ANALYSIS OF SPATIO-TEMPORAL TRENDS USING STANDARDISED PRECIPITATION INDEX (SPI)

Siti Nazahiyah Rahmat[1], Niranjali Jayasuriya[2], Mohd Shalahuddin Adnan[1] and Muhammed Bhuiyan[2]
[1]Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia
[2]School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia
E-Mail: nazahiya@uthm.edu.my

ABSTRACT

The trend of Standardised Precipitation Index (SPI) was investigated for more than 100 years of data using non-parametric trend technique Mann Kendall (MK) to detect wet (increasing) and dry (decreasing) periods across Victoria, Australia. Preliminary trend analysis was carried out for five different stations out of the 70 stations selected for this study. Out of five stations, two stations showed significant decreasing, indicating an increase in magnitude of dry periods. While the other two stations exhibited significant increasing trends. The analysis was repeated using recent data from approximately half the data set between 1949 and 2011. Contrasting results from the original full data set analysis were revealed. Based on the conclusions drawn from the preliminary analysis, the trend analysis was applied using the MK test for the remaining 65 stations for full set of data. Overall, 29 stations exhibited a significant downward trend. These regions have experienced frequent drought events and evidenced by the presence of a negative trend in the SPI series obtained from the present study. On the other hand, 21 stations showed a significantly upward trend, indicating a shift towards wetter conditions. No significant trend was identified for the remaining 20 stations. In addition, this paper analysed the spatial pattern of the historical droughts using SPI. Conclusions drawn from this paper, point to the importance of selecting the time series data length in identifying trends. Due to the climate variability, trend testing results might be biased and strongly dependent on the data period selected. Therefore, the use of full data set available would be required in order to improve understanding on change or before to undertake any further studies.

Keywords: mann kendall test, non-parametric trend test, standardised precipitation Index.

INTRODUCTION

Parametric and non-parametric methods are the most commonly used techniques to detect significant trends in hydro-climatologic time series (Tabari *et al.* 2011). The purpose of trend tests is to determine if the values of a random variable generally increase (or decrease) over a selected period of time in statistical terms (Helsel and Hirsch, 2002). To name a few, the Mann-Kendall (MK) and Spearman's Rho (SR) statistical tests are examples of non-parametric tests that have been applied to detect trends (Yue *et al.* 2002; Drapela and Drapelova, 2011; Paulo *et al.* 2012). One advantage of these tests is that the data do not have to fit any particular probability distribution to validate the tests. A number of studies have been carried out and concluded that SR provides results almost similar to those obtained for the MK test identifying time series trends (Yue *et al.* 2002; Yenigun *et al.* 2008; Nazahiyah *et al.* 2012; Tabari *et al.* 2012). Hence, the use of one of the techniques is sufficient to obtain a reliable result. In this current study, only MK test is applied.

Precipitation hardly follows a typical normal distribution for the whole duration of the data set, therefore Standardized Precipitation Index (SPI) has been computed to overcome this limitation for analyzing the wet and dry spell of precipitation (McKee *et al.* 1993; Shahid and Behrawan, 2008). The standardized precipitation index (SPI) is a probability-based indicator that depicts the degree to which the cumulative precipitation of a specific period departs from the average state. Due to its robustness and convenience to use, SPI has already been widely used to characterize dry and wet conditions in many countries (Paulo *et al.* 2005; Nalbantis, 2008; Khalili *et al.* 2011; Xu *et al.* 2011; Du *et al.* 2012). However, very few relevant studies have been carried out in Australia. Moreover, the SPI was proved to be a useful tool for assessing and monitoring meteorological droughts in Victoria (2014).

Therefore, the objectives of this study are: (1) to apply the SPI and (2) to determine the temporal trends of dry/wet conditions at five selected meteorological stations in Victoria using two different time periods of the precipitation data set. Based on the conclusions drawn from the analysis, the MK trend test was applied using the full data set for another 65 rainfall stations to determine the variability of SPI trends. The results obtained are presented and discussed.

DATA AND METHODS

Preliminary trend analysis was carried out for five different stations selected for this study (see Table-1). Irymple station is located in north-west Victoria and in the region of Mildura and has a long history of agriculture and irrigation. Rainbow and Edenhope stations are in the Wimmera-Mallee regions of western Victoria and cover the dryland farming area. Dookie station is located in the Goulburn Valley region and also part of the Murray-Darling Basin. This region is one of the most productive agricultural areas and mostly irrigated. MRO station is within the Yarra River catchment and located in the urbanised areas. These stations were selected as they are located within important catchment basins in Victoria, for

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primary production and for urban water supply. Due to the wide climatic difference prevailing in the province, the selected stations also represent both drier and wetter regions of Victoria. More than 100 years of monthly rainfall data were downloaded from the Bureau of Meteorology web site for the study. Based on the preliminary results, the trend test was then applied to other 65 rainfall stations in Victoria. The summary of number of years of rainfall data used for are given as a frequency diagram in Figure-1. The number of years of available data varied from one station with a minimum of 64 years to two stations with a maximum of 157 years of monthly data.

Table-1. Description of rainfall stations for the preliminary analysis.

Stn. ID.	Stn. Name	Mean Annual Rainfall (mm)
76015	Irymple (Arlington)	279
77051	Rainbow	349
79011	Edenhope (Post Office)	583
81013	Dookie	551
86071	Melbourne Regional Office	650

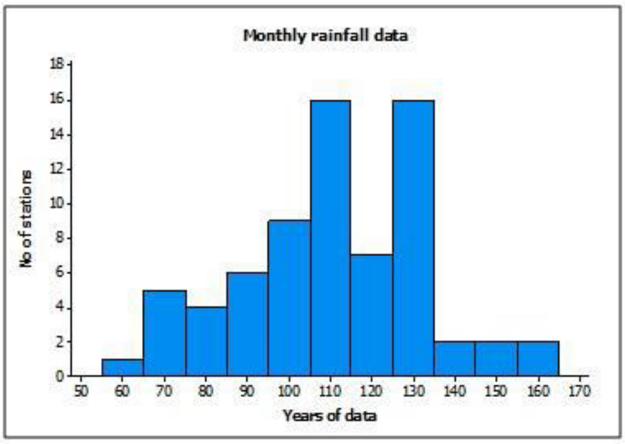


Figure-1. Histogram of number of years of rainfall data for all the 70 stations.

Detecting Trends using Mann-Kendall (MK) Test

In In this study, the non-parametric MK test is used to detect trends of the severity, magnitude and duration of droughts. The Mann-Kendall test is used for determining monotonic trends and is based on ranks (Helsel and Hirsch, 2002) takes into account a seasonality. This is a test for correlation between a sequence of pairs of values. The significance of the detected trends can be obtained at different levels of significance (generally taken as 0.05). The MK test statistic and the sign function are calculated using the formula:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \quad (1)$$

$$sign(x_j - x_i)\begin{cases} +1 & x_j > x_i \\ 0 \quad if & x_j = x_i \\ -1 & x_j < x_i \end{cases} \quad (2)$$

where, n is the number of data points, x is the data point at times i and j ($j > i$). The variance of S is as follows:

$$var\ (S) = \frac{1}{18}[n(n-1)(2n+5)] \quad (3)$$

For n larger than 10, the standard test statistic Z is computed as the *MK* test statistic as follows:

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

The presence of a statistically significant trend is evaluated using the Z value. Positive values of Z indicate increasing trends, while negative values show decreasing trends. To test for either an increase or decrease monotonic trend (a two-tailed test) at level of significance, H0 should be rejected if the $|Z| > Z1\text{-}\alpha/2$, where $Z1\text{-}\alpha/2$ is obtained from the standard normal cumulative distribution tables. For example, at the 5% significance level, the null hypothesis was rejected if $|Z| > 1.96$. A higher magnitude of Z value indicates that the trend is more statistically significant.

Standardized Precipitation Index (SPI)

The SPI was designed by McKee *et al.* (1993) and his colleagues at Colorado State University to quantify the precipitation deficit for multiple time scales (i.e. 1, 3, 6, 12, 24 and 48 month). SPI is a continuing index of certain duration using a monthly precipitation data set. The computation of the SPI index requires the following steps (McKee *et al.* 1993; Wu *et al.* 2007):

1. Fit a cumulative probability distribution function (PDF) (usually gamma distribution) on aggregated monthly (k) precipitation series (say k = 12 months in this study). The gamma PDF (g(x)) is defined as:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad (5)$$

where β is a scale parameter; α is a shape parameter, which can be estimated using the method of maximum likelihood; x is the precipitation amount; and $\Gamma(\alpha)$ is the gamma function at α. The estimated parameters can be used to find the cumulative probability distribution function of observed precipitation events for the given month and particular time scale. The cumulative distribution function (CDF), $G(x)$ is obtained by integrating Equation 5 and given in Equation 6.

$$G(x) = \int_0^x g(x)dx = \int_0^x \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})} x^{\hat{\alpha}-1} e^{-\frac{x}{\hat{\beta}}} dx \quad (6)$$

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \quad (7)$$

n = number of precipitation observations and $\bar{x}$ refers to the sample mean of the data.

$$\hat{\beta} = \frac{\hat{x}}{\hat{\alpha}} \quad (8)$$

2. Transform the cumulative distribution function (CDF) to the CDF of the standard normal distribution with zero mean and unit variance, which is given as follows (Equation 9):

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \quad (9)$$

This transformed probability is the SPI (see Figure-2). A positive value for SPI indicates that precipitation is above average and a negative value denotes below average precipitation.

$$SPI = \psi^{-1}[G(x)] \quad (10)$$

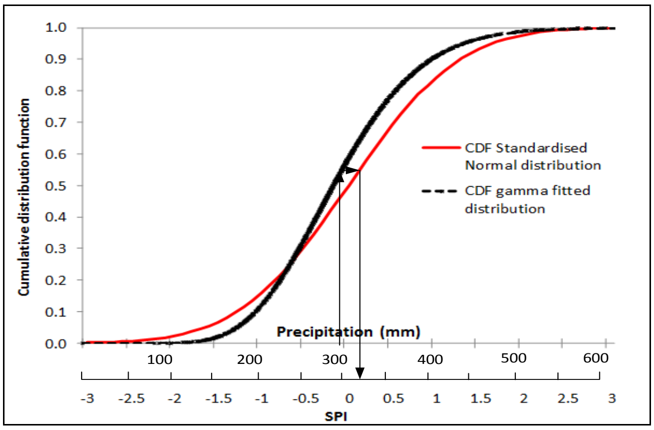


Figure-2. Example of equiprobability transformation from fitted gamma distribution to the standard normal distribution.

McKee *et al.* (1993) used the classification system using SPI values depicted in Table 2 to define dry intensities associated with a certain SPI value.

Table-2. Classification scale for SPI values.

SPI values	Category
1.0 to 1.49	Moderate wet
0 to -0.99	Near normal
-1.0 to -1.49	Moderate dry
-1.5 to -1.99	Severe dry
-2 and less	Extreme dry

RESULTS AND ANALYSIS

Preliminary Trend Analysis of the SPI

To determine whether this region has experienced a wet or dry period, the trend analysis technique for the time scale 12-months of SPI was applied to five stations. Trends in the severity series were determined by using the MK test. The Z statistics obtained from the MK test using the full set (more than 100 years of data) and approximately half of the data set (from 1949 to 2011) of 12-month time scale of SPI for all five stations are presented in Table-3.

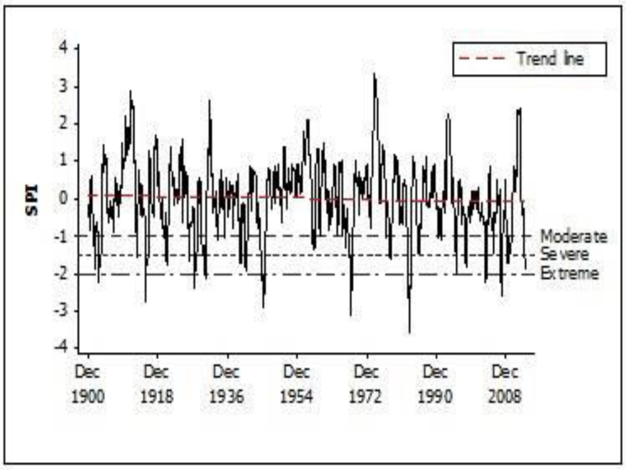
Table-3. Z statistic values from MK test.

Stations	1909-2011**/ 1900-2011	1949-2011
Irymple (Arlington)**	0.1	**-5.4**
Rainbow	**-2.7**	**-8.5**
Edenhope (Post Office)	**2.1**	**-5.3**
Dookie	**3**	**-3**
Melbourne Regional Office	**-2.9**	**-10**

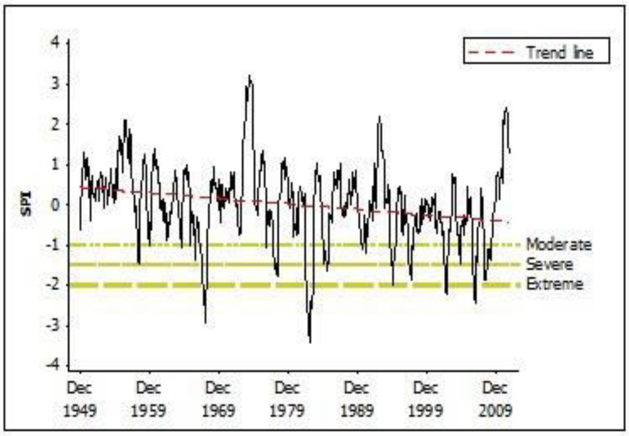
*Results in boldface indicate significant trends
** Irymple station data (1909-2011) and other stations (1900-2011)

Using full data set, four stations display significant trends, with two increasing (Edenhope and Dookie stations) and two decreasing (Rainbow and MRO stations). In contrast, Irymple station shows no significant trend. For an example, more negative values (dry period) are observed at Rainbow station, showing a significant downward trend (see Figure-3(a)).

In contrast to the first analysis using the whole data set (with the exception of Rainbow and MRO stations), all stations show a statistically significant downward trend between 1949 and 2011 (see Table 3). For all five stations, the Z values range from -3 to -10. Figure-3(b) shows the SPI trend line (data from 1949 to 2011) plot for Rainbow station. It could be said that the reduction at this station is part of a short-term climatic cycle and not a decline in long-term rainfall. Also, it can be observed that the occurrence of extreme events (i.e. prolonged dry period or droughts) have led to the significant downward trends (see Figures-3 (a) and (b)). It is difficult to predict whether extreme events will occur more frequently in the future. Great care is needed when interpreting results. For example, with short rainfall data series there may be a statistically significant trend, but the trend might not have been detected if a longer record had been considered. Therefore, it is suggested that for a trend analysis study, the length of the time series considered should be as long as possible. A longer time scale would be useful for assessing climate variability and change.



(a)



(b)

Figure-3. The SPI 12-month time scale trend lines for Rainbow station (a) full data set and (b) data from 1949 to 2011.

Temporal Trend Analysis of Wet/Dry Periods for All Stations

Based on the conclusions drawn from the preliminary analysis, the trend analysis technique was applied using the MK test using the full data set for other 65 stations. Overall, 29 stations exhibit a significant downward trend indicating an increase in the number of dry periods (see Figure-4).

Most of the stations are located in north-west and south-west Victoria and seven stations are in south-east Victoria. 21 stations show a significant upward trend, indicating a shift towards near normal or wetter conditions in most of the important region (i.e. for water supply and agricultural), particularly in the center and north Victoria. No significant trend is identified for the remaining 20 stations. It should be noted that there is a considerable spatial variability in SPIs in different parts of Victoria. There are also stations showing similar characteristics which can be grouped and clustered together.

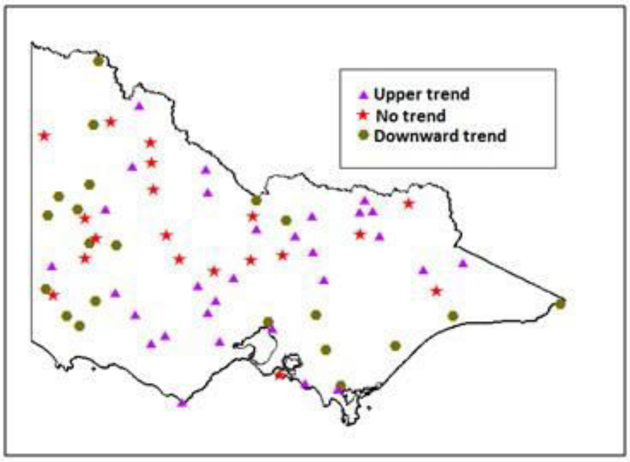


Figure-4. Trend analysis of SPI for all 70 stations.

Spatial Trends of Droughts Identified Using the SPI

As the SPI provides a standardized classification of severity, it was used to examine the severity of droughts based on two historical droughts which occurred in 1982/83 and 2002/2003 for all 70 stations. The 1982-1983 droughts was short and intense. Over much of 2002-03, drought affected significant areas of rural Australia, and 59 municipalities in Victoria had been officially drought declared by August 2003. A drought event is defined as a period in which the SPI is continuously negative and reaching a value of -1.0 or less (McKee *et al.* 1993; Paulo and Pereira, 2006).

The maximum severity of 1982 drought was examined for all 70 stations across Victoria and the plot is shown in Figure-5. The severity values ranged from -3.2 to -1.4 and all stations experienced a drought during this period. It can be observed that north-west Victoria showed the most severe drought while south-east Victoria experienced the least severe. Overall, the 1982 drought, which are said to be the most widespread droughts in Victoria, was confirmed to be so based on the results of the current study.

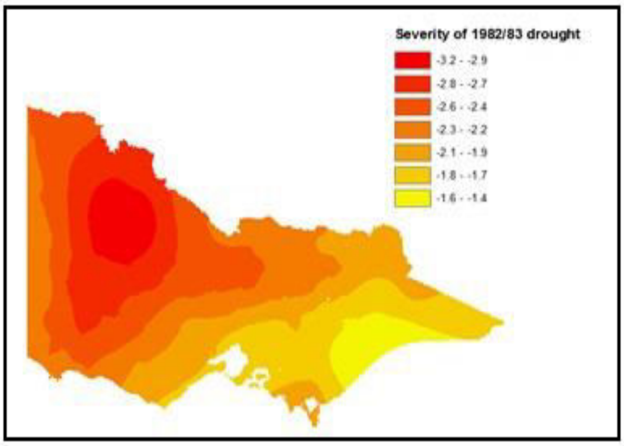


Figure-5. Severity of 1982/83 drought identified for all stations.

Based on the SPI values, the 2002/03 drought was less severe than the 1982/83 drought. The numbers of stations showing moderate, severe and extreme droughts are 19, 28, 8, respectively. In contrast to the 1982/83 drought, the most severe drought was observed in northern Victoria (Figure-6). Some parts of Victoria did not affected by this drought.

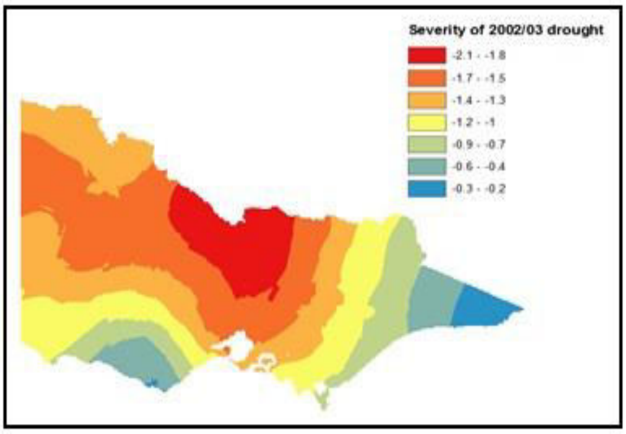


Figure-6. Severity of 2002/03 drought identified for all stations

CONCLUSIONS

It was found that different trend results were obtained when the original data set was divided into two separate samples and the analysis was repeated using the second half of the original data set. Therefore, this present study suggests that for a trend analysis study, the length of the time series considered should be based on the objective of the study. A longer time scale would be useful for assessing climate variability and change and for studying slow responding receptors such as the impact on flora and fauna. Often, the main problem with hydro-climatic data is that they are too short at some locations. If data could be obtained from a neighbouring station which has a much longer data length, this may be of assistance. In conclusion, the SPI is a valuable tool for assessing the spatiotemporal variability of dryness/wetness due to its capacity to represent precipitation anomaly. It could also be a potential tool for monitoring extreme events (i.e. drought or flood) risk and for short-term prediction.

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