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Precipitation trends in Victoria, Australia

Siti Nazahiyah Rahmat, Niranjali Jayasuriya and Muhammed A. Bhuiyan

ABSTRACT

Annual rainfall series trends were investigated for more than 100 years of data using two non-parametric trend tests Mann–Kendall (MK) and Sen's slope (*Q*) for five selected meteorological stations in Victoria, Australia. The annual rainfall time series showed no significant trends for any of the five stations. To assess the sensitivity of trends to the length of the time periods considered, the annual rainfall 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. All five stations showed decreasing trends with two stations showing significant trends suggesting that this recent time period has added more low precipitation data to the time series. The year of abrupt changes for all the five stations identified using the sequential MK test varied. Conclusions drawn from this paper, point to the importance of selecting the time series data length in identifying trends and abrupt changes. Due to the climate variability, trend testing results might be biased and strongly dependent on the data period selected. Therefore, use of the full data set available would be required in order to improve understanding of change or to undertake any further studies.

Key words | Mann–Kendall test, non-parametric trend test, Sen's slope, sequential Mann–Kendall test

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INTRODUCTION

Variability in rainfall imposes a challenge for the sustainable management of water resources. Understanding this variability and the factors influencing this phenomenon is very important for water managers and policy makers (Loch *et al.* 2013). The Intergovernmental Panel on Climate Change (IPCC) (2007) reported that significant trends have been observed in precipitation in many regions from 1900 to 2005. Precipitation decreased in the Mediterranean coast, southern Africa and parts of southern Asia, whereas precipitation increased significantly in eastern parts of North and South America, northern Europe and northern and central Asia.

The detection of changes in climatic variables is significant in planning climate change adaptation measures, hydrologic modelling studies, establishing the validity of the data set for frequency analysis and infrastructure design. Changes in climatic variables might be in the form of gradual trends over some period in time, a more abrupt change or in a more complex form (Kundzewicz & Robson 2004). Why is the analysis of trend or detecting the abrupt change important? In water systems for example, such analysis could avoid over- or under-design especially if there are abrupt changes in rainfall. Abrupt change involves a sudden jump from one value to a much greater or lower value of rainfall.

Hydro-climatic trends are highly dependent on the start and end dates of analysis. Trend analysis carried out by Smith (2004) found that no trend exists in Australian rainfall over the period from 1900 to 2006. Similarly, Stern *et al.* (2004) reported that Melbourne, Australia displayed no overall long-term trend (from 1855 to 2004) of rainfall. However, Barua *et al.* (2012) found a decreasing trend in annual rainfall (from 1953 to 2006) at 15 stations of the Yarra River catchment, Australia. This result was different to earlier studies due to the time period that they had selected. For the same location but with

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different lengths of data, the rainfall series showed different trends. Therefore, the selection of the time period is very important and the results need to be carefully interpreted.

Recent studies have suggested that analysis of hydro-climatic variables should be performed at the local scale rather than at a large or global scale because the trends and their effects might be different from one location to another (Sharma & Shakya 2006; Barua *et al.* 2012). The aim of this study is to analyse the temporal changes in historic rainfall variability at a given location and to gain an insight into the importance of the length of data record. The current study identified the point rainfall trends at five stations in Victoria, Australia. The study will: (1) determine annual rainfall trends using the non-parametric Mann–Kendall (MK) and Sen's slope (Q) trend tests at five selected meteorological stations with long historical records; (2) explore whether similar trends could be obtained by separately studying long and short periods of the same data set; and (3) pin-point the year when a trend begins using the sequential MK test. The sequential MK test is widely used in hydrology for the identification of significant or abrupt changes in meteorological and hydrological time series.

METHODOLOGY

Study area

The State of Victoria in Australia has a varied climate despite its relatively small size (237,629 km^2). It ranges from semi-arid and hot in the north-west, to temperate and cool along the coast. Rainfall in Victoria increases from the north of the State to the south, with higher averages in areas of high altitude. Monthly rainfall data from 1900–2011 (4 stations) and 1909–2011 (1 station) were downloaded from the Bureau of Meteorology web site (http://www.bom.gov.au/climate/data/) for the study. This length of record was selected to ensure the reliability of the results and to have a sufficient length of record to extract a sub-set to reflect more recent conditions in the region.

The five rainfall stations selected for this study are shown in Figure 1 and their characteristics are given in Table 1. Irymple station is located in north-west Victoria and in the region of Mildura. The region has a long history of being an important producer of food, supported mostly by irrigated agriculture. As such the region could be categorised as a drought-prone region due to its history of receiving low rainfall for relatively long periods of time.

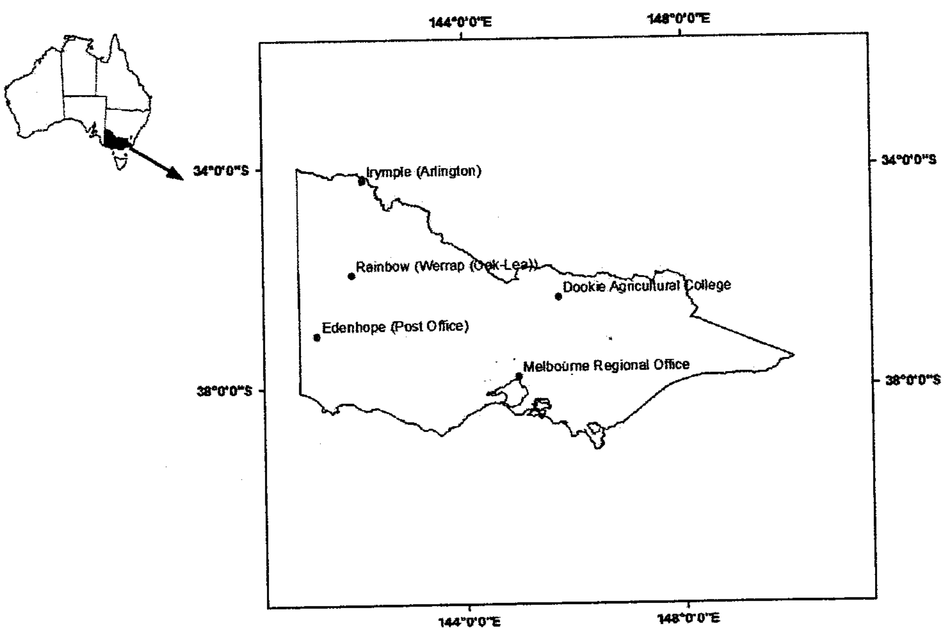

Figure 1 | Locations of the study sites.

Table 1 | Description of rainfall stations

Station ID.	Station name	Mean annual rainfall (mm)	% of missing rainfall
76015	Irymple (Arlington)	279	–
77051	Rainbow (Werrap (Oak-Lea))	349	0.8
79011	Edenhope (Post Office)	583	1.4
81013	Dookie Agricultural College	551	0.5
86071	MRO	650	–

Rainbow and Edenhope are in the Wimmera–Mallee regions of western Victoria covering the dryland rain-fed farming areas. The Dookie station is located in the Goulburn Valley region and is also a part of the Murray–Darling River Basin, Australia's food bowl. This region is one of the most productive agricultural areas in Australia and is predominantly irrigated. The Melbourne Regional Office (MRO) station is located in the urbanised area of the Yarra River catchment, which supplies most of the drinking water to Melbourne city. Stations Irymple and Rainbow were chosen due to the fact that these stations generally receive low rainfall. Although the annual rainfall is high in Edenhope, Dookie and MRO stations, these were selected as these stations are located within important catchment basins in Victoria, the Murray–Darling Basin for primary production and the Yarra River catchment for urban water supply. Thus, study on rainfall pattern in these stations is very important. If there are any changes observed, it might have effects on water availability and the changes need to be properly taken into account for the long-term catchment-scale water management.

Figure 2 presents the time series data of annual rainfall for all stations and their averages. The mean annual rainfall values during the study period were 279 mm for Irymple station, 349 mm for Rainbow, 583 mm for Edenhope, 551 mm for Dookie and 650 mm for the MRO station (Table 1).

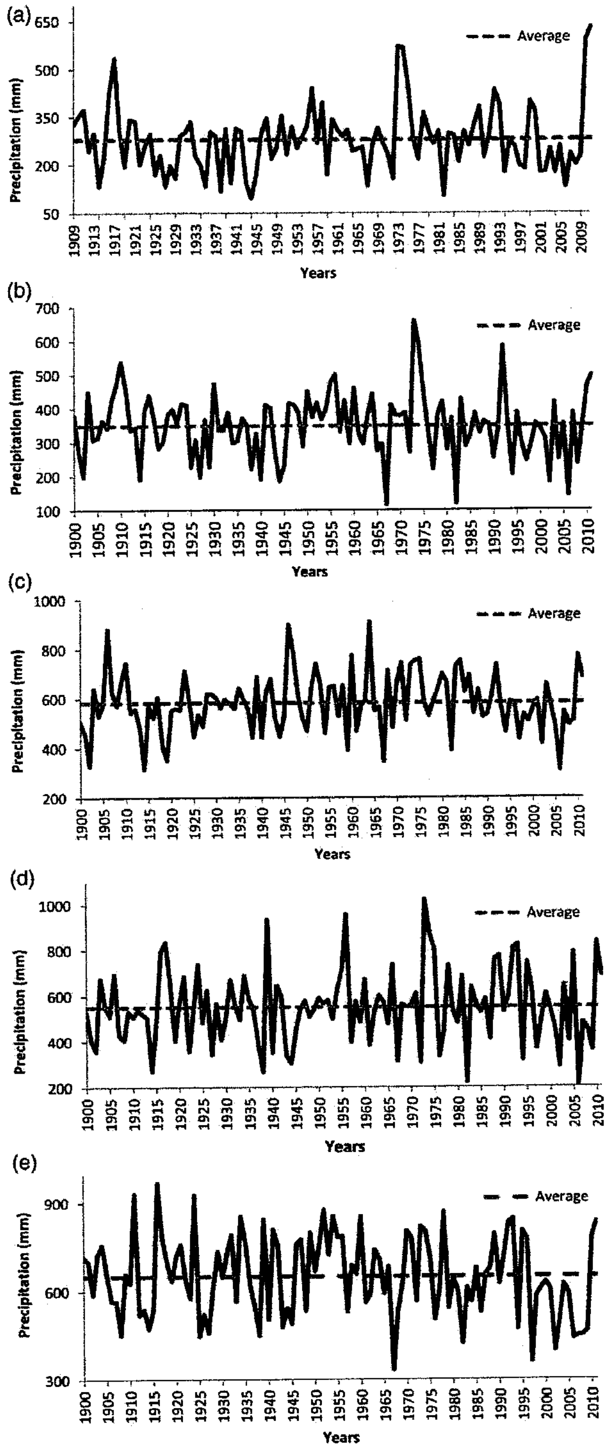

Figure 2 | Annual rainfall (mm) for (a) Irymple (from 1909–2011) and (b) Rainbow, (c) Edenhope, (d) Dookie and (e) MRO stations (from 1900–2011).

Detecting trends using non-parametric trend analysis

Parametric and non-parametric methods are the most commonly used methods to detect significant hydro-climatologic time series trends (Tabari *et al.* 2011). The purpose of trend tests is to determine if the value of a random variable generally increases or decreases over a selected period of time in statistically significant terms (Helsel & Hirsch 2002). To name a few, the MK, Spearman's Rho (SR) and Sen's slope (Q) tests are examples of non-parametric tests that have been applied to detect trends and slopes (Yue *et al.* 2002; Drapela & Drapelova 2011; Paulo *et al.* 2012). One advantage of MK and SR tests is that the data do not have to fit any particular probability distribution to validate the tests. The studies of Yue *et al.* (2002), Yenigun *et al.* (2008), Tabari *et al.* (2012), Nazahiyah *et al.* (2012) and Soltani *et al.* (2012) showed that SR provides results similar to those obtained for the MK test when identifying time series trends. Hence, using one of the techniques is sufficient to get a reliable result.

Several methods have been used to identify the year when a trend begins in data series. Tests for abrupt change include Pettitt's test (Burn & Hag Elnur 2002), Wilcoxon–Mann–Whitney test, Cumulative Summation (CUSUM) test, sequential MK test, etc. The main limitation of the Wilcoxon test is that it can detect only one single change point whereas the sequential MK and CUSUM tests are useful for sequential step change analysis (Sonali & Nagesh Kumar 2013). Out of all of the tests mentioned, the sequential MK test is widely used as it is reputed to have an advantage over other methods in terms of accuracy (Jiang & You 1996; Mu *et al.* 2012) and it cannot be influenced by a small number of outliers for sequence analysis (Zang & Liu 2013). This method has been successfully applied in a number of studies in China (Zhang *et al.* 2006; Yang & Tian 2009; Tian *et al.* 2010; Zang & Liu 2013), Turkey (Partal & Kahya 2006), India (Sonali & Nagesh Kumar 2013) and Europe (Guerreiro *et al.* 2014), but it has never been tested in Australia.

The outline of the trend tests used in this current study is shown in Figure 3. In order to identify gradual trends in rainfall series, the MK test and Sen's slope were applied. Change point analysis was then performed using the sequential MK test to detect abrupt changes.

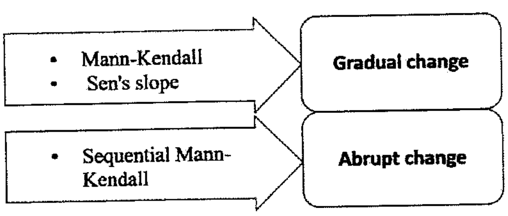

Figure 3 | Outline of the trend analysis.

MK test

The MK test is used for determining monotonic trends and is based on ranks by taking into account seasonality (Helsel & Hirsch 2002). The significance of the detected trends can be obtained at different levels of significance (generally taken at 0.05). The MK test statistic and the sign function are calculated using the formula

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

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

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:

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

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

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

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 increasing or decreasing monotonic trend (a two-tailed test) at α level of significance, H_0 should be rejected if the $|Z| > Z_{1-\alpha/2}$, where $Z_{1-\alpha/2}$ 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.

Sen's estimator of slope

Sen's slope (Q) estimator method accounts for seasonality of the precipitation data. This method uses a simple non-parametric procedure developed by Sen (1968) to estimate the slope. The variance of the residuals should be constant in time. The equation used for calculating the slope of two rainfall records is as follows:

$$Q_i = \frac{(x_j - x_k)}{j - k}, \quad \text{for all combinations of } j > k \tag{5}$$

where x_j and x_k are the rainfall values at times j and k, respectively. Q_i is the slope between data points x_j and x_k. The median of these N values of Q_i is Sen's estimator of slope.

Sequential MK test

The sequential of the MK test $u(t)$ (progressive) and $u'(t)$ (retrograde) is used to detect the change points that may occur in the temporal behaviour of a time series, especially to identify points at which the trend changes from upwards to downwards or vice versa (Sneyers 1990; Partal & Kahya 2006; Weglarczyk 2009; Karpouzos *et al.* 2010). The separation point of the upward and downward curves indicates the starting point of abrupt runoff change. The application of this test has the following steps in sequence. The magnitudes of x_i annual mean time series, $(i = 1, \ldots, n)$ are compared with x_j, $(j = 1, \ldots, i-1)$. At each comparison, the number of cases $x_i > x_j$ need to be counted and denoted by n_i.

A statistic t can therefore be defined as follows:

$$t_i = \sum_{1}^{i} n_i \tag{6}$$

The distribution of the test statistic has a mean and a variance as

$$E(t) = \frac{n(n-1)}{4} \tag{7}$$

$$\text{var}\,(t_i) = [i(i-1)(2i+5)]/72 \tag{8}$$

To search for a change-point in a possible trend, $u(t)$ (progressive) is determined. The sequential values of the statistic $u(t)$ could be computed as

$$u(t) = \frac{t_i - E(t)}{\sqrt{\text{var}(t_i)}} \tag{9}$$

Here, $u(t)$ is a standardised variable that has zero mean and unit standard deviation. Therefore, its sequential behaviour fluctuates around the zero level. The values of $u'(t)$ (retrograde) are then computed backwards starting from the end of the series

$$u'(t) = \frac{t'_i([(n-1)(n-i+1)]/4)}{\sqrt{\{(n-i)(n-i+1)[2(n-i+1)+5]\}/72}} \tag{10}$$

The intersection point of the statistics $u(t)$ and $u'(t)$ provides the point in time of the beginning of a developing trend within the time series. If the intersection point is significant at the 5% level, then the critical point of change is at that period (Yang & Tian 2009). The application of this test has been widely used to detect trends in climate and other environmental variables (Sneyers 1990; Smadi & Zghoul 2006; Croitoru *et al.* 2012; Zang & Liu 2013).

RESULTS

Trend analysis of annual rainfall for a full length of record (more than 100 years)

The Z and Q statistics obtained from MK and Sen's slope tests using the full set of annual rainfall data are presented in Table 2. Overall, no significant trends were found for any stations.

Rainbow and MRO stations showed statistically insignificant decreasing annual precipitation trends with Z values of −0.7 and −0.97, respectively. The slopes (mm/year) of the downward trend obtained for these two stations were −0.2 and −0.43, respectively. For Irymple, Edenhope and Dookie stations there were statistically insignificant increasing trends in annual rainfall. After 13 years (1996–2009) of below-average annual precipitation as reported in Gergis

Table 2 | Z statistic values from MK and Sen's slope (Q) tests

	1909–2011**/1900–2011		1949–2011	
Station	Z	Q (mm/year)	Z	Q (mm/year)
Irymple (Arlington)**	0.003	0.008	−1.5	−0.9
Rainbow (Werrap (Oak-Lea))	−0.7	−0.2	**−2.2**	**−1.4**
Edenhope (Post Office)	0.78	0.27	−1.5	−1.3
Dookie Agricultural College	0.93	0.47	−0.8	−1.0
MRO	−0.97	−0.43	**−3.0**	**−3.1**

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

et al. (2012), most of the stations experienced relatively wet years in 2010 and 2011 (Figure 2). The Z values obtained from the MK trend test at Irymple, Edenhope and Dookie stations were 0.003, 0.78 and 0.93, respectively and the annual rainfall increased by 0.008 mm/year, 0.27 mm/year and 0.47 mm/year, respectively.

Trend patterns in annual rainfall for a short period of record (1949–2011)

The analysis was then repeated using annual rainfall data from 1949 to 2011; approximately half the original data set. The Rainbow and MRO stations showed statistically significant trends (Table 2). The Z values obtained were −1.5 for Irymple station, −2.2 for Rainbow station, −1.5 for Edenhope station, −0.8 for Dookie station and −3.0 for the MRO station. The downward slope identified at all stations ranged from −0.9 to −3.1 mm/year. This analysis of the precipitation subset series suggests that all stations had a decreasing trend during this part of the study period.

Identifying the change point of the trend

Figures 4 and 5 present the results of the sequential MK test using the full set and the second half set of the annual precipitation data series respectively. The starting time of abrupt change and significant trend (if any) determined by sequential MK test results are tabulated in Table 3. The

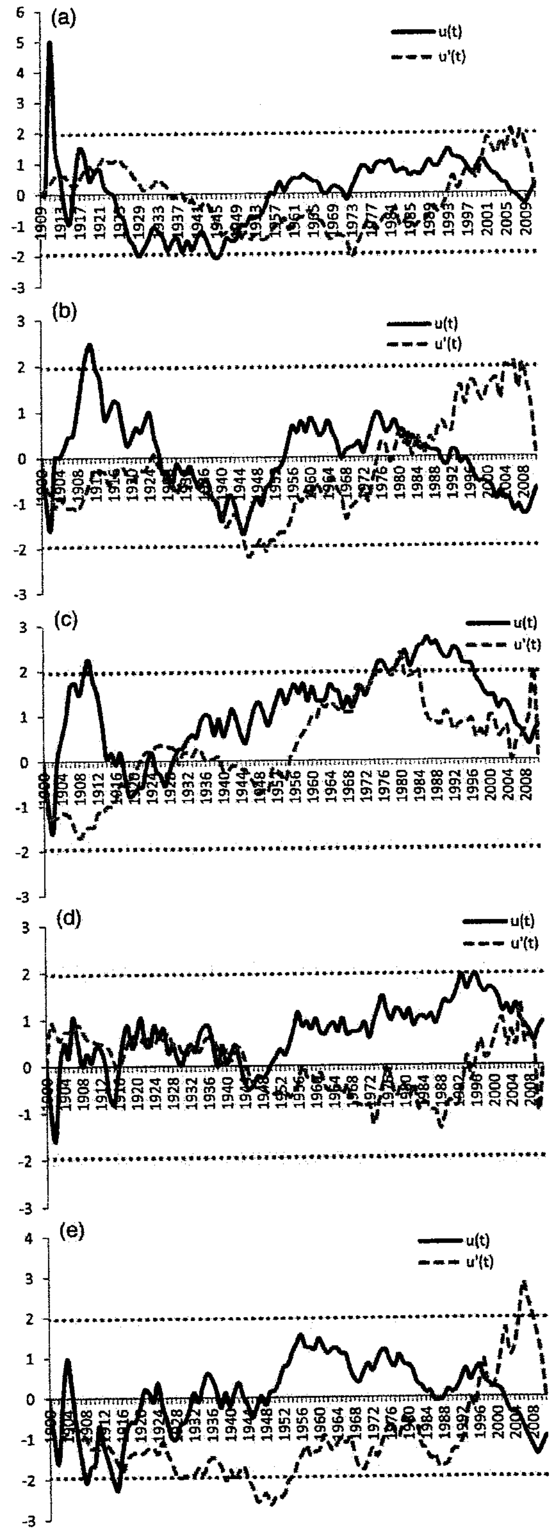

Figure 4 | Sequential values of the statistics $u(t)$ and $u'(t)$ for more than 100 years of annual precipitation for (a) Irymple, (b) Rainbow, (c) Edenhope, (d) Dookie and (e) MRO stations.

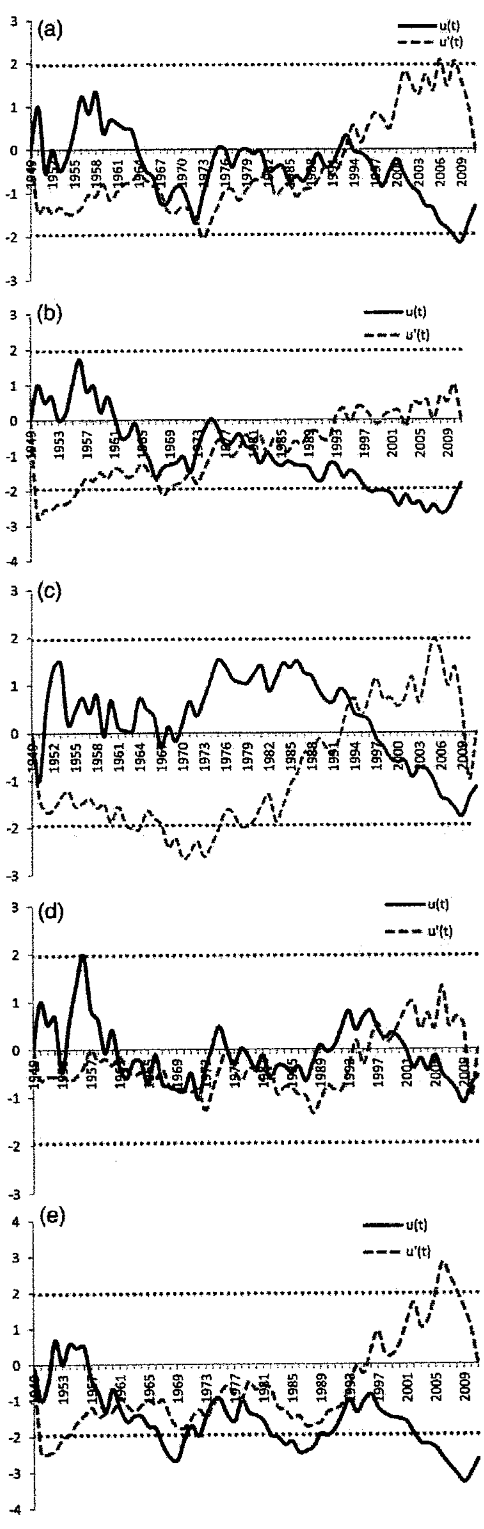

Figure 5 | Sequential values of the statistics $u(t)$ and $u'(t)$ for annual precipitation (from 1949–2011) for (a) Irymple, (b) Rainbow, (c) Edenhope, (d) Dookie and (e) MRO stations.

sequential values of the statistics $u(t)$ and $u'(t)$ are illustrated by solid and dotted lines, respectively and the horizontal dotted lines correspond to the confidence limit at ±5% significance level.

As shown in Figure 4(a), Irymple station exhibited insignificant abrupt change starting in 1949 which again occurred in 2000. However, different results were obtained when the shorter time period 1949 to 2011 was considered (Figure 5(a)). The test revealed the starting year of an abrupt change in 1994 which later became a significant decreasing trend in 2007. This feature dominated the trend for the whole period.

Rainbow station identified an insignificant abrupt change in 1985 (Figure 4(b)). By observing the recent trend as shown in Figure 5(b), this station identified two abrupt changes with the first one occurring in 1949. In contrast to the full data set, an abrupt change identified in 1983 was followed by a significant decreasing trend commencing in 1997.

Edenhope station showed an abrupt change in 1902 with a significant increasing trend initiating in 1910 (Figure 4(c)). Again this station showed an abrupt change in 1930 and a significant increasing trend in 1973. On the other hand, in the second half of the time period in Figure 5(c), there were two points of abrupt change in 1950 and 1995, but there was no significant trend detected as the progressive line did not exceed the 5% significant threshold level.

As shown in Figure 4(d), Dookie station exhibited an abrupt change starting in 1945 and showing statistically significant increase in 1993, however no abrupt change occurred in the recent period (Figure 5(d)).

For the MRO station, there were abrupt changes in 1916 and 2000 as seen in Figure 4(e) but these were not significant. The sequential test for the second half of the period showed there was an abrupt change in 1993 with significant decrease in 2002 (Figure 5(e)).

DISCUSSION

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 on the second half of the original data set. For the same location, Barua et al. (2012) concluded that there had been a consistent reduction in rainfall at 15 stations over the past 50 years (from 1953 to

Table 3 | Starting time of abrupt change time and rainfall trend determined by sequential MK test

	1909–2011*/1900–2011		1949–2011	
Station	**Abrupt change**	**Significant trend**	**Abrupt change**	**Significant trend**
Irymple (Arlington)*	1949 2000	No No	1994	2007 (↓)
Rainbow (Werrap [Oak-Lea])	1985	No	1949 1983	No 1997 (↓)
Edenhope (Post Office)	1902 1930	1910 (↑) 1973 (↑)	1950 1995	No No
Dookie Agricultural College	1945	1993 (↑)	No	No
MRO	1916 2000	No No	1993	2002 (↓)

*Irymple station data (1909–2011) and other stations (1900–2011).

2006) and if this reduction continues, droughts can be expected to be more frequent in the future. In order to identify possible dry trends in Victoria, Nazahiyah *et al.* (2012) carried out a study using a drought index namely, the Standardised Precipitation Index (SPI) for the same five stations. The SPI uses only rainfall data and provides a normalised system to classify and represent dry and wet climates in the same manner as Sirdas & Sen (2003). Positive values imply that the observed rainfall is larger than the mean precipitation and vice versa (Morid *et al.* 2006).

Nazahiyah *et al.* (2012) analysed trends for the whole period of time (1949–2010) and also grouped the stations into two time periods 1949–1982 and 1977–2010 for comparison. All five stations showed a statistically significant downward trend when the whole period was considered, illustrating conditions becoming drier over the last 60 years. However, a significantly decreasing trend was observed at only two stations for the first period (1949–1982) and at all stations during the second period (1977–2010). It could be said that the reduction at most of the stations is part of a short-term climatic cycle and not a decline in long-term rainfall. Moreover, there is no trend found when the long-term period of rainfall is considered in this current study. Therefore, it is difficult to predict whether extreme events or droughts would occur more frequently in the future. Great care is needed when interpreting results. For example, with a 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.

It is worth mentioning that trends are sensitive to the length of the time series being considered. Barua *et al.* (2012) in their study mentioned that they had performed an abrupt change test (i.e. CUSUM) to check for the existence of statistically significant change in trends and thus identify the trend beginning year. If a statistically significant trend beginning year was found, the trend analysis (e.g. MK, Sen's slope, etc.) was then performed using the data set after that year. However, Guerreiro *et al.* (2014) concluded that performing the trend test before and after the change points does not make any difference because it is not possible to separate the effect that the change point might have on the trend from the effect of reducing the length of the record.

Therefore, this paper 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 and for studying slow responding receptors, such as impact on flora and fauna. Often, the main problem with hydro-climatic data is that they are too short at some places. If data could be obtained from a neighbouring station which has a much longer data length then this may be of assistance.

The results obtained using the sequential MK test were consistent with the MK and *Q* tests. As mentioned in the methodology section, the MK test is developed to detect a monotonic change. As changes in hydro-climatic data might be in the form of gradual or abrupt change, the application of trend and change point tests are recommended in order to provide more meaningful information.

Overall, the starting time of change points identified in this study varied. Using the full data set of rainfall, only two stations (Irymple and MRO) showed a similar year in detecting abrupt change which occurred in 2000. When half of the data set was used, 1993–1995 was the period with abrupt changes (to dry period) for Irymple, Edenhope and MRO stations. This recent period captured the starting year of the current dry period well, as reported in Verdon-Kidd & Kiem (2009) and Ummenhofer *et al.* (2009).

CONCLUSIONS

The study aimed at identifying possible rainfall trends, on the one hand using the full available data set and on the other a subset (nearly half) of the full data set, by applying the non-parametric MK and Sen's slope tests. Also, the sequential MK test was used to detect change in rainfall time series. The main conclusions may be summarised as follows:

(1) When annual rainfall was analysed with more than 100 years of data, two out of five stations (Rainbow and MRO) showed negative trends and the other three stations (Irymple, Edenhope and Dookie) exhibited upward trends. However, all trends were not statistically significant. To examine the sensitivity of trends to the length of the time period considered, annual rainfall was reanalysed using the second half of the original annual series rainfall record. Different results were obtained as all stations had recently experienced reductions in rainfall. It could be concluded that when the data length increases it can absorb more variability while for low data length it could vary on either a decreasing or increasing trend depending on data obtained.

(2) The sequential MK test successfully detected the change point of the beginning of the trend. For the full data set, abrupt changes were identified at Irymple (1949, 2000), Rainbow (1985), Edenhope (1902, 1930), Dookie (1945) and MRO (1916, 2000) stations. However, for the second half of data set, abrupt changes were found for Irymple (1994), Rainbow (1949, 1983), Edenhope (1983), Dookie (1950, 1995) and MRO (1993) stations. The year indicated in the parentheses represents the trend starting time. Depending on the length of the time series data, the change point and the significance level varied.

(3) Climatic trends were observed to be highly dependent on the start and end dates of analysis. It is recommended that selection of the time period for trend analysis should consider the availability of the data. Longer data series would give more meaningful results. In addition, it is also beneficial if trend tests are applied to several time frames on a single series in order to improve understanding of climate change.

(4) Based on the results, it could be observed that significant downward abrupt changes (see Figure 5(a), 5(b) and 5(e)) have led to the occurrences of extreme events (i.e. prolonged dry period or drought).

(5) Even though this study did not seek to determine any possible causes or explanations of increasing or decreasing trends that were observed, the results presented herein will be useful as a benchmark towards further analysis of the effect of climate change.

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