

Long-term Rainfall trends in South Africa

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Abstract

Using the observed rainfalls from a recently developed daily rainfall database, the rainfall trends in South Africa are evaluated. Because of large discontinuities in data and seasonality, the non-parametric seasonal Mann-Kendall trend test and the Mann-Kendall magnitude of trend estimator are applied. The proportion of rainfall series at least 60 years long found to have trends are 60, 50 and 37% at the 90, 95 and 99% significance level. Rejection of rainfall series on the basis of trend may thus lead to significant non-use of valuable hydrological information and could bias designs and system performance evaluation.

An 11-year moving average analysis reveals no trend of the overall rainfall in South Africa. An analysis of the spatial variation of trend however suggests a downward trend to the west of Western Cape and an upward trend to the east of the Eastern Cape.

Introduction

Rainfall is the major input into the land phase of the hydrological cycle where water resource systems are planned, designed, constructed and managed. Rainfall is one of the major inputs of Water resource system models. Water resource system analysts are always keen to check for rainfall trends (Basson *et al* (1994)). Rainfall series that exhibit significant trends are at times regarded suspicious and discarded (e.g. Department of Water Affairs and Forestry (2000)). It is probable that trends are not an indication of errors in data and discarding such data may not be justified. Discarding data on the basis that it has significant trend could bias hydrologic design and estimates of the long-term system performance. This paper reports an analysis of South Africa's observed long-term rainfalls for trends. The analysis evaluated the extent of the trends and their spatial variation. A recently developed daily rainfall database (Lynch (2002)) provided the rainfall data.

Method of Analysis

The daily rainfalls obtained from the daily rainfall database (Lynch (2002)) were aggregated into months and years. Years with incomplete observed records,

with data problems and all series shorter than 20 years were discarded. This left 5292 series out of the 11705 series contained in the database. Because of the large discontinuities of the annual series and high seasonality, the non-parametric seasonal Mann-Kendall test was used as an indicator of trend. The Mann-Kendall magnitude of trend estimator was used to quantify the trend magnitude. The trend estimator was modified to apply annual rainfalls instead of monthly rainfalls in order to reduce the required computational effort.

Mann-Kendall seasonal test

The Mann-Kendall test has been used by Lattenmeir *et al* (1994) to study the hydro-climatological trends in the continental United States. Yu *et al* (1993) and Hirsh *et al* (1982) have applied the Mann-Kendall test to analyze trends of water quality data. A description of the test as applied here follows.

Let $rm_{i,j}$ represent the monthly rainfall for month i of year j . If there are n_i years of data, the trend indicator statistic S_i for month i is computed as

$$S_i = \sum_{k=1}^{n_i-1} \sum_{j=k+1}^{n_i} \text{sgn}(rm_{i,k} - rm_{i,j}) \quad (1)$$

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

The variance of S_i is computed as

$$Var[S_i] = \frac{n_i(n_i-1)(2n_i+5) - \sum_{t_i} t_i(t_i-1)(2t_i+5)}{18} \quad (3)$$

where t is the extent of any given tie (the number of rainfalls in a given tie).

Equations 1-3 describe the Mann-Kendall test (Mann (1945), Kendall (1975)) that is applied to deseasonalized or non-seasonal data. Both Mann and Kendall showed that for even small lengths of data (e.g. $n_i = 10$), the distribution of S_i closely approximates the normal distribution if one computes the standard normal variate Z as follows.

$$Z = \begin{cases} \frac{S_i - 1}{\sqrt{Var(S_i)}} & \text{if } S_i > 0 \\ 0 & \text{if } S_i = 0 \\ \frac{S_i + 1}{\sqrt{Var(S_i)}} & \text{if } S_i < 0 \end{cases} \quad (4)$$

Hirsh *et al* (1982) showed that the normal distribution approximation works quite well even for records as short as 3 years. To prevent bias that seasonality would cause if annual rainfalls were used, the monthly statistics were summed up to obtain the overall trend statistic S' .

$$S' = \sum_{i=1}^{12} S_i \quad (5)$$

The variance of the overall statistic was obtained as

$$Var[S'] = \sum_{i=1}^{12} Var[S_i] + \sum_{i=1}^{12} \sum_{l=1, l \neq i}^{12} cov(S_i, S_l) \quad (6)$$

The covariance between month i and month l $cov(S_i, S_l)$ was estimated using the method proposed by Deitz and Killeen (1981) and applied by Hirsh and Slack (1984).

$$cov(S_i, S_l) = \frac{K_{i,l}}{3} + \frac{(n_{i,l}^3 - n_{i,l})r_{i,l}}{9} \quad (7)$$

where

$$K_{i,l} = \sum_{m < p} \text{sgn}[(rm_{i,p} - rm_{i,m})(rm_{l,p} - rm_{l,m})] \quad (8)$$

$$r_{i,l} = \frac{3}{n_{i,l}^3 - n_{i,l}} \sum_{m,p,q} \text{sgn}(rm_{i,p} - rm_{i,m})(rm_{l,p} - rm_{l,q}) \quad (9)$$

where $n_{i,l}$ is the number of years where all monthly data for months i and l is complete. The analysis here used only years with complete data so n_i was the same for all months. The overall standard normal distribution variate was computed by applying the overall statistic S' to equation 4.

Mann-Kendall slope estimator

The Mann-Kendall test detects trends but does not estimate their magnitude. The slope estimator estimates the magnitude. The estimator as applied by Hirsh *et al* (1982) used seasonal values. In the current analysis, annual rainfalls were used. The estimator B was obtained as

$$B = \text{median}(D_{j,k}) \quad (10)$$

where $D_{j,k} = \frac{ra_j - ra_k}{(j - k)}$

for all pairs $1 \leq j < k \leq n$

where ra_j is the rainfall in year j and n is the total number of years of data.

Results and discussion

Figure 1 shows the standard normal distribution variate Z (for the trend indicator S') and the magnitude of trend estimator B values for the 5292 rainfall series. Figure 1 illustrates how Z and B vary with the length of series. The trend indicator variate (Z) is independent of the length of data while the trend magnitude (B) is highly

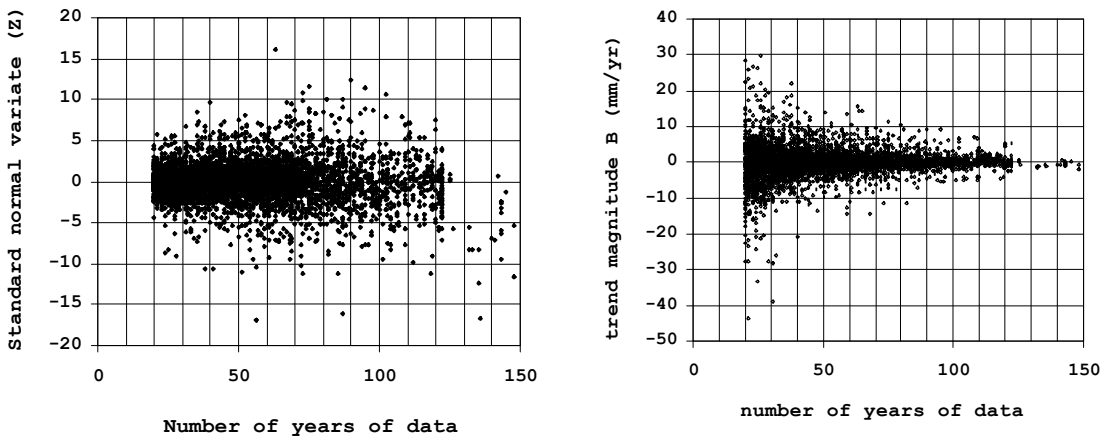


Figure 1: Standard normal variate of trend indicator (Z) and magnitude of trend (B) for 5292 stations.

dependent on the length of data. Most of the series 130 years or longer obtained negative Z and B values suggesting a long-term reduction of rainfall with time. Figure 1 also reveals that a large proportion of the series exhibit significant trends. Sixty percent of the series equal to or longer than 60 years (1985 out of the 5292) have significant trends at the 90% level. The percentages at 95 and 99% significance level are 50.7 and 37.1% respectively.

The overall average values of Z and B for the 5292 rainfall series were -0.015 and -0.007 respectively. There were 95 series at least 120 years long with most being located in the Southern third of South Africa. These gave an average Z value of -2.017 and an average B of -0.0624 . Plots of Z and B against longitude and latitude for the 95 series revealed some clustering. Figure 2 illustrates this. The clustering indicates that the observed trends are unlikely to be the result of errors in measurement.

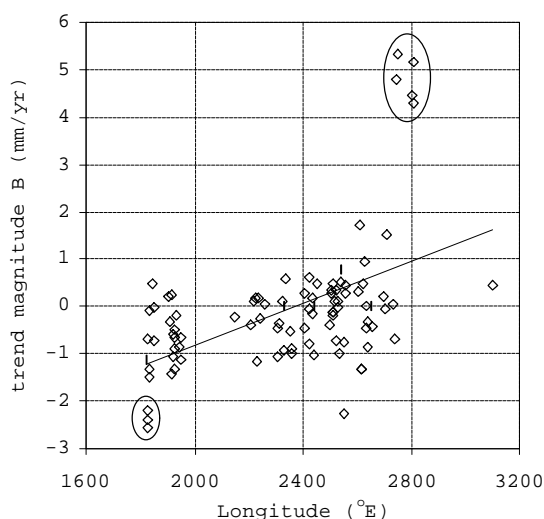


Fig. 2. Variation of trend magnitude with longitude for all series at least 120 years

Because the spatial distribution of the rainfall stations is not uniform, values obtained by simple averaging are biased towards areas with a higher density of stations. An additional analysis using a single representative series for each 1° by 1° grid was therefore carried out. The longest series within a grid was

selected as the representative. Analysis was done for three cases: i) for all representative series at least 60 years long, ii) for all representative series at least 90 years long and iii) for all representative series at least 120 years long. Ninety nine representative series were at least 60 years long, 49 at least 90 years long and 23 were 120 years or longer. Figure 3 shows the spatial distribution of the stations which gives a reasonable coverage of south Africa. The average Z values were -0.037 , -0.617 and -1.674 for case i, ii and iii respectively. The corresponding values of the trend magnitude B were 0.283 , 0.352 and 0.113 . The average Z values indicate a downward trend while the average B values indicate an upward trend. These apparently conflicting observations are considered to be a consequence of a small sample sizes. The average of the 11-year moving averages of the 99 representative series at least 60 years long is shown in Fig. 4. An additional curve showing the

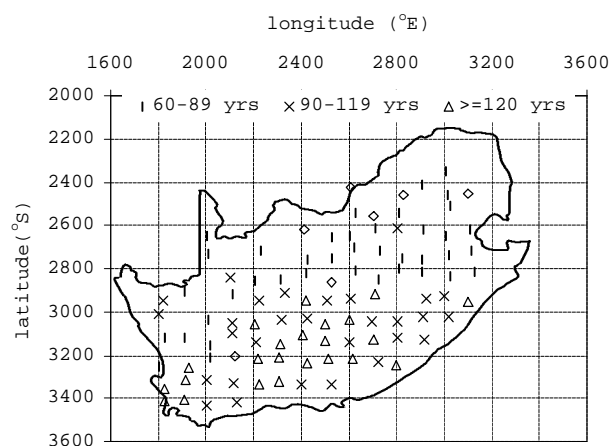


Fig. 3. Location of representative stations

number of representative series used for each year is also plotted in Fig. 4. Figure 4 reveals a high rainfall period from mid 1850s to 1870s. This is however based on only two representative stations located in neighbouring grids. The severe drought of the 1930s and the later ones of 1968 and 1982 are evident from Fig.4.

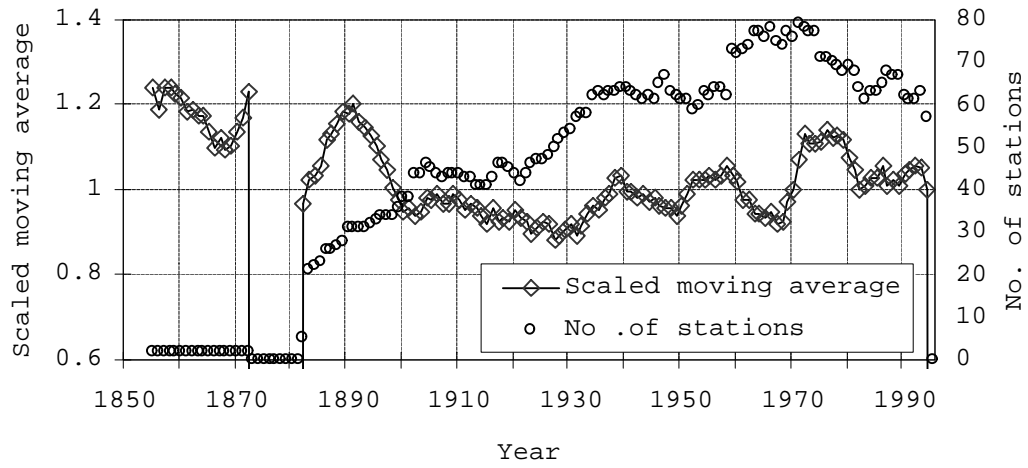


Fig. 4. Overall eleven year moving average plot and number of representative series.

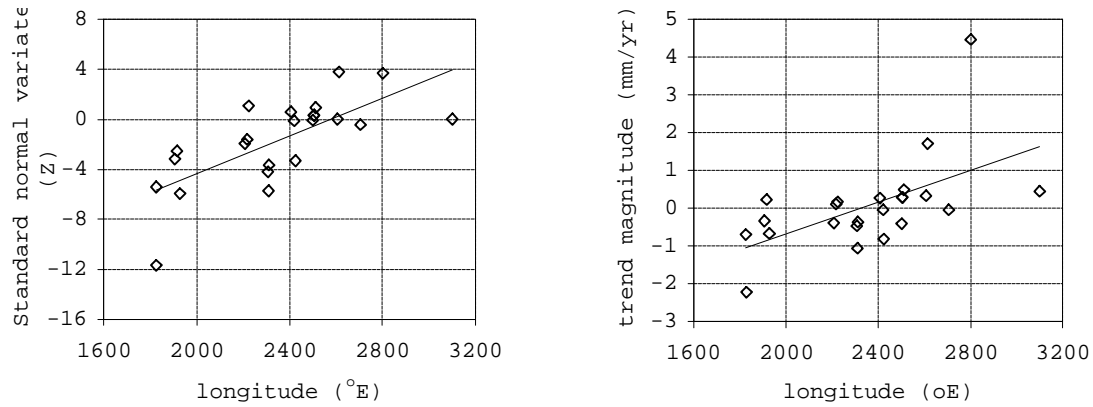


Fig. 5. Variation of standard normal variate (Z) of trend indicator (S') and trend magnitude (B) with longitude for representative series 120 years or longer

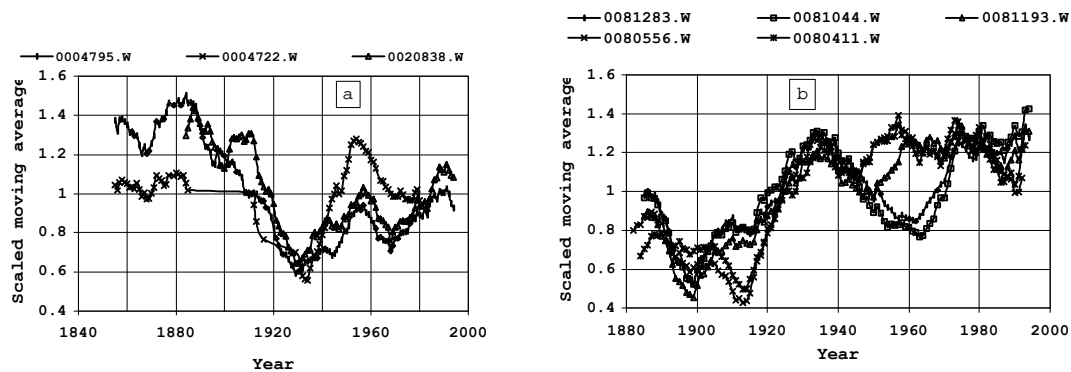


Fig. 6. Eleven year moving average plots for rainfall series clusters with large downward trends (a) and large upward trends (b)

Although the overall moving average gave no evidence of an overall trend, the spatial variation of Z and B reveals a probable decline of rainfall in the west of the Western Cape and an increase in the east of the Eastern Cape. Figure 5 illustrates this. Figure 6 shows the 11-year moving averages of some neighbouring stations where probable local climate change has occurred. These correspond to the clusters circled in Fig.2. A worrying observation from Fig. 4 is the steadily declining rainfall measurement coverage in South Africa since the early 1970s.

Conclusions

On the basis of the Mann-Kendall trend test, a large proportion of rainfall stations in South Africa possess significant trends. As an example, 50% of all series at least 60 years long have significant trends at 95% significance level. This is an indication that rainfall series with trends should not necessarily be viewed suspiciously. Discarding rainfall series on the basis of trend alone may simply mean the loss of valuable hydrological information and could lead to biased designs and biased estimates of water resource system reliability.

Acknowledgement

The rainfall database used was developed as part of the Water Research Commission project 'The Development of an improved gridded database of annual, monthly and daily rainfall'. The project is being carried out by the School of Bioresources Engineering and Environmental Hydrology (BEEH), University of Natal. The rainfall data for the project was obtained from the SA Weather Bureau, the SA Sugar Association, the Agricultural Research Council and private individuals.

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