

Spatiotemporal Trend Analysis of Extreme Rainfall Events in Victoria, Australia

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Abstract Extreme rainfall events are among the natural hazards with catastrophic impacts on human society. Trend analysis is important to understand the effects of climate change and variability on extreme rainfalls. In this study, extreme rainfall (i.e., annual maximums) trends were investigated in Victoria (Australia) using data from 23 stations for storm durations of 10 and 30 min, and 1, 3, 6, 12, 24 and 48 h. The Mann-Kendal and Spearman's Rho tests were employed for detection of temporal trends. Moreover, the spatial variability of extreme rainfall trends was investigated through interpolation of Theil-Sen's estimator over Victoria. In general, increasing extreme rainfall trends were detected for short storm durations (i.e., 10 and 30 min, and 1 and 3 h), whereas decreasing extreme rainfall trends were found for long storm durations (i.e., 6, 12, 24 and 48 h). Increasing trends for short storm durations were mostly statistically significant, while decreasing trends for long storm durations were statistically insignificant. Trend analysis with respect to the four regions (i.e., Western, Northern, Central and Gippsland) in Victoria showed that increasing trends were present in general in the Northern and east Central Region, whereas decreasing trends were detected in the Western and west Gippsland Regions.

Keywords Extreme rainfall · Trend · Spatial variability

1 Introduction

Extreme rainfall events and the resulting floods, landslides and mudflows are among the natural hazards with catastrophic impacts on human society. These impacts could lead to enormous economic losses and in some cases loss of lives. Extreme rainfall related problems have been more concern for the last few decades due to increases in intensity and frequency of

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extreme rainfall events, as reported by several studies (e.g., Groisman et al. 2005; Min et al. 2011). Such increases may have significant consequences on many socio-economic sectors such as agriculture, transportation, power generation. These changes can also very likely have serious effects on ecosystems, hydrology and water resources (Kysely 2009).

Increases in intensity and frequency of extreme rainfalls can arise due to natural and/or anthropogenic changes in atmospheric forcings (IPCC 2007). Anthropogenic changes in atmospheric forcings are caused by human activities, including the emission of greenhouse gases as well as anthropogenic aerosols. On the other hand, natural changes in atmospheric forcings are caused by natural climate variability, which may be a result of internal dynamics of the climate system (such as El Niño-Southern Oscillation phenomenon) or external forcing such as abrupt changes due to volcanic eruptions (Ishak et al. 2013).

Trend analysis has been commonly conducted in the literature to investigate changes in intensity and frequency of extreme rainfall events (e.g., Shahid 2011; Yilmaz 2014). Trend analysis has been used to understand the effects of climate change and variability in the past on extreme rainfalls. Moreover, better understanding of past changes in the characteristics of extreme rainfall events is critical for reliable projections of future changes (Min et al. 2011).

Trends in intensity and frequency of extreme rainfall events can have significant effects on water infrastructure and flood protection structures, since the trend can be an indicator of non-stationary climate. Design rainfall intensity estimates, which are essential inputs for design of water infrastructure and flood protection projects, are currently derived under the stationary climate assumption, i.e., that the probability of occurrence of extreme event does not depend on time (Bonaccorso et al. 2005). However, such a hypothesis may not be suitable, when trend exists in observed series of extreme rainfalls (Khaliq et al. 2006). Therefore, it is necessary to investigate trends in extreme rainfall events prior to calculate design rainfall intensities under the stationary climate assumption. Due to this importance of trend analysis, the number of studies investigating trends in hydro-meteorological data has grown rapidly during the last few decades worldwide. Some examples can be shown in Europe (e.g., Kiktev et al. 2003; Hundecha and Bárdossy 2005), Asia (e.g., Wan Zin et al. 2010; Iwasaki 2012), North America (e.g., Groisman et al. 2001; DeGaetano 2009), South America (e.g., Haylock et al. 2006; Khan et al. 2007) and Africa (e.g., New et al. 2006).

Several studies had been conducted in investigating rainfall trends in Australia (e.g., Collins and Della-Marta 2002; Smith 2004; Murphy and Timbal 2008; Barua et al. 2012), however the Australian studies on extreme rainfall trends are limited. For example, Gallant et al. (2007) investigated rainfall trends including extreme events (95th and 99th percentiles) over two periods (i.e., 1910–2005 and 1951–2005) using daily data from 95 stations for six regions in southwest and east of Australia. They found significant decrease in extreme rainfalls in the eastern coast in particular during summer and winter seasons after 1950. Chowdhury and Beecham (2013) examined extreme rainfall intensities of the events with return periods from 1 month to 10 years for ten cities in Australia. They reported between 20 and 40 % increases in extreme rainfall in Perth and Darwin, and no significant change in the other cities. It should be noted that abovementioned studies in Australia did not consider sub-daily rainfall data in their analysis, although extreme rainfall trends can show large variations over short durations (Bonaccorso et al. 2005).

There have been very few studies in Australia considering sub-daily rainfall data for extreme rainfall trend analysis. Westra and Sisson (2011) reported significant increases in extreme rainfalls (annual maximums) for short storm durations, and smaller increases in extreme rainfalls for longer storm durations by analysing data from 30 sub-daily gauges in

east Australia. Yilmaz and Perera (2014) investigated trends in annual maximum rainfall data of various storm durations from a single station in Victoria. They reported statistically significant increasing trends in extreme rainfalls for short storm durations, and statistically insignificant decreasing trends for long storm durations. However, these studies did not provide detailed analysis (both temporal and spatial analysis) of many stations (with long record of quality controlled data) in Victoria.

This paper contributed to better understanding of the relationship between extreme rainfalls and climate change and/or variability in Victoria through the following tasks: (a) detection of temporal trends in extreme rainfalls (annual maximums) of various durations (i.e., ranging from 10 min to 48 h), and (b) detection of spatial variability of temporal trends over Victoria.

2 Study Area and Data

Victoria, which is located in south east Australia, was selected as the study area. Victoria is the second most populated state in Australia, although it has the second-smallest land area (237,629 km²) (Nedovic-Budic et al. 2004). The Department of Environment and Primary Industries (DEPI) defined four regions (i.e., Western, Northern, Central and Gippsland) in Victoria, as shown in Fig. 1, to develop regional sustainable water strategies in order to secure the water future of Victoria (DEPI 2014). In Fig. 1, the areas denoted by 1, 2, 3 and 4 correspond to Western, Northern, Central and Gippsland Regions respectively.

Quality controlled annual maximum rainfall data from 23 stations in Victoria were used for the analysis of this study. Annual maximum rainfall data of eight storm durations (i.e., 10, 30 min, and 1, 3, 6, 12, 24, 48 h) were considered in the trend analysis. Since the length of the data record is significant for the accuracy of trend analysis, longer rainfall records were selected in this study. Selected stations along with their descriptive information are shown in Table 1.

3 Methods

3.1 Temporal Trend Detection

The Mann-Kendall (MK) and Spearman's rho (SR) tests were employed for temporal trend detection of extreme rainfalls (i.e., annual maximums) in this study. The MK and SR are well established non-parametric tests, which were widely used in trend detection of hydro-meteorological time series data (Yue et al. 2002; Yilmaz et al. 2011, 2014; Barua et al. 2012; Laz et al. 2014). The MK and SR tests are distribution-free tests; therefore, they are appropriate for trend analysis of rainfall data, which in general are non-normally distributed (Kundzewicz and Robson 2000).

3.1.1 Mann-Kendal Test

The Mann-Kendall test is a rank-based test and it is less sensitive to outliers relative to parametric tests. The test statistic of the MK test, S , is computed as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (1)$$

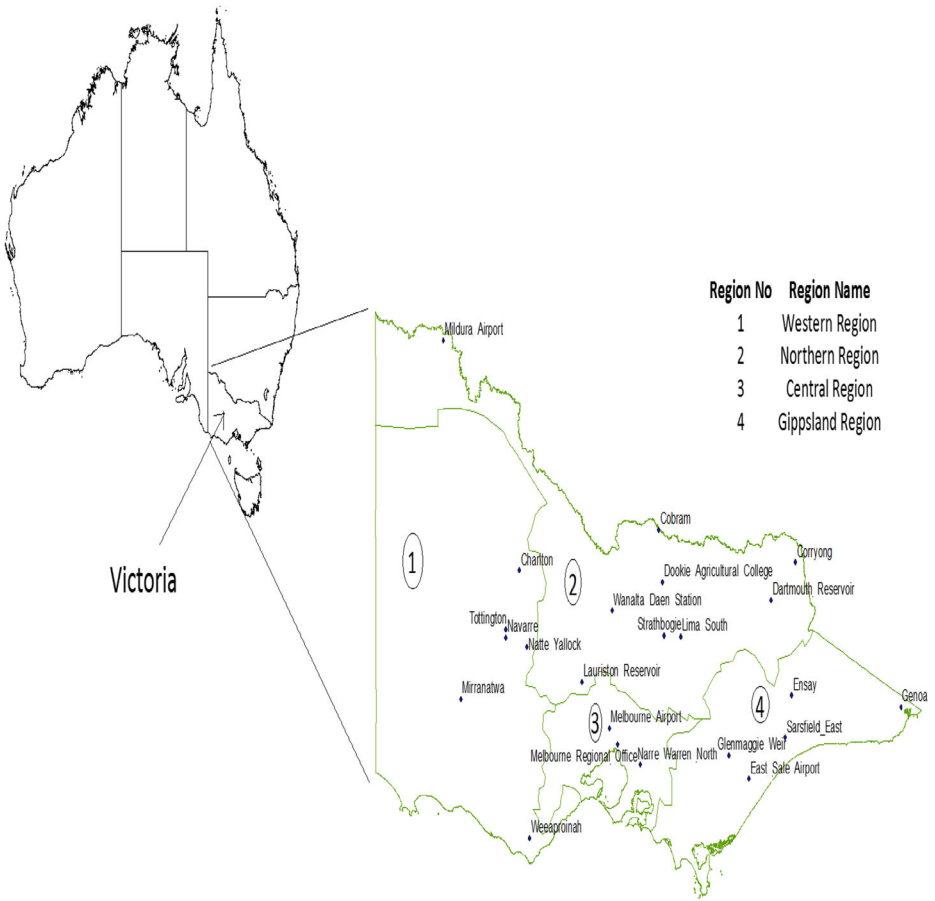


Fig. 1 Approximate locations of selected rainfall stations

where x_j and x_k are the sequential data values, n is the number of the observations.

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

The variance of S , $Var(S)$, is calculated using Eq. (3).

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

The standardized z statistic is computed by Eq. (4).

$$z = \begin{cases} \frac{S-1}{Var(S)} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{Var(S)} & \text{if } S < 0 \end{cases} \tag{4}$$

Table 1 Selected stations for the study

Regions	Station No	Station name	Latitude	Longitude	Height (m)	Data period
Northern Region	76031	Mildura Airport	-34.2	142.1	50	1953–2011
	82076	Dartmouth Reservoir	-36.5	147.5	365	1975–2013
	82011	Corryong	-36.2	147.9	313.5	1972–2006
	80109	Cobram	-35.9	145.6	113	1957–2011
	81013	Dookie Agricultural College	-36.4	145.7	185	1950–2013
	81115	Wanalta Daen Station	-36.6	144.9	115	1974–2011
	82042	Strathbogie	-36.8	145.7	502	1974–2011
	82107	Lima South	-36.9	146.0	273	1968–2011
	88037	Lauriston Reservoir	-37.3	144.4	487.6	1958–2012
	Western Region	79079	Tottington	-36.8	143.1	228.6
80067		Charlton	-36.3	143.3	130	1951–2011
79086		Navarre	-36.9	143.1	262.1	1973–2011
81038		Natte Yallock	-36.9	143.5	198.1	1974–2011
89019		Miiranatwa	-37.4	142.4	248	1974–2013
90083		Weeaprounah	-38.6	143.5	492	1974–2011
Central Region	86071	Melbourne Regional Office	-37.8	145.0	31.2	1873–2011
	86282	Melbourne Airport	-37.7	144.8	113.4	1970–2013
	86085	Narre Warren North	-38.0	145.3	120	1974–2011
Gippsland Region	84015	Ensay	-37.4	147.8	240	1972–2011
	84078	Sarsfield East	-37.8	147.7	8	1962–2011
	85034	Glenmaggie Weir	-37.9	146.8	95	1957–2011
	85072	East Sale Airport	-38.1	147.1	4.6	1953–2011
	84122	Genoa	-37.5	149.6	21	1966–2013

In the MK test, the positive test statistic indicates increasing trend, whereas the negative test statistic indicates decreasing trends. The null hypothesis (H_0) of the Mann-Kendal test is “there is no trend”. If the calculated z statistic is larger than the critical values (derived from normal distribution tables) at the specified significance levels (0.1, 0.05 and 0.01 significance levels were considered in this study), then H_0 is rejected, and the alternative hypothesis (H_A), which is “there is a trend”, is accepted (Yilmaz and Perera 2014).

3.1.2 Spearman's Rho Test

The SR is a rank based test that is used to determine if the correlation between two variables is significant. In the SR test, one variable is considered as the time itself, whereas the other variable is the corresponding time series data. Time series values are replaced with their ranks in the SR test, and SR test statistic, ρ_s , is calculated as follows:

$$\rho_s = \frac{S_{xy}}{(S_x S_y)^{0.5}} \quad (5)$$

where

$$S_x = \sum_{i=1}^n (x_i - \bar{X})^2 \quad (6)$$

$$S_y = \sum_{i=1}^n (y_i - \bar{Y})^2 \quad (7)$$

$$S_{xy} = \sum_{i=1}^n (x_i - \bar{X})(y_i - \bar{Y}) \quad (8)$$

In above equations, x_i corresponds to time, y_i is the variable of interest, \bar{X} and \bar{Y} refer to the average values of x_i and y_i . Null and alternative hypothesis of the SR test are same as in the MK test. Also, the procedure of the SR test to determine whether there is a trend is same as that of the MK test.

3.2 Effect of Serial Correlation (Data Dependency) on Trend Tests

Data independency is a pre-condition to be able to apply trend tests. The presence of serial correlation (i.e., data dependency) may result in detection of trends with a higher significance level than the correct ones by increasing the probability of rejecting the null hypothesis (no trend). Therefore, it is necessary to remove the serial correlation effects from data before the application of MK and SR tests for detection of trends.

Von Storch (1995) proposed a method namely pre-whitening to remove the undesired influence of serial dependency on the trend tests by eliminating the effect of the lag-1 serial correlation (AR1) (Bayazit and Onoz 2007). However, Yue et al. (2002) explained that when both trend and AR1 are present in a time series, the removal of AR1 by von Storch's pre-whitening will also remove a portion of the trend. Therefore, Yue et al. (2002) modified the pre-whitening method as Trend Free Pre-Whitening (TFPW) to avoid effects of removal of the AR1 on trends. The TFPW method was adopted in several studies (e.g., Dinpashoh et al. 2011; Kumar et al. 2009; Novotny and Stefan 2007), which dealt with hydro-meteorological data. The TFPW procedure is applied in four steps:

- 1- The slope (β) of a trend in sample data is calculated using the approach proposed by

Theil (1950) and Sen (1968). The slope (β) is also called Theil–Sen's estimator (Shifteh Some'e et al. 2012). β is the magnitude of the monotonic change and calculated by:

$$\beta = \text{Median} \left(\frac{x_i - x_j}{i - j} \right) \quad \forall i < j \quad (9)$$

where x_i and x_j are data values at times i and j respectively.

- 2- Sample data were de-trended using Eq. (10) assuming that the trend is linear.

$$Y_i = X_i - (\beta \times i) \quad (10)$$

where β correspond to the Theil–Sen's estimator and X_i is the observed data series.

- 3- The lag-1 serial correlation coefficients (r_1) of the de-trended series (Y_i) were computed. If r_1 is not significantly different from zero, the sample data are considered to be serially independent and the trend tests are directly implemented on the original sample data. Otherwise, data is considered as serially dependent and pre-whitening is applied before using the trend tests. The autocorrelation test (based on r_1) as explained in Chiew and Siriwardena (2005) was used to calculate r_1 and to determine whether there is a significant serial dependence in the series of this study. Then, the pre-whitening was applied to de-trended series, and residual series (Y_i') were obtained as follows:

$$Y_i' = Y_i - r_1 \times Y_{i-1} \quad (11)$$

- 4- The identified trend ($\beta \times i$) and residuals (Y_i') were then combined and the blended series (Y_i'') were derived by:

$$Y_i'' = Y_i' + (\beta \times i) \quad (12)$$

The Y_i'' series include trend and no longer influenced by serial correlation. Then the trend tests (i.e., MK and SR tests) were applied to the blended series to assess the significance of the trend.

3.3 Spatial Variation of Trends

Spatial variability of trends were investigated through interpolation of Theil–Sen’s estimator over the study area as recommended by several studies (e.g., Shifteh Some’e et al. 2012). The Theil–Sen’s estimator is a robust estimate of the magnitude of the trend, and has been commonly used in hydrological studies (Mohsin and Gough 2009; Dinpashoh et al. 2011). The positive and negative values of Theil–Sen’s estimator indicate increasing and decreasing trends respectively. The spline technique was used for interpolation of Theil–Sen’s estimators over Victoria, as adopted for interpolation of hydro-meteorological data by several studies (e.g., Hong et al. 2005; Basistha et al. 2008). Details of the spline interpolation can be found in Hartkamp et al. (1999).

4 Results and Discussion

As explained in Section 3, the MK and SR tests were applied to all extreme rainfall (annual maximums) data sets of all storm durations (i.e., 10, 30 min, and 1, 3, 6, 12, 24, 48 h) at 23 stations in Victoria after conducting TFPW for all data sets. In this study, storm durations were classified into two groups as short (i.e., less than or equal to 3 h) and long (i.e., equal to or greater than 6 h) durations.

The MK and SR test results were summarized in Table 2. As can be seen from Table 2, mostly increasing trends in extreme rainfalls were detected for short storm durations (10 and 30 min, and 1 and 3 h), whereas in general decreasing extreme rainfall trends were found for long storm durations (6, 12, 24 and 48 h). Fig. 2 shows the percentage of the stations demonstrating decreasing or increasing extreme rainfall trends according to the MK and SR tests.

Table 2 Trend analysis results

Regions	Station Name/Storm Durations		10 minute		30 minute		1 hour		3 hour		6 hour		12 hour		24 hour		48 hour		
	Test statistics	MK	SR	Test statistics	MK	SR	Test statistics	MK	SR	Test statistics	MK	SR	Test statistics	MK	SR	Test statistics	MK	SR	
Northern Region	Mildura Airport	1.87 ^c	0.97	1.04	0.42	0.46	0.02	0.16	-0.11	-0.10	-0.15	-0.14	-0.32	-0.30	-0.61	-0.59			
	Dartmouth Reservoir	3.68 ^a	4.10 ^a	3.96 ^a	3.82 ^a	2.78 ^a	2.68 ^a	3.03 ^a	2.58 ^a	2.19 ^b	2.07 ^b	1.22	1.22	1.22	0.54	0.57			
	Corryong	1.72 ^c	1.87 ^c	1.65 ^c	1.71 ^c	1.10	1.19	0.57	0.55	-0.10	-0.26	-0.36	-0.46	-0.29	-0.32	-0.43	-0.39		
	Cobram	-0.43	-0.61	-1.03	-1.09	-0.85	-0.82	-0.71	-0.77	-0.70	-0.68	-0.27	-0.25	0.30	0.24	0.05	0.01		
	Dookie Agricultural College	2.11 ^b	1.89 ^c	0.57	0.52	0.60	0.49	1.07	0.95	0.46	0.53	-0.18	-0.24	-0.25	-0.23	-0.83	-0.86		
Western Region	Wanalta Daen Station	1.85 ^c	1.92 ^c	0.64	0.81	0.50	0.81	0.79	0.78	1.62	1.29	1.16	1.09	1.07	1.00	1.16	1.13		
	Strathbogie	0.85	1.16	0.44	0.50	-0.33	-0.18	-0.37	-0.33	0.38	0.49	2.10 ^b	2.16 ^b	0.64	0.78	0.00	0.01		
	Lima South	0.90	1.03	0.07	0.07	-0.84	-0.86	-1.19	-1.26	-1.60	-1.52	-1.60	-1.44	-1.15	-0.96	-1.37	-1.33		
	Lauriston Reservoir	-0.46	-0.55	0.48	0.34	0.68	0.54	0.83	0.85	0.30	0.25	0.24	0.12	0.72	0.85	0.68	0.80		
	Tottington	0.50	0.54	0.28	0.19	0.45	0.44	-0.22	-0.22	-1.04	-0.97	-1.53	-1.43	-1.36	-1.27	-1.07	-1.13		
Central Region	Charlton	0.47	0.59	-0.01	0.10	-0.41	-0.36	-0.55	-0.73	-0.68	-0.87	-1.21	-1.32	-0.64	-0.63	-0.89	-0.87		
	Navarre	1.08	1.00	-0.42	-0.48	-0.65	-0.71	-1.38	-1.42	-1.46	-1.61	-1.90 ^c	-1.90 ^c	-1.35	-1.41	-0.86	-1.00		
	Natte Yallock	1.88 ^c	1.91 ^c	0.74	0.66	0.84	0.81	-0.73	-0.65	-0.82	-0.99	-0.79	-0.85	0.03	-0.05	-0.09	-0.20		
	Mirrnatwa	2.08 ^b	1.94 ^c	2.34 ^b	2.18 ^b	0.93	1.01	-0.71	-0.73	-0.79	-0.86	-0.21	-0.25	-0.18	-0.14	-0.39	-0.57		
	Weeppoinah	0.84	0.90	1.22	1.22	1.21	1.28	0.51	0.52	0.51	0.54	-0.10	-0.16	-0.07	-0.16	-0.67	-0.77		
Gippsland Region	Melbourne Regional Office	2.39 ^b	2.18 ^b	2.45 ^b	2.21 ^b	1.83 ^c	1.63	0.75	0.75	-0.13	-0.01	0.01	0.10	-0.72	-0.72	-0.63	-0.65		
	Melbourne Airport	1.08	1.14	0.02	0.06	-0.15	-0.12	-0.54	-0.59	-0.33	-0.43	-1.00	-1.07	-0.99	-1.09	-0.65	-0.74		
	Narre Warren North	3.28 ^a	3.28 ^a	2.84 ^a	2.77 ^a	2.71 ^a	2.53 ^b	1.17	1.25	0.86	0.95	1.26	1.28	1.45	1.45	2.1 ^b	2.06 ^b		
Gippsland Region	Ensay	2.55 ^b	2.60 ^a	2.14 ^b	2.19 ^b	0.90	0.88	0.24	0.33	0.86	0.99	0.57	0.70	0.03	-0.01	-0.62	-0.68		
	Sarsfield East	2.05 ^b	2.12 ^b	1.54	1.55	1.07	1.14	0.43	0.44	-0.34	-0.39	-0.72	-0.84	-1.19	-1.13	-1.8 ^c	-1.76 ^c		
	Glenmaggie Weir	0	0.11	0.45	0.49	0.92	1.10	0.58	0.38	0.35	0.39	-0.11	-0.23	-0.59	-0.80	-0.62	-0.77		
East Sale Airport	5.04 ^a	4.96 ^a	4.40 ^a	4.30 ^a	3.15 ^a	3.22 ^a	1.15	1.18	0.62	0.55	0.17	0.25	-0.47	-0.51	-0.85	-0.87			

Table 2 (continued)

Regions	Station Name/Storm Durations	10 minute		30 minute		1 hour		3 hour		6 hour		12 hour		24 hour		48 hour		
		Test statistics	MK	SR	Test statistics	MK	SR	Test statistics	MK	SR	test statistics	MK	SR	Test statistics	MK	SR	Test statistics	MK
Genoa		2.41^b	1.40	1.49	1.11	1.08	0.37	0.44	0.54	0.40	0.26	0.20	-0.10	-0.07	-0.52	-0.42		

Critical values at 0.1, 0.05, and 0.01 significance levels are 1.645, 1.96, and 2.576 respectively

Significant trends at different significance levels were written with bold characters

a, b and c (superscripts) correspond to significance levels of 0.01, 0.05 and 0.1 respectively

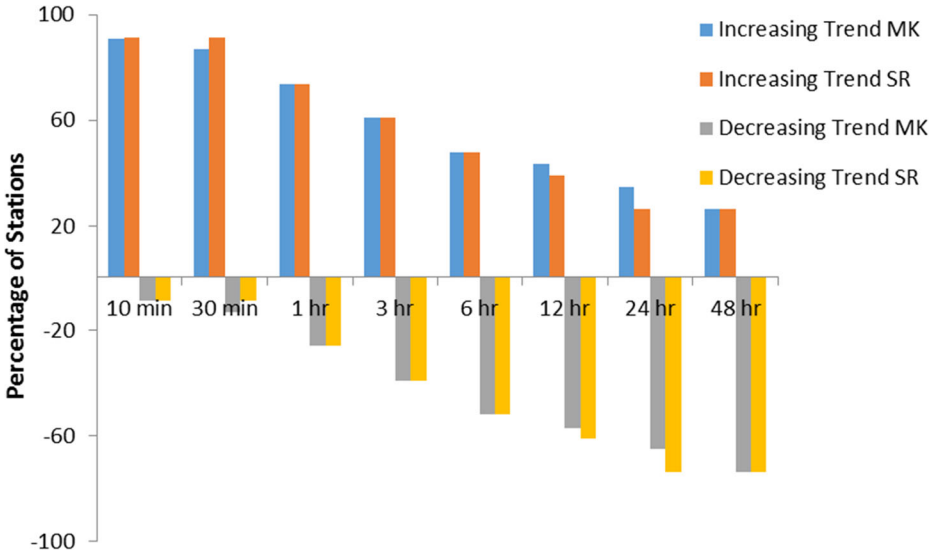


Fig. 2 Percentage of stations showing increasing or decreasing trends

In Fig. 2, percentage values include both statistically significant (at least 0.1 significance level) and statistically insignificant trends. Figure 3 illustrates the percentage of stations showing only statistically significant increasing or decreasing trends at least at the 0.1 significance level based on the MK and SR tests. Figures 2 and 3 and Table 2 showed that results from the MK and SR tests were very similar.

As can be seen from Fig. 3, the percentages of stations showing statistically significant trends were much higher for short storm durations of 10 and 30 min, and 1 h in comparison to the higher duration storms. In average, 27 and 26 % of all stations showed statistically significant increasing trends for short storm durations (i.e., 10 and 30 min, and 1 and 3 h)

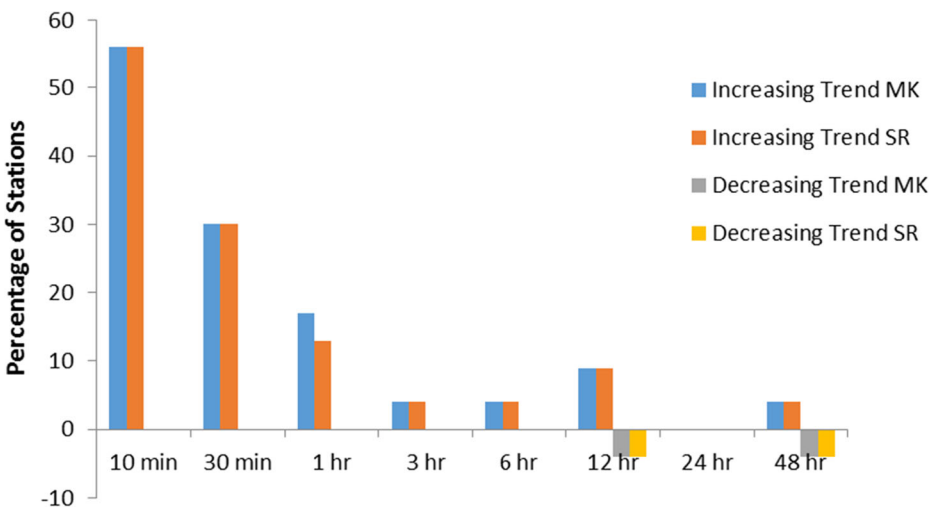


Fig. 3 Percentage of stations showing significant increasing or decreasing trends

based on the MK and SR tests respectively, whereas none of the stations in the study area showed statistically significant decreasing trends for short storm durations. On the other hand, 4 % of all stations showed statistically significant increasing trends for long storm durations (i.e., 6, 12, 24 and 48 h, while only 2 % of all stations demonstrated statistically significant decreasing trends for long storm durations.

As explained in Section 2, DEPI defined 4 regions (i.e., Western, Northern, Central and Gippsland Regions) in Victoria to develop regional water strategies. The results of the MK and SR tests were described below with respect to the four regions of DEPI. Results (percentage of the stations showing trends) of the trend tests with respect to the four regions were summarized in Table 3.

Table 3 shows that 25 % of all stations in the Northern Region demonstrated statistically significant increasing trends for short storm durations, whereas 8 % of all stations showed statistically significant increasing trend for long storm durations. None of the stations showed statistically significant decreasing trends (for both short and long storm durations) in the Northern Region. In the Central Region, statistically significant increasing trends in particular for short storm durations were more noticeable. In average, 50 and 42 % of all stations according to MK and SR tests respectively indicated statistically significant increasing trend for short storm durations in the Central Region, whereas statistically significant increasing trends were detected only for 8 % of the stations for long storm durations. None of the stations showed significant decreasing trend in the Central Region. In the Gippsland Region, significant increasing trends for short storm durations were found in average 35 % of all stations. None of the stations showed statistically significant increasing trends for long storm durations in the Gippsland Region. Also, none of the stations showed statistically significant increasing trend for long storm durations in the Gippsland Region, whereas 5 % of the stations in the Gippsland Region demonstrated statistically significant decreasing trend. In the Western Region, none of the stations showed statistically significant increasing trend (both for short and long storm durations). However, statistically significant decreasing trends were detected for 4 % of the stations only for long storm durations.

Regional analysis of extreme rainfall trends in Victoria (as explained above) showed that extreme rainfall trends showed spatial variation. As explained in Section 3, Theil–Sen’s

Table 3 Results (percentage of the stations showing trends) of the trend tests with respect to the four regions

Regions	Durations	Significant and insignificant trends (Percentage of stations)				Only significant trends (percentage of stations)			
		Increasing		Decreasing		Increasing		Decreasing	
		MK	SR	MK	SR	MK	SR	MK	SR
Northern	Short storm durations	75	75	25	25	25	25	0	0
	Long storm durations	53	53	47	47	8	8	0	0
Western	Short storm durations	63	67	37	33	0	0	0	0
	Long storm durations	8	4	92	96	0	0	4	4
Central	Short storm durations	83	83	17	17	50	42	0	0
	Long storm durations	42	42	58	58	8	8	0	0
Gippsland	Short storm durations	100	100	0	0	35	35	0	0
	Long storm durations	40	35	60	65	0	0	5	5

estimators (as an indicator of magnitude of trend) of all stations (and for all storm durations) were interpolated over Victoria to identify the spatial variability of extreme rainfall trends. Figure 4 illustrates the spatial variability of extreme rainfall trends (based on interpolated Theil–Sen’s estimators) for short storm durations.

As can be seen from Fig. 4, high Theil–Sen’s estimator values corresponding to the increasing trends were detected in east Northern Region and east Central Regions. Low values of Theil–Sen’s estimator were in the Western Region (with minor exceptions such as 30 min storm duration) and west Gippsland Region (except 3 h storm duration).

Figure 5 was generated through interpolation of Theil–Sen’s estimator values for long storm durations. Similar to Fig. 4, high values of Theil–Sen’s estimator (i.e., significant increasing trends) were found in the Northern and east Central Regions. Low Theil–Sen’s estimator values (i.e., significant decreasing trends) were detected in the Gippsland (except storm durations of 6 and 12 h) and the Western Regions.

In summary, in Victoria, trend analysis showed that significant increasing trends were detected mostly for short storm durations, whereas the analysis of long storm durations resulted in mostly decreasing trends. In general, decreasing trends were not statistically significant with minor exceptions. Storm durations less than 6 h were defined as urban flash flood producing storm durations (Hapuarachchi et al. 2011), and significant increasing trends were mostly detected for these storm durations. It is important to highlight that the highest percentage of the rainfall stations showing statistically significant increasing trends were

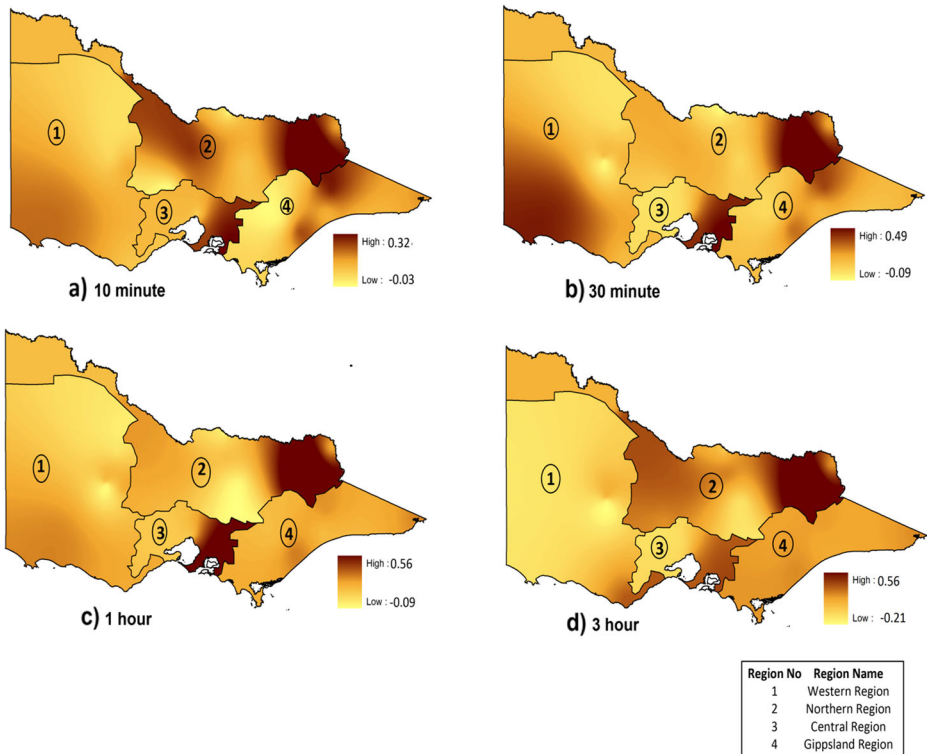


Fig. 4 Spatial variability of trends for short storm durations

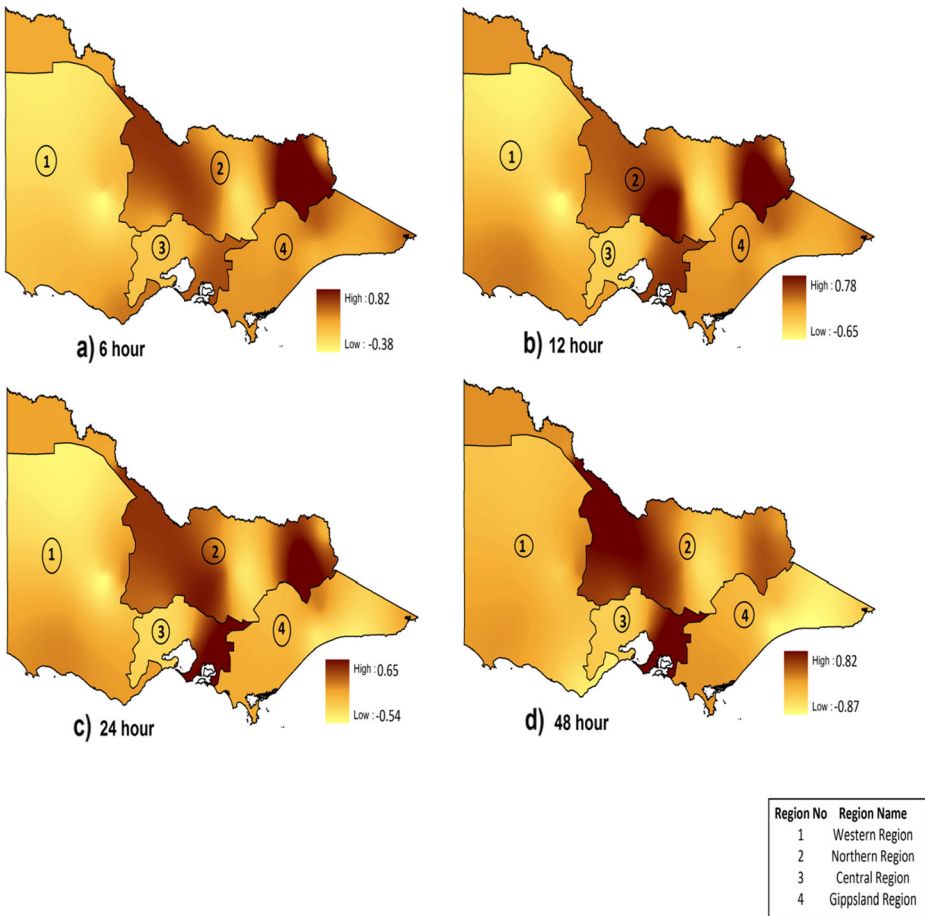


Fig. 5 Spatial variability of trends for long storm durations

detected in the Central Region (the most urbanized region in Victoria), which includes the Melbourne city with an approximate population of 4.2 million (ABS 2014). Therefore, the increasing trends in urban flash flood producing hourly storm durations can cause significant flooding problems in Melbourne.

Two main factors could contribute to extreme rainfall trends: (1) natural variability due to climate oscillations, and (2) anthropogenic climate change, as mentioned in Section 1. The ENSO with El Nino and La Nina phases (Verdon et al. 2004), the Indian Ocean Dipole (IOD) (Ashok et al. 2003), the Southern Annual Mode (SAM) (Meneghini et al. 2007), and the Interdecadal Pacific Oscillation (IPO) (Yilmaz et al. 2014) were pointed as influential climate oscillations on the precipitation variability in Victoria. In addition to climate oscillations, anthropogenic climate change has potential to cause trends in extreme rainfalls. It should be noted that anthropogenic climate change can also affect the dynamics of key climate oscillations, which can cause changes in magnitude and frequency of extreme rainfalls. A few studies (e.g., Murphy and Timbal 2008; CSIRO 2010) investigating rainfall changes in south eastern Australia (includes Victoria) stated that although there is no clear evidence to attribute rainfall

change directly to the anthropogenic climate change, it still cannot be neglected. Change in rainfall is linked at least in part to climate change in south eastern Australia including Victoria. However, it is very difficult to identify the contribution of anthropogenic climate change effects on trends due to limited historical records and the strong effects of natural climate variability. Further analysis to investigate the causes of the extreme rainfall trends is beyond the scope of this paper.

5 Summary and Conclusions

This study focused on an investigation of trends of extreme rainfalls (i.e., annual maximums) of different storm durations and their spatial variability in Victoria, Australia. Non-parametric trend tests (i.e., Mann-Kendal and Spearman's Rho) were applied to extreme rainfall data of the storm durations ranging from 10 min to 48 h at 23 stations. The results of the trend tests were analysed with respect to the 4 regions (i.e., Western, Northern, Central and Gippsland Regions) defined by The Department of Environment and Primary Industries (DEPI). Moreover, the Theil-Sen's estimator values (as an indicator of the magnitude of trends) were interpolated over Victoria for all storm durations, and spatial variability of trends was investigated. Following major conclusions were derived from the study.

- In general, increasing extreme rainfall trends were detected for short storm durations (i.e., 10 and 30 min, and 1 and 3 h), whereas decreasing trends were found for long storm durations (i.e., 6, 12, 24 and 48 h).
- Trends (increasing) of short storm durations were mostly statistically significant.
- Trends for long storm durations were not statistically significant with minor exceptions.
- In general, for both short and long storm durations, large increasing trends of extreme rainfalls were found in the Northern Region and east of the Central Region, whereas large decreasing trends of extreme rainfalls were detected in the Western and Gippsland Regions.
- Significant increasing extreme rainfall trends for short storm durations were noticeable in the Central Region, which includes the city of Melbourne. The Central Region is also the most urbanized region in Victoria, and these increasing trends in short duration storms are likely to produce urban flash floods, which will cause significant economic and social consequences.

It should be noted that the annual maximums of various storm durations were used as extreme rainfall data in investigating trends in this study. The results can be improved using peaks over threshold (POT) method to construct extreme rainfall data set (through selection of rainfall values above a certain threshold), since this method results in a larger extreme rainfall data set (than annual maximums), which is important for accuracy of trend analysis. Moreover, using POT data enables to investigate extreme rainfall trends not only in magnitude but also in frequency. However, the POT analysis is beyond the scope of this paper.

Conflict of Interest The authors declare that they have no conflict of interest.

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