.2	14.3
3	63.1	70.4	14.2	0.124	29.0	32.5	18.8
5	71.5	79.3	13.4	0.133	31.5	36.4	22.2
7	78.1	86.5	13.0	0.143	33.5	38.8	22.9

Comparison of the mean of the annual maxima of the first and the second half of each series also revealed an increase in the maxima as can be seen in columns 2–5 of Table 2. The estimates of trend magnitude whose averages are in column 5 of Table 2 were obtained using equation (6):

$$M_2 = \frac{(aam_2 - aam_1)}{(0.5nl)} \tag{6}$$

where aam_1 and aam_2 are the averages of the annual maxima from the first and the second half of the series respectively, and *nl* is the actual length of data including years with discontinuous rainfall. It is noteworthy that the division of the series was based on the years with complete data and not *nl*. The average of the magnitude of trend estimates obtained by the two methods (M_1 and M_2) compared reasonably well for all four durations of annual maxima. Columns 6–8 of Table 2 indicate that, on average, the variability has also increased considerably. The average of the actual lengths (*nl*) was 116 years giving 58 years as the overall average time over which the percent increases in columns 4 and 8 of Table 2 happened. No significance level tests were carried out for the percent changes in the annual maxima in the first and the second half of the series. The average increases of magnitudes M_1 of Table 1 and M_2 of Table 2 are, however, comparable thus indirectly indicating that the Mann-Kendall results (Table 1) can give an indication of the significance of the changes in the average annual maxima (M_2). Graphical presentation showing the distribution of the changes in mean and standard deviation for the 786 stations are shown in Figs 1 and 2.

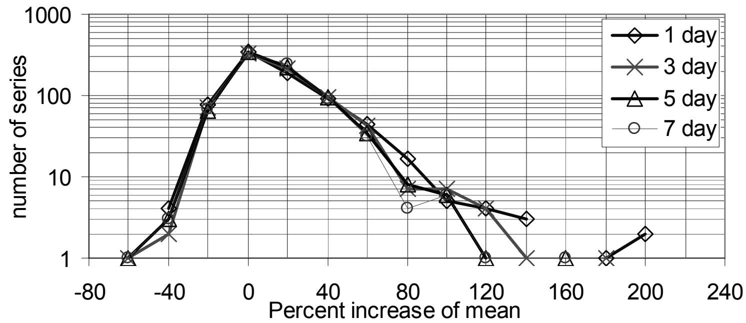

Fig. 1 The distribution of the change in mean annual maxima for 786 stations.

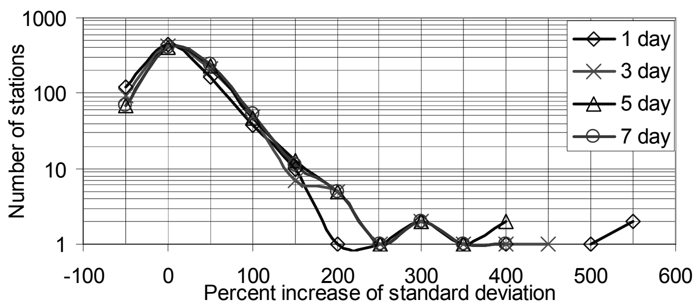

Fig. 2 The distribution of the change in standard deviation of annual maxima for 786 stations.

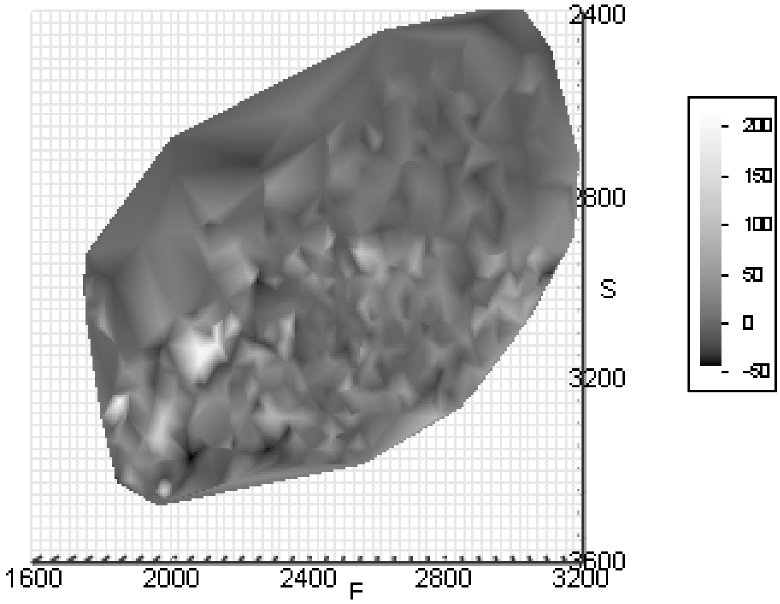

Fig. 3 Spatial distribution of the percent change in mean of annual maxima of 1-day duration.

It is again seen that there are many more stations exhibiting increases in the mean and the standard deviation than those giving reductions. This would still hold true even if upper tips of Figs 1 and 2 were considered outliers. An exploration of the spatial distribution of the percent increases (Fig. 3) indicates that some of the very high percent increases may not be outliers as they are lumped closely. In the region of high percent increase located near 31°S and 21°E in Fig. 3, six representative stations had percent increases greater than 120 with three of these exceeding 180. No comprehensive quality control was done in the selection of the representative stations and altered results may be obtained with this. It is however highly unlikely that the observed increase in trends would be invalidated even with a rigorous quality control. According to IPCC (2001), there has been a statistically significant increase in global precipitation over the 20th century. Several regional studies (Angel & Huff, 1997; Iwashima & Yamamoto, 1993; Suppiah & Hennessy, 1998; Pielke & Downton, 2000) also indicate overall increases in heavy rainfall magnitude.

IMPLICATIONS OF FINDINGS ON DESIGN RAINFALL ESTIMATION

The results have provided ample evidence that annual maximum rainfall in South Africa has been increasing. Long-duration rainfall estimates in South Africa (e.g. Smithers & Schulze, 2000) have been done on the basis that the maxima are stationary. Although the process of estimating design runoff is often riddled with many uncertainties, the changes in annual rainfall maxima obtained in this analysis may be large enough as not to be ignored. This is important considering that flood damage mitigation structures are usually long-term investments. These results call for studies for quantifying the impact of trends on the long-term performance of flood mitigation structures and other systems. If trends are significant, approaches to incorporate trends would then need to be developed. A practical approach may be the derivation of regional indices of trend.

CONCLUSIONS

An analysis of the long-term trends of annual maximum rainfalls of 1, 3, 5 and 7-day duration in South Africa using 786 representative series has revealed a general increase of the maxima over South Africa. For the 1-day maxima, Mann-Kendall analysis of trend detection showed that 42.1% of the series indicated an increase, while only 9.5% indicated a decrease at the 90% significance level. By dividing each series of annual maxima into two equal sub-series and comparing their mean and standard deviation, overall increases in the mean and standard deviation varying from 13 to 15.2% and 14.3 to 22.9%, respectively, were obtained. Estimates of the magnitude of trend obtained by Mann-Kendall's method obtained increases ranging 0.087–0.126 mm year^{-1}. Spatially, the changes in trend were found to be highly varied. One region with six representative stations that gave increases in mean exceeding 120% was identified.

These results indicate it may not be reasonable to assume annual maxima are stationary as is the usual practice in deriving design rainfalls. Studies for quantifying the effects of trends on the reliability of flood damage mitigation systems are considered valuable especially in this era of increased climatic uncertainty. If significant, practical approaches of incorporating trends would then need to be developed.

REFERENCES

Angel, J. R. & Huff, F. A. (1997) Changes in heavy rainfall in midwestern United States. *J. Water Resour. Plan. Manage.* **123**(4), 246–249.

Hirsh, R. M., Slack, J. R. & Smith, R. A. (1982) Techniques of trend analysis for monthly water quality data. *Water Resour. Res.* **18**(1), 107–121.

IPCC (Intergovernmental Panel on Climate Change) (2001) *Climate Change 2001: Synthesis Report* (ed. by R. T. Watson and the Core Writing Team). Contributions of Working Groups I, II, and III to the Third Assessment Report of the IPCC Cambridge University Press, Cambridge, UK.

Iwashima, T. & Yamamoto R. (1993) A statistical analysis of extreme events: long term trend of heavy daily precipitation. *J. Met. Soc. Japan* **71**, 637–640.

Kundzewicz, Z. & Robson, A. J. (2004) Change detection in hydrological records-a review of the methodology. *Hydrol. Sci. J.* **49**(1), 7–19.

Lattenmeir, D. P., Wood, E. F. & Wallis, J. R. (1994) Hydroclimatological trends in the United States. *J. Climate* **7**, 586–607.

Lynch, S. D. (2002) The development of an improved gridded database of annual, monthly, and daily rainfall. WRC Project K5/1156/0/1. Water Research Commission, South Africa.

Ndiritu, J. G. (2003) Long-term rainfall trends in South Africa. In: *South African National Committee of IAHS (SANCIAHS)* (ed. by D. A. Hughes) (Proc. 11th Symp., Port Elizabeth, South Africa), 5 pp in CDROM.

Pielke, R. A. & Downton, M. W. (2000) Precipitation and damaging floods: trends in the United States, 1932–97. *J. Climate* **13**, 3625–3637.

Smithers, J. C. & Schulze, R. E. (2000a) Long duration design rainfall estimates for South Africa. *WRC Report no. 811/1/00.* Water Research Commission, South Africa.

Smithers, J. C. & Schulze, R. E. (2000b) Development and evaluation of techniques for estimating short duration design rainfall in South Africa. *WRC Report no. 681/1/00*. Water Research Commission, South Africa.

Suppiah, R. & Hennessy, K. J. (1998) Trends in total rainfall, heavy rain events and number of raindays in Australia, 1910–1990. *Int. J Climatol*. **10**, 1141–1164.

Yu, Y., Zou, S. & Whittemore, D. (1993) Non-parametric trend analysis of water quality data of rivers in Kansas. *J. Hydrol*. **150**, 61–80.