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Rainfall trend and its implications for water resource management within the Yarra River catchment, Australia

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Abstract

Rainfall is the key climatic variable that governs the regional hydrologic cycle and availability of water resources. Recent studies have analyzed the changes in rainfall patterns at global as well as regional scales in Australia. Recent studies have also suggested that any analysis of hydro-climatic variables should be done at the local scale rather than at a large or global scale because the trends and their impacts may be different from one location to the other. Since, no studies were found specific to the Yarra River catchment, which is an important catchment in Victoria (Australia), this study performs a spatio-temporal trend analysis on long-term rainfall records at 15 measuring stations within the catchment. The Mann–Kendall test was used to detect trends and Sen's slope estimator was used to calculate the slopes in both monthly and annual rainfall. Moreover, cumulative summation technique was used to identify the trend beginning year and pre-whitening criteria were tested to check for autocorrelation in the data. The results showed that the monthly rainfall has generally decreasing trends except in January and June. Significant decreasing rainfall trends were observed in May (amongst the autumn months of March, April and May) at majority of the stations and also in some other months at several stations. Decreasing trend was also observed in the annual rainfall at all stations. This study indicates that there has been a consistent reduction in rainfall over the catchment, both spatially and temporally over the past 50 years, which will have important implications for future management of water resources.

Keywords: Rainfall trend; Mann-Kendall test; water resources management; Yarra River catchment.

INTRODUCTION

During the last decade, ecological and environmental deterioration processes have attracted widespread attention in south-eastern Australia due to the low records of rainfall (Kiem *et al.*, 2008; Tan and Rhodes, 2008). It was reported that this remarkable decline in rainfall substantially constituted a long-term drought in the history (Tan and Rhodes, 2008). A question which remains unanswered is whether this drought is part of a short-term climatic cycle or a decline in long-term rainfall brought on by global climate change. Therefore, rainfall trend analysis studies have become important, as observational and historical rainfall data are generally used for planning and design of water resource projects.

There are many parametric and non-parametric methods that have been used for trend analysis (Zhang *et al.*, 2006). Parametric trend tests are more powerful than non-parametric ones, but they require data to be independent and normally distributed (Chen *et al.*, 2007). The basic assumptions of classical parametric methods, i.e. normality, linearity, and independence, are generally not satisfied by hydrological data (Xu *et al.*, 2007). On the other hand, non-parametric trend tests only require the data to be independent and can tolerate outliers in the data (Hirsch *et al.*, 1993). Therefore, non-parametric trend tests were considered for this study to detect the rainfall trends. Performances of four non-parametric methods; the Sen's T, Spearman's rho, Mann–Kendall (MK) and seasonal Kendall methods were tested by Kahya and Kalayci (2004); they found that the four methods gave quite similar results in most cases. However, Yu *et al.* (1993) in their comparative study found that the MK method is more powerful than the Seasonal Kendall method. Therefore, the MK test (Mann, 1945; Kendall, 1975), which is one of the most widely used non-parametric test for detecting trend in hydro-climatic time series (e.g. Burn and Elnur, 2002; Xu *et al.*, 2003; Gemmer *et al.*, 2004; Birsan *et al.*, 2005; Aziz and Burn, 2006; Zhang *et al.*, 2006; Burn and Hesch, 2007; Gao *et al.*, 2007; Rodrigo and Trigo, 2007; Aldrian and Djamil, 2008; Bae *et al.*, 2008; Chowdhury and Beecham, 2010) was used in this study to detect the trend in rainfall time series.

Many researchers have suggested that pre-whitening (PW) should be done on the datasets before conducting the MK test to eliminate the autocorrelation effect in the data, but some others suggested not to do it unless characteristics of the dataset meet certain conditions (e.g. Wang and Swail, 2001; Bayazit and Onoz, 2007). Since there was some ambiguity regarding when to undertake PW and when not to, this study attempts to clear those ambiguities based on a detailed literature review. This will be useful for future trend detection studies.

The MK test will not give accurate results if the trend in the data changes sign (i.e. from positive trend to negative or vice versa). Therefore, before applying the MK test, it is important to check for the trend beginning year (to detect if the trends have changed sign) and then apply the MK test to the data starting from that year (Kampata *et al.*, 2008; Chowdhury and Beecham, 2010). This was accomplished in this study using the Cumulative Summation (CUSUM) technique. Sen's slope estimator was also used to quantify the magnitude of change in rainfall over time for each station, which was applied to the data starting from the trend beginning year.

To date, many studies have been conducted on detecting rainfall trends at a regional and national scale in Australia (Hennessy *et al.*, 1999; Fawcett, 2004; Smith, 2004; Gallant et al., 2007; Fu *et al.*, 2008; Murphy and Timbal, 2008; Taschetto and England, 2009; Chowdhury and Beecham, 2010; Kiem and Verdon-Kidd, 2010). However, none of these studies was conducted at a local scale, specifically with regards to rainfall trends at stations within the Yarra River catchment, although a few studies have been conducted at a regional scale for south-eastern Australia (SEA) (Hennessy *et al.*, 1999; Gallant et al., 2007; Murphy and Timbal, 2008; Kiem and Verdon-Kidd, 2010). These studies have shown that the trend in SEA rainfall since 1950 has been towards drier conditions, with the linear trend in SEA annual rainfall since 1950 being -20.6 mm/decade. Each of the seasons has had a negative linear trend, with a decline of -11.2 mm/decade in autumn, -3.3 in winter, -3.5 in spring and -2.7 mm/decade in summer (Murphy and Timbal, 2008). Thus, the majority of the rainfall decline (~60%) in SEA is due to much drier autumn months (March, April and May). Murphy and Timbal (2008) further compared the monthly mean SEA rainfall for the period from 1997-2006 with that for the period from 1961-1990 and concluded that statistically significant reduction in SEA rainfall in the decade starting from 1997 is confined to the three autumn months.

As far as the detection of rainfall trend beginning year is concerned, only a few studies have been conducted for rainfall data from within the Yarra River catchment, and that too for annual rainfall data. Fawcett (2004) used gridded annual rainfall data (at 21 equally spaced grid points) from Melbourne and surrounding region to detect the 'change points' in rainfall regimes. He found that there was a jump to a higher rainfall regime around 1945/1946 and a fall to a lower rainfall regime around 1996/1997. In another study, Kiem and Verdon-Kidd (2010) analysed rainfall and streamflow data from nine catchments spatially spread across Victoria (including the Yarra River catchment) to understand the hydroclimatic changes within the state. For each of the nine catchments, they used a single rainfall station close to the catchment centroid to represent the whole catchment. To examine occurrence of 'step changes' in annual rainfalls, they used a moving window of 20 years and subjected each window to Mann-Whitney U test to determine the statistical significance of any step changes. They concluded that shifts in annual rainfall patterns are not unprecedented in Victoria and the most recent shift being a switch to drier conditions in 1994 for six out of the nine catchments (including the Yarra River catchment).

Sharma and Shakya (2006) mentioned that any analysis of hydro-climatic variables should be done at the local scale rather than at a large or global scale. This is because, although climate change is a global phenomenon, the trends and their impacts may be different from one location to the other due to the variations of hydro-climatic variables from one region to the other. Therefore, the present study was focused on rainfall trend analysis at a local scale within the Yarra River catchment, rather then at a regional or global scale. Historic rainfall data from multiple rainfall stations were used, as it provides more detailed information on the spatial variability of rainfall trends within the Yarra River catchment.

The Yarra River catchment was selected for this study as it is a major source of water for over one-third of Victoria's population in Australia. The catchment thus has an important contribution towards the sustainable development of Victoria's economy. Therefore, rainfall trend analysis within the Yarra River catchment is important, which could have implications for the management of water resources within the catchment. The outcomes of this study will assist water resources managers for effective water supply and demand management, and also for the application of Water Sensitive Urban Design (WSUD) (Kandasamy *et al.*, 2008; Chowdhury and Beecham, 2010).

This paper begins with a brief description of the study area and the dataset used, followed by a detailed description of methodology used in this study. Then the results of the spatio-temporal trend analysis and discussion are presented, followed by implications of this study for management of water resources within the Yarra River catchment. Finally, the conclusions drawn from this study are presented.

STUDY AREA AND DATASET USED

The study site

The Yarra River catchment, which was used as the case study catchment, is presented in Figure 1. The Yarra River travels 245 kms from its source in the Great Dividing Range to the end of its estuary at Port Phillip Bay (www.catchment.crc.org.au), which has a catchment area of 4,044 square kilometers. The Yarra River catchment is divided into three reaches – *upper*, *middle* and *lower*. The upper reach of the catchment and its major tributaries flow through forested and mountainous areas, which have been reserved for water supply purposes for more than 100 years (http://ouryarra.melbournewater.com.au/). The middle reach is notable as it is the only part of the catchment with an extensive flood plain. The lower reach of the catchment flows through the urbanized area of Melbourne. Most of the land along rivers and creeks in the middle and lower sections have been cleared for agriculture or urban development. The three landuse patterns (i.e. forest, agricultural and urban areas) are also presented in Figure 1.

INSERT FIGURE 1 NEAR HERE

The Yarra River catchment is a complex water management catchment. The catchment water resources support a range of uses valued by Melbourne's community (in Victoria), including urban water supply, agricultural and horticultural industries, and downstream user requirements as well as flow requirements for maintaining environmental flows. There are seven storage reservoirs located within the catchment that supply water to Melbourne. There are also numerous farm dams within the catchment, and water extraction from the rivers and creeks for agriculture is prevalent. A range of recreational activities, metropolitan parks and biodiversity conservation are also located around the catchment waterways. Along with the diversity of these activities, pressure upon water resources management within this catchment has become more intense due to frequent drought occurrences in recent years (Tan and Rhodes, 2008). Therefore, the management of water resources is of great importance within the Yarra River catchment.

The Melbourne Water (MW) Corporation is responsible for managing the water resources within the Yarra River catchment. They have developed a Drought Response Plan (DRP) (Melbourne Water, 2007) to provide an effective, systematic and integrated framework for planning and responding to the impacts of drought on licensed water users in the Yarra River. This plan is designed to enable, identify and implement the appropriate actions in response to expected or worsening low-flow conditions. The main features of the DRP are; 1) manage access to water by all users and the environment, 2) define the conditions under which restrictions or bans on use will be required for drought and the process by which these will be implemented, 3) outline obligations of both MW and water users, and 4) enable MW to meet statutory obligations. This plan also allows MW enough flexibility to address situations where strict adherence to, or reliance on, a specific warning level would be inappropriate. It also aims to ensure that this flexibility does not weaken a proactive approach to the management of water resources by preventing timely responses that warn water users of a forthcoming shortage. Nevertheless, in order to make this plan as valuable and effective as possible, timely review of the DRP was recommended subject to the changes in availability of water resources in future.

The dataset used

Daily rainfall data from 15 measuring stations within the Yarra River catchment were used in this study, which were collected from Bureau of Meteorology, Australia. The station numbers, names, geographical coordinates and elevations of each of these rainfall measuring stations are presented in Table I and their spatial locations are shown in Figure 1. Out of the 15 rainfall measuring stations, 5 are located in the forested upper reaches of the Yarra River catchment (which are given IDs 1 to 5), 5 are in the agricultural areas (with IDs 6 to 10) and the remaining 5 stations (with IDs 11 to 15) are located in the urban areas.

INSERT TABLE I NEAR HERE

Time series data of monthly rainfall for each of the twelve months were obtained from daily data by accumulating rainfall amount over the month, and then these twelve monthly time series data were used for the trend analysis. Study on this micro scale helps to reveal the trends that cannot be seen at the seasonal and annual time scale. In addition to the monthly rainfall time series data, annual rainfall time series was also used for trend analysis which provides comparative evaluation with the results found in monthly time scale. Therefore, a total 195 rainfall time series (i.e. 12 monthly and 1 annual time series for each of the 15 stations) were used for spatial and temporal trend analysis. Based on data availability, 54 years of data (from 1953 to 2006) were used in this study. This adequately meets the minimum length required in searching for evidence of climate change in hydro-climatic time series, as suggested by Burn and Elnur (2002), who stated that a minimum record length of 25 years may ensure statistical validity of the trend results. A plot of the annual rainfall cycle indicating the monthly average rainfall for the catchment based on the available data is presented in Figure 2. The figure shows that rainfall in the Yarra River catchment varies from one month to the other, ranging from an average of 55.6 mm (in February) to 99.0 mm (in September). Generally, wet conditions persist from August through October, whereas dry conditions are observed from January through March.

INSERT FIGURE 2 NEAR HERE

METHODOLOGY USED

As was mentioned earlier, non-parametric MK test was preformed on the monthly rainfall time series data from 15 stations within the Yarra River catchment to detect the spatial and temporal trends. The CUSUM test was first preformed on each of the time series to check the existence of any statistically significant change in trends and thus identify the trend beginning year. If a statistically significant trend beginning year was found, the dataset after that year was considered for rest of the trend analysis (i.e. for MK test as well as Sen's slope estimator) as the recent trends would be of relevance. If there were no statistically significant trend beginning year in the data, then the complete time series was considered for the trend analysis.

Thereafter, the rainfall time series data were individually analyzed for the pre-whitening (PW) criteria to check if the PW process was required or not. The MK test was then performed on the rainfall time series data to detect the increasing/decreasing rainfall trends. Finally, the Sen's slope estimator was used to calculate the slope of rainfall and to quantify the magnitude of change over time. The mathematical details of CUSUM test, MK test and the Sen's slope estimator are presented in this section. Mathematical details of the PW process are not presented here as its application was found to be not necessary in this study, as discussed later in the section on results and discussion. However, as an in-depth review of literature on the criteria to check if the PW process was necessary or not, was conducted in this study; a brief summary of this is also presented in this section. Readers interested in the computational procedure of the PW process are referred to Wang and Swail (2001), Partal and Kahya (2006) and Luo *et al.* (2008).

Cumulative Summation test

As mentioned earlier, the CUSUM test has been used to check the existence of statistically significant change in trends in rainfall time series data and thus to identify the trend beginning year, if it exists (Kampata *et al.*, 2008; Chowdhury and Beecham, 2010). The CUSUM test as described in Chowdhury and Beecham (2010) is as follows:

$$y_i = (x_i + x_{i-1} + x_{i-2} + \cdots x_n) - i \cdot \bar{x} \tag{1}$$

where, y_i is the computed CUSUM value at any time i, n is the sample size, x_i, …, x_n is the original rainfall time series, $\bar{x}$ is the average of the total rainfall time series. The plot of y_i versus i normally oscillates around the horizontal axis when the original series (x_i, …, x_n) is free from statistically significant change in trends (Kampata *et al.*, 2008). A deviation from the oscillatory pattern suggests a possibility of change in trend, starting from the year of observation of such a change.

Pre-whitening process

Effect of serial dependence in a time series is often called *Serial Correlation Effect*, which is one of the causes of inaccuracy while detecting and interpreting trends in hydrologic time series data (Partal and Kahya, 2006). It was suggested that if positive serial correlation exists in the data, then the non-parametric MK test will indicate a significant trend more often than specified by a significant level (Kulkarni and Von Storch, 1995). Yue and Wang (2002) have investigated this issue using Monte Carlo simulation of a time series that had data consisted of a linear trend and a lag-one autoregressive (AR(1)) process with a noise to check its ability to accomplish such a task. They found that when sample size (i.e. $n > 70$) and magnitude of slope of trend are large enough (i.e. $|Q| > 0.005$), then the serial correlation no longer has a major affect on the MK test statistic. Moreover, they observed that in the above circumstances, removal of positive AR(1) by PW will remove a portion of trend and hence will reduce the possibility of rejecting the null hypothesis (i.e. no trend) while it might be false. Contrarily, the removal of negative AR(1) by PW will inflate trend and lead to an increase in the possibility of rejecting the null hypothesis while it might be true. However, in a recent study, Bayazit and Onoz (2007) found that the PW process causes a real loss of power only when the coefficient of variation (C_v) is very low, and the slope of trend and sample size exceed certain values when the C_v is moderate or high. Otherwise, although there is a reduction of power in the MK test due to the PW process, it will not bring the power below the value that the test has when there is no serial correlation. Therefore, Bayazit and Onoz (2007) recommended that the PW process should not be done if any one of the following two conditions are satisfied:

1) Dataset having very small value of C_v (i.e., $C_v \leq 0.1$), or
2) Dataset having large value of C_v (i.e., > 0.1), but sample size is large enough (i.e., $n \geq 50$) with high magnitude of slopes (i.e., $|Q| \geq 0.01$).

When any one of the above two conditions are met, it would cause statistically significant power loss if the PW process is applied, because serial correlation has negligible effect on the rejection rate of the test in these cases. It should be applied, however, in other cases to prevent the detection of a non-existent trend. Therefore, data used in this study were tested with the aforementioned criteria presented by Bayazit and Onoz (2007) to check if the PW process has to be applied or not before the trend analysis.

Mann-Kendall test

The MK test (Mann, 1945; Kendall, 1975) is a rank-based test for identifying statistically significant trends in a time series and is resistant to the effects of outliers (Hirsch *et al.*, 1993). In the MK test, a time series x_i was ranked from i = 1, 2, …, n-1 and another time series x_j from j = 2, 3, …, n, where n is the number of data points. Each data point in x_i was then used as a reference point and compared with all other data points in x_j ($j > i$), to obtain the values of the sign for each comparison using Equation (2).

$$\operatorname{sgn}(x_j - x_i) = \begin{Bmatrix} +1 & if & x_j > x_i \\ 0 & if & x_j = x_i \\ -1 & if & xj < xi \end{Bmatrix} \tag{2}$$

The Kendall's statistic S was then calculated using Equation (3).

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{3}$$

where, n is the number of observed data points. For $n \geq 10$, the statistic S is approximately normally distributed with zero mean (Mann, 1945; Kendall, 1975). The variance of S was computed using Equation (4).

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p - 1)(2t_p + 5)}{18} \tag{4}$$

where, g is the number of tied groups (a tied group is a set of sample data having the same value) and t_p is the number of data points in the p^{th} tied group.

The MK test statistic Z was then computed using Equation (5):

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if \quad S < 0 \end{cases} \quad (5)$$

A positive Z indicates an upward trend while a negative Z indicates a downward trend. The statistic Z follows the standard normal distribution. The presence of a statistically significant trend was evaluated using the Z value. In a two sided test, the null hypothesis of no trend, H_o was rejected at a certain significance level if $|Z| > Z_{crit}$, where Z_{crit} is the point on the normal distribution that has a probability of exceedance at a certain significance level. For example, at the 5% significance level, the null hypothesis was rejected if $|Z| > 1.96$. Higher magnitude of Z value indicates that the trend is more statistically significant.

Sen's slope estimate

The slope of rainfall (i.e., change in rainfall over time) was estimated by using *Sen's Slope Estimator* developed by Sen (1968). This method assumed that the slope is linear (Salmi *et al.*, 2002). The equation used for calculating slope of two rainfall records is as follows:

$$Q_i = \frac{x_k - x_j}{k - j} \text{ for all combinations of } k > j \quad (6)$$

where, x_k and x_j are the rainfall values at times k and j respectively. Q_i is the slope between data points x_k and x_j. For a time series with the length of n years data, there will be a total of $N = n(n-1)/2$ estimates of slopes. Having N numbers of calculated Q_i values, they were arranged in ascending order. The slope of rainfall (Q) in the Sen's slope estimator was taken as the median slope using Equation (7).

$$Q = \begin{cases} Q_{[(N+1)/2]} & \text{if } N \text{ is odd} \\ \frac{1}{2}(Q_{[N/2]} + Q_{[(N+2)/2]}) & \text{if } N \text{ is even} \end{cases} \quad (7)$$

The 95% two-sided confidence intervals of the slope estimate were obtained by a non-parametric technique based on normal distribution to determine whether the slope was statistically different from zero. A confidence interval was developed by estimating the rank for the lower and upper confidence interval and using the slopes corresponding to these ranks to define the actual confidence interval for *Q*. To estimate the range of ranks for the specified confidence interval (i.e. 95%), first *C* was calculated using Equation (8), where *Var(S)* was defined in Equation (4).

$$C = 1.96\sqrt{Var(S)} \tag{8}$$

Using the value of *C*, the ranks of the lower (M_1) and upper (M_2+1) confidence limits were calculated using Equations (9) and (10).

$$M_1 = (N - C)/2 \tag{9}$$

$$M_2 = (N + C)/2 \tag{10}$$

Finally, the slope corresponding to ranks M_1 and M_2+1 as the lower and upper confidence limits respectively was calculated. This slope was then defined as statistically significant if zero does not lie between the upper and lower confidence limits.

RESULTS AND DISCUSSIONS

In this section, results obtained from rainfall trend study for the monthly and annual rainfall time series data are presented. The results of the CUSUM test showed that out of a total of 195 rainfall time series data, only 11 have statistically significant change in trend. These 11 time series with their trend beginning year (at a 1% significance level) are presented in Table II. It can be seen from Table II that the majority of time series which have a statistically significant trend beginning year is for the month of May and also that the trend beginning year lies in between 1974 and 1985. As discussed earlier, for these 11 stations with a statistically significant trend beginning year, the trend analysis was conducted on the dataset after the trend beginning year.

INSERT TABLE II NEAR HERE

The MK test statistics at different significant levels (i.e. 5%, 10% and >10%) are presented in Table III, where statistically significant values at 5% and 10% level are shaded dark. In Table III, positive Mann-Kendall statistic *Z* indicates an increasing trend, while negative *Z* value indicates a decreasing rainfall trend. The slope (*Q*) of rainfall for each time series data are also presented in Table III. This table shows that the absolute values of *Q* (i.e., |Q|) for all time series are higher than 0.01 except at station 14 for time series of February and November, and station 2 for March (these three time series had *Q* = -0.01). Moreover, it was found that all the time series data used in this study have the C_v values > 0.1, but with high magnitude of slopes (presented in Table III). As was mentioned before, 54 years of data records were used for this trend analysis. Therefore, this study satisfies one of the two criteria proposed by Bayazit and Onoz (2007) (i.e., dataset having C_v values > 0.1, but with |Q| ≥ 0.01 as well as the sample size being ≥ 50) for not applying the PW process. Thus, the MK test was applied to the rainfall time series data without performing the PW of data.

INSERT TABLE III NEAR HERE

It can be seen from Table III that there are decreasing rainfall trends at all stations in all monthly rainfall time series data, except in January and June for all stations and in December, February, March and April for some stations. The reason for increasing trends at all stations in January and June were observed possibly due to the increase in the extreme rainfall events and that inter-annual variations were generally driven by changes in heavy rainfall events (Hennessy *et al.*, 1999). The changing pattern in rainfall during the months of December, February, March and April are similar. Both increasing and decreasing trends are detected in these 4 months, but not at a statistically significant level (i.e. at 10% level), except at station 1 where significant trend at 10% level is detected in April. Monthly rainfall time series in May showed the strongest magnitude in rainfall decrease, with the MK statistic being statistically significant at 10% level for majority of stations (Table III). While significant decreasing rainfall trends are detected in May, the other two autumn months of March and April exhibited a combination of increasing and decreasing trends, most of which were not statistically significant. Although previous studies related to SEA have concluded (as discussed earlier) that the statistically significant reduction in rainfalls since 1950 are confined to autumn months, this study shows that most statistically significant decreasing trends amongst the autumn months is in May. On the contrary, the month of April exhibited increasing trends at ten stations out of the fifteen (although not statistically significant). Thus, it can be concluded that the rainfall trend results at a local scale (Yarra River catchment presented in this study) can be quite different to that at a regional scale (SEA from previous studies mentioned earlier). The month of June exhibited just the opposite trend to that of May, with increasing trends at all stations. During the next five months from July to November, decreasing trends at all stations are detected. Amongst these months that exhibited decreasing rainfall trends, July and August are winter months whereas September to November are the spring months. From Table III, it can also be observed that this decreasing trends are statistically significant (i.e. at 10% level) at some stations. In December, both increasing and decreasing trends are detected, but none at a significant level. The month of December could be the transitional month as some stations for January shows strong increasing trends, while months from July to November shows decreasing trends, which may indicate a shift in the annual cycle of the hydrologic regime (Zhang *et al.*, 2001).

It is worthwhile to mention that the study conducted by Chowdhury and Beecham (2010) was only on monthly time series data at station 14 (i.e., Melbourne Regional Office) and they found no statistically significant trend at 5% level. Similar results were also found for this station in this study for all months (Table III), although statistically significant decreasing trend at 10% level were observed in August and September as well as at 5% level in the annual time series data. In Table III, trends in annual rainfall time series data shows that all stations have decreasing trends in rainfall. Moreover, this study shows that the decreasing rainfall trends (both monthly and annual) are more pronounced in the urban and agricultural areas, and these are more statistically significant as compared to decreasing rainfall trends in the forest areas (Table III). On the contrary, the increasing rainfall trends in January are more statistically significant in the forest areas. The slopes of rainfall trends (Q) presented in Table III show that the significant (i.e. 10% level) increasing monthly rainfall slope are ranging from 0.40 mm per year in June (at station 9) to 0.80 mm per year in January (at station 3), and the decreasing monthly rainfall slope values are ranging from -0.27 mm per year in August (at station 14) to -1.46 mm per year in May (at station 1). In annual rainfall data, the range is from -2.25 (at station 3) to -5.44 mm per year (at station 7).

Percent of stations showing increasing/decreasing trends at different significant levels are presented in Table IV. The months that show either increasing or decreasing trends (i.e. one or the other, and not a combination) at all 15 stations are shaded dark; the rest of the months showed a combination of both increasing and decreasing trends. From Table IV, it can be seen that in the months with increasing trends, 40% and 7% of the total stations have increasing trends at 10% level of significance in January and June respectively. In the decreasing months, the most noticeable results were observed in May where 53% of the stations showed significant decreasing trend at 10% level, out of which 40% of the total stations shows significant decreasing trends at 5% level. In the annual rainfall time series data, 67% of the total stations have significant decreasing trends at 10% level, out of which 47% are at 5% significance level (Table IV). This shows that annual rainfalls have been significantly reducing within the Yarra River catchment over that last 50 years.

INSERT TABLE IV NEAR HERE

The spatial distributions of trend in monthly and annual rainfall data are presented in Figure 3 and Figure 4 respectively. In both figures, increasing trends are presented with the upward arrows and triangles, whereas decreasing trends are presented with the downward arrows and triangles. The significant trends at 5% and 10% significance levels are represented with triangles and bold arrows respectively, while normal arrows represented non significant trends. Figure 3 shows that the significant increasing trends in January and June are observed in the middle and upper reaches of the Yarra River catchment (which are agricultural and forest areas respectively). On the other hand, decreasing rainfall trends during the months of July, August, September and October are more significant in the lower urban areas of the catchment. Figure 3 also shows that strong statistically significant decreasing rainfall trends are detected in May throughout the catchment. In the spatial distribution of annual rainfall trends presented in Figure 4, it can be seen that there are decreasing rainfall trends throughout the catchment and statistically significant decreasing trends are more dominant in the southern part of the catchment.

INSERT FIGURE 3 AND FIGURE 4 NEAR HERE

Finding out the possible causes of observed trends was not attempted in this study. However, several previous studies have attempted to determine the reasons behind Australian climate variability. It was found that changing mode in El Nino - Southern Oscillation (ENSO) could have an effect on change in rainfall as ENSO was shown to modulate rainfall over most of Australia (Nicholls, 1989). It was also recognized that the tropical Pacific Ocean has a significant impact on large-scale atmospheric circulation and Australian climate (Murphy and Timbal, 2008). A study conducted by McBride and Nicholls (1983) showed that the rainfall is mainly affected by ENSO in the winter and spring months, but its impact was recently shown to be asymmetric (Power *et al.*, 2006). Therefore, to find the possible causes of changes in rainfall within the Yarra River catchment, it is recommended that future studies be conducted to analyze relationships between observed rainfall changes and the changing patterns of ENSO.

IMPLICATIONS FOR WATER RESOURCES WITHIN THE YARRA RIVER CATCHMENT

Any changes in rainfall pattern would have affects on water availability, which in turn affects urban water supply and agricultural, residential and industrial water uses. As was seen in this study, significant decreasing rainfall trends are observed within the Yarra River catchment. Thus the changing scenario of water availability needs to be properly taken into account for the long-term catchment scale water management. If this reducing trend continues, then the severity and duration of droughts can be expected to increase and more frequent droughts can be expected in the future than in the past, which consequently will reduce the streamflows. Reduction of streamflows will in turn lead to reduction in reservoir inflows. The reducing trends in rainfall observed in this study indicate that the current Drought Response Plan (DRP) will need to be considered for further review. Tan and Rhodes (2008) have also suggested timely review of DRP taking into account the climate change effects for its effective application. In particular, it may be necessary to review the existing restrictions and bans trigger levels used in the DRP for defining low flow conditions during the drought period. Moreover, the amount of extractable water by licensed water users may also need to be reassessed.

In the Yarra River catchment, the most important sectors that are likely to be adversely affected due to changing rainfall patterns are urban water supply, maintaining environmental flow (which is important to save the unique and rich flora and fauna), water quality and irrigation. Reduced environmental condition of streams also has associated implications for water harvesting in regulated and unregulated streams. The urbanized lower part of the catchment is highly dependent on water supply from the storage reservoirs located in the upper and middle reaches of the catchment. Therefore, this region is more likely to be the risk-prone region. Decreasing rainfall patterns may also have led to reduced health of waterways due to changes in base flows. This could lead to negative water quality impacts in Port Phillip Bay due to increased concentration of pollutants and higher ambient water temperatures in the Bay. There will also be increased risk of bushfires in the catchment areas with associated risk of decreased streamflows. Therefore, effective measures should be taken to reduce possible damage due to the reduction in rainfall patterns and the need for the development of an effective water supply and demand strategy in light of the reducing rainfalls has become very timely.

CONCLUSIONS

Several studies have been carried out at the national and global scale throughout the world to reveal the climate change impacts on hydro-climatic variables. In the recent past, some studies have been undertaken in south-eastern Australia due to the scarcity of water resources in this region. Some recent studies have also suggested that any analysis of hydro-climatic variables should be done at the local scale rather than at a large or global scale. This is because, although climate change is a global phenomenon, the trends and their impacts may be different from one location to the other. However, no studies were found specific to the Yarra River catchment, which is the most important water resources catchment for Victoria's inhabitants in Australia. In the last decade, this catchment has experienced a long-term drought and it is of interest to water resource professionals to know if this drought is part of a short-term climatic cycle or a decline in long-term rainfall brought about by global climate change. To address this issue, a spatio-temporal rainfall trend analysis was preformed in this study using the widely used Mann–Kendall test. Monthly as well as annual rainfall data ranging from 1953 to 2006 at 15 measuring stations within the Yarra River catchment were used for this analysis.

This study indicated that decreasing rainfall trends were detected in monthly rainfall time series at all stations except in January and June. Remarkable statistically significant decreasing rainfall trends were observed in May for majority of the stations and also in some other months for several stations. Decreasing rainfall trends were also observed in annual rainfall time series at all stations. These imply that there was appreciable reduction in water resources availability within the Yarra River catchment in the past 50 years. If this reduction persists, then the severity and duration of droughts can be expected to be more frequent in the future than in the past. In such a situation, the current Drought Response Plan (DRP) will need to be considered for further review. Moreover, the urbanized lower part of the catchment will be more likely the risk-prone area, since it is highly dependent on water supply from the storage reservoirs located in the middle and upper reaches of the catchment.

The results presented in this study may have resulted from possible climate change and/or from the impact of other human activities. However, this study did not attempt to reveal the possible causes of decreasing rainfall trends that were observed, which will have to be addressed in future studies. Nevertheless, the results presented here will be useful as an initial step towards further investigation of the impact of climate change and human induced activities on hydrological processes within the Yarra River catchment.

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Hydrological Processes, Vol. 27, Issue 12, pp. 1727-1738 (2013)
The published article can be downloaded from: http://dx.doi.org/10.1002/hyp.9311

List of Tables:

Table I. Description of rainfall measuring stations

ID	Station No.	Station Name	Latitude (°S)	Longitude (°E)	Elevation (m a.s.l)[a]
Stations in forest area					
1	86090	O'Shannassy Reservoir	-37.71	145.79	240.0
2	86094	Powelltown Dnre	-37.86	145.74	189.1
3	86121	Warburton	-37.75	145.68	170.0
4	86142	Mt St Leonard DPI	-37.57	145.50	620.0
5	86219	Coranderrk Badger Weir	-37.69	145.56	360.0
Stations in agricultural area					
6	86036	Epping	-37.63	144.99	140.0
7	86073	Mickleham	-37.55	144.88	270.0
8	86106	Silvan	-37.83	145.44	259.0
9	86117	Toorourrong	-37.48	145.15	219.0
10	86131	Yan Yean	-37.56	145.13	198.0
Stations in urban area					
11	86018	Caulfield (Racecourse)	-37.88	145.04	48.8
12	86035	Eltham	-37.70	145.15	35.0
13	86066	Lilydale	-37.75	145.34	113.0
14	86071	Melbourne Regional Office	-37.81	144.97	31.2
15	86096	Preston Reservoir	-37.72	145.00	94.0

[a] Metres above sea level

Table II. Time series having statistically significant change in trends and their trend beginning year

ID	Monthly/Yearly time series	Significant change point at 1% level
Stations in forest area		
2	May	1975
3	May	1983
5	June	1975
Stations in agricultural area		
7	May	1974
8	May	1975
Stations in urban area		
11	May	1981
11	August	1985
12	May	1983
12	Yearly	1978
14	May	1981
15	May	1981

Hydrological Processes, Vol. 27, Issue 12, pp. 1727-1738 (2013)
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Table III. Mann-Kendall *Z* statistic and slope of rainfall (statistically significant values at 5% and 10% levels are shaded dark)

ID	Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Stations in Forest area														
1	Z	1.55	-0.56	-0.26	-1.67	-2.69	0.31	-1.32	-1.48	-1.48	-0.75	-2.28	-0.40	-1.01
	Signif.	>0.10	>0.10	>0.10	0.10	0.05	>0.10	>0.10	>0.10	>0.10	>0.10	0.05	>0.10	>0.10
	Q	0.43	-0.25	-0.05	-0.77	-1.46	0.15	-0.85	-0.78	-0.78	-0.43	-1.04	-0.18	-1.55
2	Z	2.18	-0.09	-0.01	-0.27	-1.70	0.50	-1.37	-1.69	-0.74	-0.83	-2.02	-0.57	-1.74
	Signif.	0.05	>0.10	>0.10	>0.10	0.10	>0.10	>0.10	0.10	>0.10	>0.10	0.05	>0.10	0.10
	Q	0.79	-0.06	-0.01	-0.13	-1.34	0.27	-0.71	-0.79	-0.39	-0.47	-1.07	-0.23	-3.71
3	Z	2.38	-0.54	0.46	-0.07	-0.72	0.83	-0.60	-1.28	-1.58	-0.84	-1.53	-0.04	-1.72
	Signif.	0.05	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	0.10
	Q	0.80	-0.26	0.11	-0.04	-0.37	0.36	-0.21	-0.61	-0.79	-0.36	-0.84	-0.04	-2.25
4	Z	2.13	-0.60	0.18	0.33	-2.22	1.52	-0.54	-0.90	-0.75	-0.76	-1.52	-0.60	-1.22
	Signif.	0.05	>0.10	>0.10	>0.10	0.05	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10
	Q	0.77	-0.22	0.13	0.17	-1.03	0.53	-0.20	-0.46	-0.39	-0.38	-0.71	-0.39	-2.49
5	Z	1.88	-0.45	0.21	0.67	-2.97	0.60	-1.21	-0.98	-0.82	-0.69	-1.60	-0.59	-1.06
	Signif.	0.10	>0.10	>0.10	>0.10	0.05	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10
	Q	0.50	-0.19	0.06	0.28	-1.19	0.51	-0.41	-0.44	-0.40	-0.35	-1.00	-0.31	-1.98
Stations in Agricultural area														
6	Z	0.59	-0.17	-0.17	0.31	-2.78	0.93	-0.90	-1.38	-1.86	-1.69	-0.37	-0.15	-2.76
	Signif.	>0.10	>0.10	>0.10	>0.10	0.05	>0.10	>0.10	>0.10	0.10	0.10	>0.10	>0.10	0.05
	Q	0.16	-0.06	-0.05	0.07	-0.84	0.14	-0.23	-0.27	-0.34	-0.45	-0.10	-0.06	-3.76
7	Z	0.40	-0.29	-0.51	-0.06	-0.99	0.32	-0.87	-1.93	-2.44	-1.69	-0.13	-0.54	-2.34
	Signif.	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	0.10	0.05	0.10	>0.10	>0.10	0.05
	Q	0.13	-0.09	-0.13	-0.03	-0.51	0.04	-0.19	-0.48	-0.50	-0.66	-0.06	-0.15	-5.44
8	Z	1.48	-0.63	-0.46	-0.17	-1.28	0.73	-1.34	-1.43	-1.07	-1.45	-1.63	0.14	-1.99
	Signif.	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	0.05
	Q	0.41	-0.21	-0.15	-0.07	-0.85	0.27	-0.51	-0.61	-0.49	-0.72	-0.67	0.07	-4.60
9	Z	1.73	-0.21	0.04	0.38	-1.81	2.03	-0.25	-0.51	-1.60	-1.29	-0.90	-0.71	-1.34
	Signif.	0.10	>0.10	>0.10	>0.10	0.10	0.05	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10
	Q	0.44	-0.09	0.01	0.11	-0.51	0.40	-0.06	-0.15	-0.35	-0.51	-0.21	-0.25	-1.76
10	Z	0.57	-0.95	-0.44	0.57	-2.16	1.46	-1.04	-1.04	-1.33	-1.12	-0.84	-0.66	-2.45
	Signif.	>0.10	>0.10	>0.10	>0.10	0.05	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	0.05
	Q	0.15	-0.25	-0.07	0.14	-0.54	0.25	-0.18	-0.27	-0.26	-0.30	-0.22	-0.23	-4.38
Stations in Urban area														
11	Z	0.40	0.24	-0.53	0.40	-0.71	0.07	-1.39	-0.70	-2.15	-2.04	-0.85	-0.33	-2.69
	Signif.	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	0.05	0.05	>0.10	>0.10	0.05
	Q	0.10	0.08	-0.13	0.13	-0.58	0.01	-0.36	-0.75	-0.58	-0.64	-0.26	-0.13	-3.73
12	Z	0.76	-1.16	-1.23	0.48	-0.65	1.00	-2.43	-1.90	-1.80	-1.55	-1.10	-0.58	-1.09
	Signif.	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	0.05	0.10	0.10	>0.10	>0.10	>0.10	>0.10
	Q	0.19	-0.31	-0.28	0.11	-0.47	0.18	-0.56	-0.43	-0.49	-0.49	-0.26	-0.18	-4.16
13	Z	2.03	-0.57	-0.63	0.34	-3.05	0.83	-1.70	-1.68	-1.54	-1.40	-1.09	-0.34	-1.95
	Signif.	0.05	>0.10	>0.10	>0.10	0.05	>0.10	0.10	0.10	>0.10	>0.10	>0.10	>0.10	0.10
	Q	0.50	-0.17	-0.15	0.10	-1.10	0.22	-0.46	-0.46	-0.44	-0.51	-0.35	-0.12	-2.30
14	Z	0.59	-0.02	-0.97	0.43	-1.01	0.55	-1.33	-1.70	-1.89	-1.50	-0.01	0.26	-2.02
	Signif.	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	0.10	0.10	>0.10	>0.10	>0.10	0.05
	Q	0.13	-0.01	-0.22	0.12	-0.97	0.11	-0.28	-0.27	-0.50	-0.43	-0.01	0.08	-3.20
15	Z	1.29	-0.19	-0.09	0.15	-1.06	1.42	-1.07	-1.07	-1.66	-1.43	-0.72	0.46	-1.97
	Signif.	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	>0.10	0.10	>0.10	>0.10	>0.10	0.05
	Q	0.35	-0.09	-0.02	0.03	-0.97	0.26	-0.19	-0.20	-0.40	-0.40	-0.16	0.20	-2.40

Z - Mann-Kendall statistic

Signif. - Trend at different levels of significance (5%, 10% and >10%)

Q - Sen's slope (mm/year)

Hydrological Processes, Vol. 27, Issue 12, pp. 1727-1738 (2013)
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Table IV. Percentage of stations showing increasing/decreasing trends

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Increasing													
at α = 0.05	27	-	-	-	-	7	-	-	-	-	-	-	-
at α = 0.1	40	-	-	-	-	7	-	-	-	-	-	-	-
at α > 0.1	100	7	27	67	-	100	-	-	-	-	-	20	-
Decreasing													
at α = 0.05	-	-	-	-	40	-	7	7	13	7	13	-	47
at α = 0.1	-	-	-	7	53	-	13	40	40	20	13	-	67
at α > 0.1	-	93	73	33	100	-	100	100	100	100	100	80	100

Months with either increasing or decreasing trends at all 15 stations are shaded dark

Hydrological Processes, Vol. 27, Issue 12, pp. 1727-1738 (2013)
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Figure Captions

Figure 1 : The Yarra River catchment with locations of the rainfall measuring stations and the three landuse patterns

Figure 2 : Annual rainfall pattern over the Yarra River catchment

Figure 3 : Spatial distribution of monthly rainfall trends (Note: figure not to scale)

Figure 4 : Spatial distribution of annual rainfall trends (Note: figure not to scale)

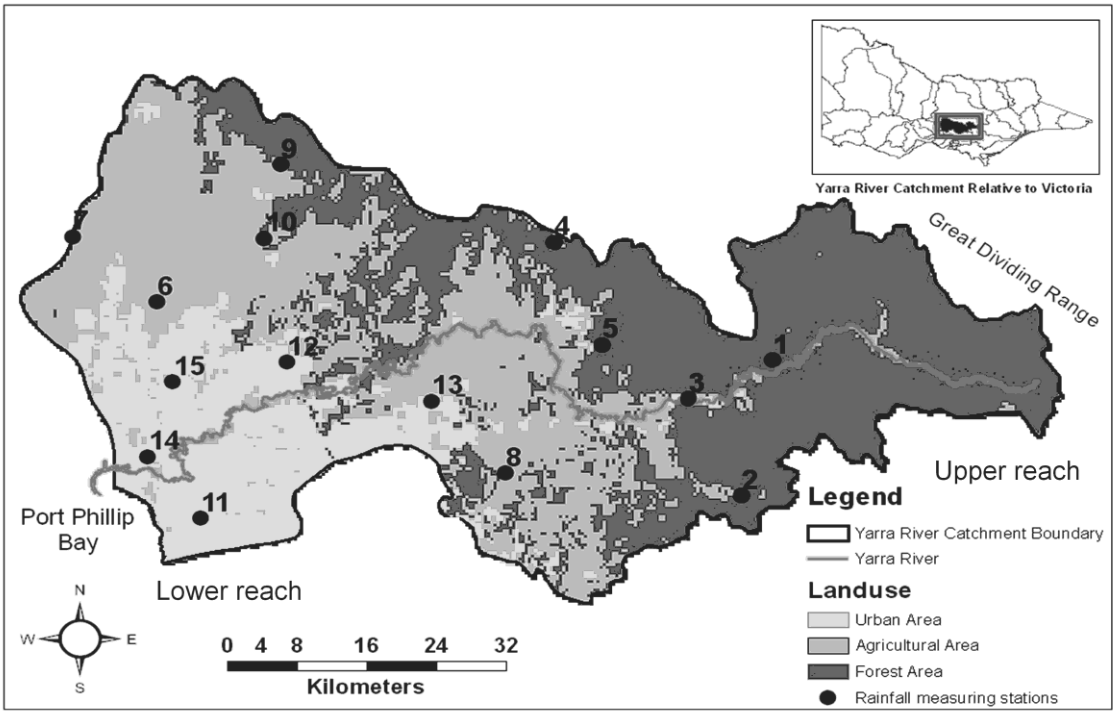


Figure 1. The Yarra River catchment with locations of the rainfall measuring stations and the three landuse patterns

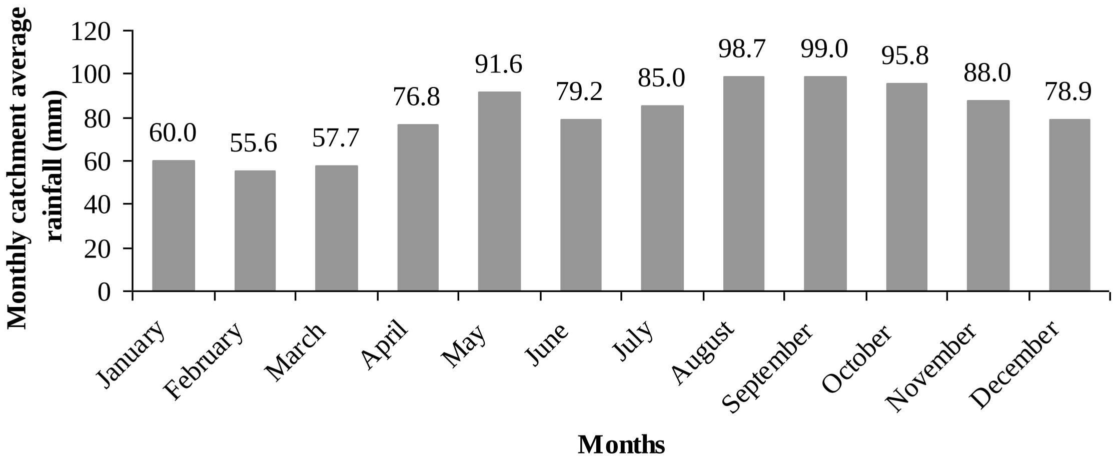
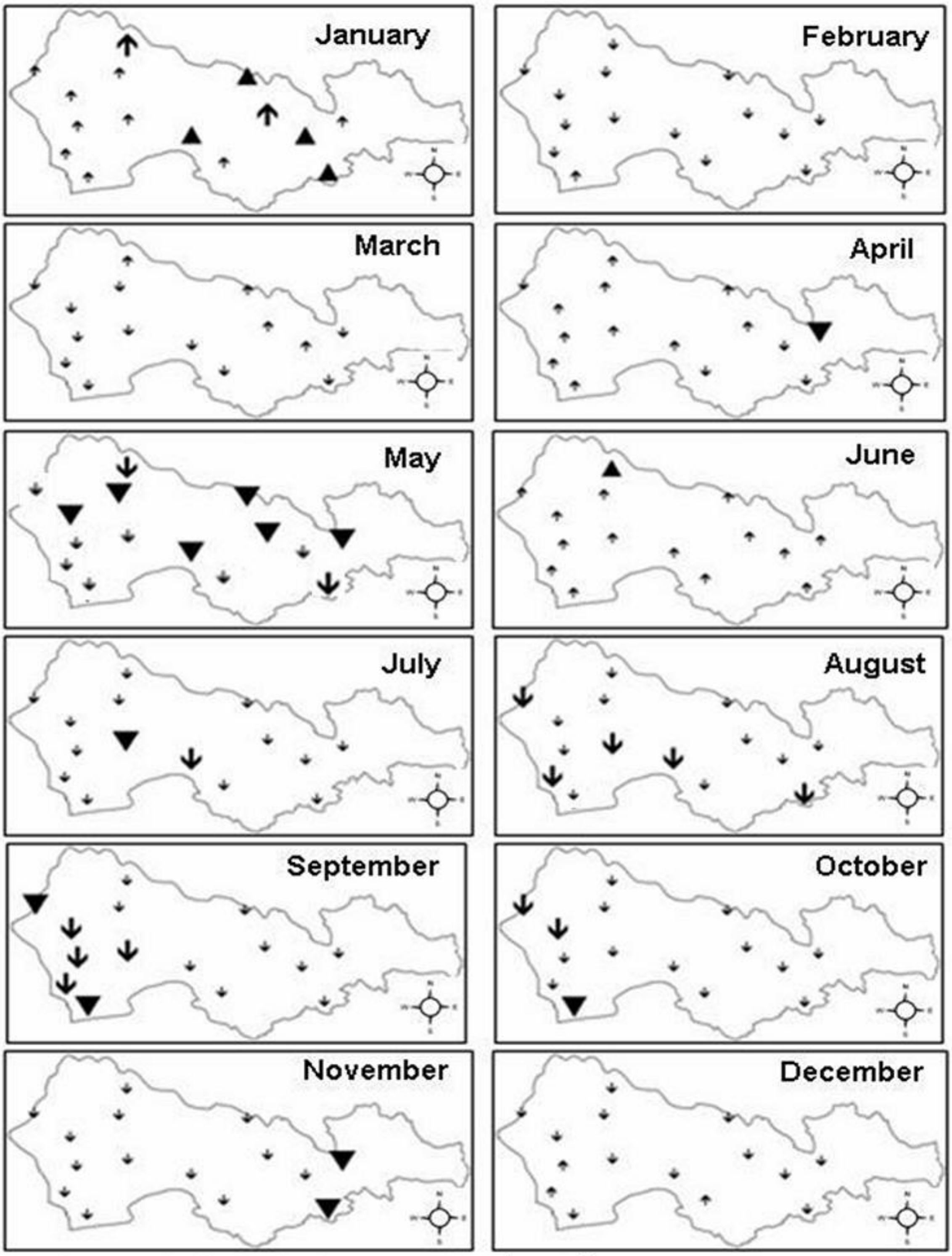
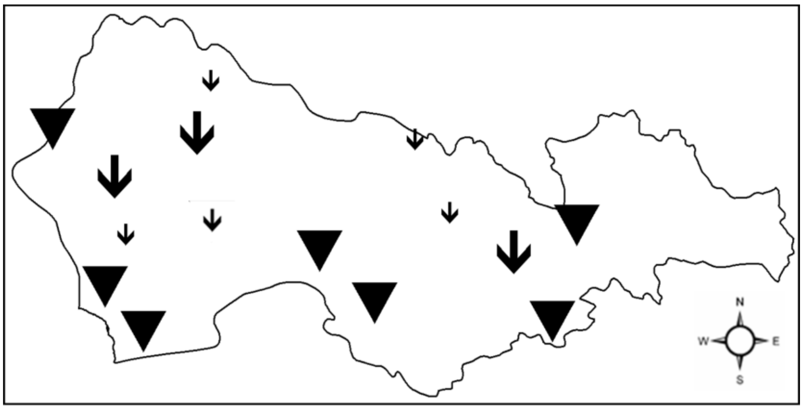


Figure 2. Annual rainfall pattern over the Yarra River catchment



Trends at 5% significance level are presented by ▲ and ▼.
Trends at 10% significance level are presented by 🡅 and 🡇.
Trends at >10% significance level are presented by ↑ and ↓.

Figure 3. Spatial distribution of monthly rainfall trends (Note: figure not to scale)



Decreasing trends at 5% significance level are presented by ▼.
Decreasing trends at 10% significance level are presented by 🡇.
Decreasing trends at >10% significance level are presented by ↓.

Figure 4. Spatial distribution of annual rainfall trends (Note: figure not to scale)