Detection of changes in flood data in Victoria, Australia from 1975 to 2011

Elias Ishak and Ataur Rahman

ABSTRACT

Changes in observed streamflow records for 131 catchments from the state of Victoria in southeast Australia are investigated for the 1975–2011 study period. Seven flood indices are considered which are derived from annual maximum, peak-over-threshold (POT) and monthly maximum flood series. Trend analyses are undertaken using Mann–Kendall (MK) and seasonal MK tests along with the bootstrap resampling approach to account for serial correlation. A common trend direction in all months in streamflow data for the majority of the stations has been identified by Van Belle and Hughes' homogeneity test. Trend analyses results show the percentages of stations exhibiting significant downward trends ranges from 4 to 35% at 5% significance level, which is generally higher than the percentage of stations to occur by chance. Good agreement is found between trends in the AM and POT flood magnitude time series, and separately in the POT flood frequency time series, but not between flood magnitude and their associated frequency series. More stations with significant negative trends have transpired in the AM than in the POT flood data series. Resemblance in the results between both the MK and seasonal MK tests for most of the catchments is also noticed.

Key words | climate change, floods, Mann–Kendall test, POT, stationarity, trends

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INTRODUCTION

Trend detection in observed hydro-climatic records, particularly in river flows, remains one of the important themes in hydrological sciences especially in the light of natural climate variability and potential climate change. Global climate is unequivocally changing with warming trends detected in several regions throughout the world, evident from both observations and global climate model studies (IPCC 2007). Warming of the climate system will intensify the global hydrological cycle and alter the magnitude and frequency of hydrological and climate parameters such as precipitation and evapotranspiration in a specific region (Xu *et al.* 2006); that in turn will have an impact on the catchment's hydrology. Thus, it is necessary to examine whether streamflow records exhibit evidence of trends that may be linked to climate change (Kahya & Kalayci 2004).

Many researchers (e.g., Kundzewicz *et al.* 2005; Khaliq *et al.* 2009; Ishak *et al.* 2013) in the world have outlined their concerns on the alterations in river flow regimes and explored their relations with global climate changes and anthropogenic activities. Some of these studies show an increase in extreme flood events. For instance, in Europe, significant positive trends in flood data were detected in the north and the central part of the continent (Lindström & Bergström 2004; Birsan *et al.* 2005; Wang *et al.* 2005; Petrow & Merz 2009). An increasing trend for high discharge was also observed in the eastern part of the continental United States (Groisman *et al.* 2001). In China, after evaluating the relationship between the temperature, the precipitation and the streamflow of the Yangtze River basin, Zhang *et al.* (2005) concluded that global warming would intensify the flood hazards in the basin. At the same time, some studies (e.g., Burn & Hag Elnur 2002; Milly *et al.* 2005) have shown evidence of decreasing trends in the flood data. For instance, Burn & Hag Elnur (2002) found decreasing trends in the Canadian annual maximum (AM) flow data in the south. A decrease in streamflow

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was also noticed in sub-Saharan Africa, southern Europe, southernmost South America and western mid-latitude North America after investigating the trends of observed global streamflow (Milly *et al.* 2005). Significant decreasing trends in Turkish river flow over the Marmara, Aegean, Mediterranean and Central Anatolia region have been reported in Topaloğlu (2006). Hu *et al.* (2011) investigated trends and variability in the hydrological regimes (both mean values and extreme events) and their links with the local climate in the source region of the Yellow River over the last 50 years (1959–2008). They found strong decreasing trends in the winter (dry season) monthly flows of January to March and September as well as in annual mean flow, annual 1-, 3-, 7-, 30- and 90-day maxima and minima flows for Maqu and Tangnag catchments over the period 1959–2008. Ehsanzadeh *et al.* (2011) found that winter low flows are increasing in eastern Canada and southern British Columbia, whereas they are decreasing in western Canada; summer low flows are increasing in central Canada, southern British Columbia and Newfoundland, whereas they are decreasing in Yukon and northern British Columbia and also in eastern Ontario and Quebec. While these studies have shown evidence of non-stationarity in hydrological data, some other studies did not find significant trends in extreme flood events (e.g., Mudelsee *et al.* 2003; Small *et al.* 2006). Kundzewicz *et al.* (2005) showed that the analysis of AM flows worldwide does not support the hypothesis of ever-present growth of high flows. It is conclusive that the spatial patterns of changes in floods are complicated and vary over the world, as different conclusions have been drawn reflecting the great diversity of regional and global climates (Milly *et al.* 2005; Ehsanzadeh *et al.* 2011).

Similarly, in Australia, various studies (e.g., Franks & Kuczera 2002; Micevski *et al.* 2006; Kiem & Verdon 2009) have investigated the changes in river flow data with emphasis on the existence of inter-annual to inter-decadal climate variability and its impact on long-term flood risks at local scales. For example, in New South Wales (NSW), the post-1945 20-year flood exceeds the pre-1945 20-year flood for most of the analysed catchments (Franks & Kuczera 2002). Micevski *et al.* (2006) found that floods in NSW which occurred in the negative phase of the Interdecadal Pacific Ocean (IPO) had peak discharges 1.8 and 1.7 times greater than floods of the same frequency which occurred during the IPO positive phase, respectively. Murphy & Timbal (2008) reported that Victoria in southeast Australia has experienced extremely low streamflow since the mid-1990s. Stratification of Victoria's streamflow according to multiple large-scale climate drivers, and antecedent catchment conditions, provides significantly different streamflow distributions according to Kiem & Verdon-Kidd (2009). Limitations of the Australian studies include the restriction of their investigations to a particular region of Australia, and their unawareness of the impact of the flood data dependency on the trend outcomes. An exemption to these studies were the analyses undertaken by Ishak *et al.* (2010, 2011, 2013) that looked at trends in Australian flood data considering the serial and inter-station correlation covering the whole of Australia as one study domain. The potential impact of climate variability on the trend results was also considered in their study. The results show a significant downward trend in the Australian flood data in the southeast and southwest regions, while an upward trend was more visible in the northwest region of Australia.

Ishak *et al.* (2010, 2011, 2013) investigated trends in AM flood data at 491 catchments across Australia, using the most extensive and comprehensive AM flood database that is now available for the first time in Australia. Using a subset of 131 catchments from the 491, mainly located in Victoria in southeast Australia, this paper extends the investigations of Ishak *et al.* (2010, 2011, 2013) in exploring whether the outcomes are comparable when using peak-over-threshold (POT) methods as opposed to using AM floods. Trends in both POT magnitude and in number of POTs per year are estimated. This paper also investigates the resemblance between the trends in seasonal flood data and the identified trends in the AM floods.

STUDY AREA AND DATABASE

The subject catchments of this paper are located in the state of Victoria, in southeast Australia. Victoria differs from other mainland Australian states in that it lies further south and has its major mountain ranges running east-west rather than north-south. Despite its small size, Victoria contains many different topographically, geographically and climatically diverse areas, ranging from the semi-arid temperate with hot summers in the west and northwest to wet in the southeast and to temperate and cool along the coast. The catchment physiography ranges from lowlands in the western part up to higher catchment in the eastern parts of the state.

Catchment selection

The selected catchments in this investigation are a subset from the main catchment population used in Ishak *et al.*'s (2013) study, with the exception that the record length of the current data set has been updated to capture the latest recorded data up to 2011. The data have been subject to quality control and check. Stations with a record length of at least 37 years with continuous records extending from at least late 1975 only were selected. Priority was given to smaller catchments with an upper limit area of 1,000 km^2. Catchments with minimal disturbance from human activities (such as deforestation, urbanization, regulations and river engineering) only were considered in this investigation. For the comprehensive details about the catchment selection criteria readers are referred to Haddad *et al.* (2010) and Ishak *et al.* (2013). The finally selected data set consists of 131 catchments with streamflow record length ranging from 35 to 85 years (median 46 years and mean 48 years). Some 63 catchments (48% overall) have record lengths in the range of 35 to 45 years, 45 (34% overall) in the range of 46 to 55 years and 23 (18% overall) in the range of 55 years and greater. The catchment areas ranges from 15 to 997 km^2 (median 289 km^2 and mean 324 km^2).

Elevation of the selected catchments ranges from 1.11 m Australian Height Datum (AHD) to 705 m AHD (average 200 m AHD; 11 catchments are over 400 m AHD and 40 catchments are below 100 m AHD). The mean annual rainfall ranges from 520 mm in the northwest to 1,769 mm in the Otway Ranges and Eastern Highlands (median 900 mm), while the mean annual evaporation ranges from 925 to 1,155 mm (median 1,030 mm). The selected catchments are mainly unregulated, have not been affected by major landuse changes over the study period and have good data quality. The geographical distribution of the selected catchments is mapped in Figure 1. As the emphasis of this study is on identifying trends in streamflow data, a longer record length is necessary to ensure any conclusions regarding identified trend are robust and meaningful. Hence, a cut off record length needs to be selected based on the total number of stations available and their record length. A cut off record length of 37 years of continuous streamflow data covering the study period from 1975 to 2011 was arbitrarily selected for this study.

Streamflow data

Seven streamflow indices were used to describe the characteristics of the high flow regime, that is, the floods. The first of these is the AM flow data series, which were used by Ishak *et al.* (2013), for the analysis of trends in floods at 491 stations in Australia. In flood-rich years, the AM flood data series only includes one of the largest flows, while in flood-poor years, a small river flow is picked up that may not necessarily be considered as flood at all. Madsen *et al.* (1997) recommended using the POT approach as an alternative way to represent the high river flows in a record regardless of when they occur. The POT series in this study consists of a series of monthly maximum flows that are made of independent daily maximum flow series and exceed a certain threshold. The POTs are selected to be proper peaks by ensuring the river flow both before and after the peak is lower than at the peak itself. Three POT indices describing flood magnitude were used: the POT1 magnitude (*POT1 mag.*), the POT2 magnitude (*POT2 mag.*) and the POT3 magnitude (*POT3 mag.*) series. The magnitude of the threshold was arbitrarily set so that on *average* 1, 2 and 3 POTs, respectively, were selected per year. The monthly maximum (*Monthly max.*) streamflow data series are also selected as an additional flood magnitude index.

In addition, the number of POTs in each year has been counted to describe the frequency (annual counts) of flood events. In doing so, three flood frequency indices have been created: the POT1 frequency (*POT1 freq.*), the POT2 frequency (*POT2 freq.*) and the POT3 frequency (*POT3 freq.*). These annual frequency series were derived from the consequent POT magnitude series. The two POT1 time series describe the magnitude and frequency of the most extreme floods (e.g., rare floods), while the four POT2 and POT3 time series characterize the behaviour of the more moderately sized floods (e.g., more frequent floods).

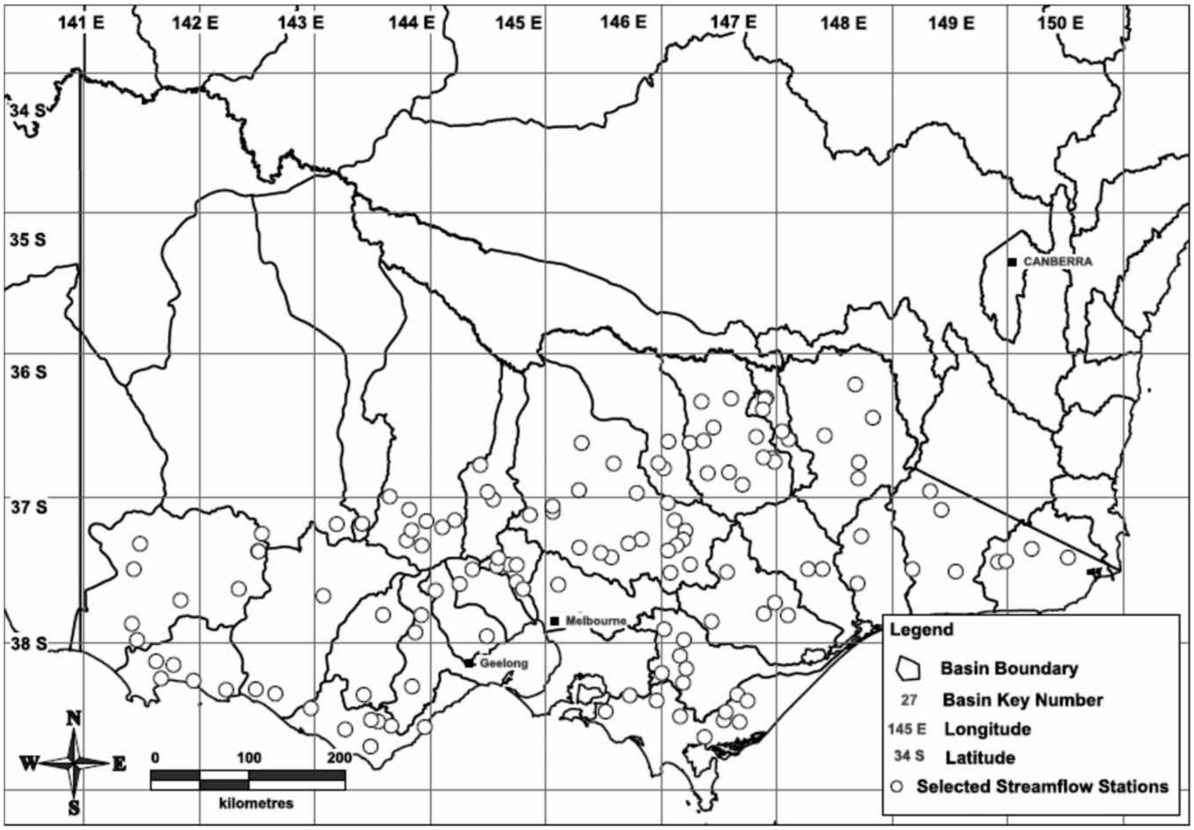

Figure 1 | Geographical distribution of the selected 131 study catchments in Victoria, Australia.

METHODOLOGY

Three different methods were used to estimate whether there is a significant positive or negative trend in the streamflow indices over Victoria in southeast Australia. The preference was given to the non-parametric methods as these are robust with respect to non-normality, nonlinearity, missing values, serial dependency, censored data and outliers (extremes) (Yue *et al.* 2002). Among the various widely used techniques, the selected non-parametric tests include the Mann–Kendall (MK), seasonal MK and Van Belle and Hughes' homogeneity of trend test. First, the homogeneity of trend in monthly maximum streamflow data is assessed before applying the seasonal MK test. Second, the MK test is applied to detect trends in AM and POT flood indices. A brief description of these tests is presented below, but readers are referred to Khaliq *et al.* (2009) and to Van Belle & Hughes (1984) for comprehensive details.

MK test

This test is the most frequently used one for identifying monotonic trends in hydrological data. The null hypothesis is that the river flow data ($X_1, X_2, \ldots, X_n$) are a sample of n independent and identically distributed random variables. The alternative hypothesis for a two-sided test is that the distribution of X_k and X_j are not identical for all $k, j \le n$ with $k \ne j$. The test statistic S is estimated using Equations (1) and (2) and has a zero mean and variance of S computed by Equation (3)

$$S = \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} \operatorname{sign}(X_k - X_j) \tag{1}$$

$$\operatorname{sign}(X_k - X_j) = \begin{cases} +1 & (X_k - X_j) > 0 \\ 0 \quad \text{if} & (X_k - X_j) = 0 \\ -1 & (X_k - X_j) < 0 \end{cases} \tag{2}$$

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{L} t_l(l)(l-1)(2i+5)}{18} \tag{3}$$

where t_l indicates the number of ties of extent l, and L is the number of tied groups. For the cases where n is larger than 10, the standardized test statistic (Z), defined in Equation (4), is approximately normally distributed

$$Z_S = \begin{cases} \dfrac{S-1}{\sigma} & \text{for} \quad S > 0 \\ \dfrac{S+1}{\sigma} & \text{for} \quad S < 0 \\ 0 & \text{for} \quad S = 0 \end{cases} \tag{4}$$

Consequently, for the two-sided test for trend the null hypothesis should be accepted if $|Z_s| \leq Z_{\text{crit}}$, at the α level of significance, where Z_{crit} is the value of the standard normal distribution with an exceedance probability of $\alpha/2$. A positive value of S indicates an upward trend and a negative value indicates a downward trend.

Seasonal MK test

This test can be used for time series with seasonal (monthly) variation and does not require normality assumption of the time series (Hirsch *et al.* 1982). This test is intended to assess the randomness of a data set X ($X_1, X_2, \ldots, X_{12}$) and X_i ($x_{i1}, \ldots, x_{in}$), where X is a matrix of the entire monthly data over n years at a station. The test statistic is a sum of the MK statistic (S similar to that in Equation (1)) computed for each month. The interpretation of the rest of the test is similar to that of the MK test.

Van Belle and Hughes' homogeneity of trend test

This test aims to investigate the homogeneity of trend direction in different months at a given station using the procedure developed by Van Belle & Hughes (1984). The test is essential, since if the trend is upward in one month and downward in another, the seasonal MK test and slope estimator will be misleading. As a result, an overall trend test at a station will lead to an ambiguous conclusion when the trend, in fact, is heterogeneous between months. For homogeneity in monthly trends at a station, the following statistic is calculated:

$$\chi^2_{\text{homogeneous}} = \chi^2_{\text{total}} - \chi^2_{\text{trend}} = \sum_{i=1}^{m} (Z_i)^2 - m(\bar{Z})^2 \tag{5}$$

and the values of (Z_i) and ($\bar{Z}$) are computed by

$$Z_i = \frac{S_i}{\sqrt{\mathrm{var}(S_i)}} \quad \text{and} \quad \bar{Z} = \frac{1}{m}\sum_{i=1}^{m} Z_i$$
$$(m = 12 \quad \text{for the monthly data}) \tag{6}$$

where S_i is the MK statistic for month i, and the $\chi^2_{\text{homogeneous}}$ has a chi-square distribution with $m-1$ degrees of freedom (*df*). To test for trend homogeneity between seasons (months) the $\chi^2_{\text{homogeneous}}$ is compared with the α level ($\alpha = 0.05$) critical value for the chi-square (χ^2_α) distribution with $m-1$ *df*. If $\chi^2_{\text{homogeneous}}$ is not significant, then a valid test for common trend is possible by referring the χ^2_{trend} to the α level ($\alpha = 0.05$) critical value for the chi-square (χ^2_α) distribution with 1 *df*. If $\chi^2_{\text{homogeneous}}$ is significant the null hypothesis of homogeneous seasonal trends over time must be rejected. However, trend tests for each season may still be obtained from the individual Z_i if desired. It is important to note that the homogeneity of the monthly trends is investigated first by this method before the above non-parametric tests are undertaken.

Handling serial-correlation impact

The MK test needs the time series data to be serially independent. If the data are positively correlated, the MK test tends to enhance the significance of trend (von Storch 1995). Thus, in the present study, the block bootstrap (BBS) resampling approach recommended by Kundzewicz & Robson (2000) is used to incorporate the effect of the serial correlation. The process involves resampling of the original data in predetermined blocks for a large number of times to estimate the significance of the MK test statistic. The autocorrelation coefficients of the time series are examined and tested against the critical value corresponding to the 95% significance level as proposed by Salas *et al.* (1980), and based on the number of adjacent significant serial-correlation coefficients the block size is determined.

After several primary tests, it was appropriately considered to make 1,000 resamples per station and index to obtain a practical consistency in the significance level estimates. The 1,000 trend estimates of the resamples were subsequently ranked in the ascending order. If the trend of the original data series was outside the 2.5 and 97.5% points of the ranked trends of the resamples (i.e., the 25th and 975th ranked values), the trend of the original data series was considered to be significant at the 5% significance level. The benefits of using the BBS resampling approach are the preservation of the original data and the incorporation of the effects of serial correlation higher than the first one. Comprehensive details including the steps involving the BBS resampling approach can be found in Khaliq *et al.* (2009).

Trend index (TI)

To make possible a correlation analysis of trends among the tested flood indices, a TI is developed for presentation purposes. The TI, ranges from −100 to +100, with negative values indicating a negative trend while positive values represent a positive trend. Hence, the higher the absolute value of the *TI*, the higher the significance of the trend. The *TI* is represented as a percentage and relates to the significance level α (also in %), of the two-sided test as

$$TI = \begin{cases} 100 - \alpha & \text{for positive trends} \\ -(100 - \alpha) & \text{for negative trends} \end{cases} \tag{7}$$

Thus, for example, a positive trend significant at the 5% level will have $TI = 95\%$.

RESULTS

The results are presented in three sub-sections: first, the homogeneity assumption of monthly trend is examined; second, all the significance levels of the trends for the different flood indices are assessed; and third, the resemblance between the trend results and their spatial distribution is discussed.

Homogeneity of trend

The homogeneity of trend directions in months at the multiple streamflow stations was assessed using the Van Belle & Hughes (1984) method, particularly before the seasonal MK non-parametric test which implicitly assumes homogeneous monthly trends in the time series under investigation. The procedures documented in Van Belle and Hughes' homogeneity of trend test was applied to the monthly maximum flood data series and the outcomes of the stations exhibiting significant trends are summarized in Table 1. Table A1 in Appendix A (available online at http://www.iwaponline.com/nh/046/064.pdf) presents the homogeneity of trend results for the full data set. As an example, the computed $\chi^2_{\text{homogeneous}}$ value for streamflow station 405238 (Mollison Creek at Pyalong) is found to be less than the critical value of the chi-square distribution that is equal to 19.68 with degree of freedom of 11, at the significance level of 5% (refer to Table 1). As the calculated $\chi^2_{\text{homogeneous}}$ value is not significant at this station, the χ^2_{trend}value is compared with the critical value of the chi-square distribution with $df = 1$ at the same significance level. As station 405238 has an χ^2_{trend} value greater than the χ^2_{critical} (equal to 3.84), its monthly streamflow trends are considered to be homogeneous, which means trends in all months have the same direction (negative trends).

As mentioned in the 'Methodology' section, if the computed $\chi^2_{\text{homogeneous}}$ is found to surpass the χ^2_{critical} (with $df = 11$), the null hypothesis of homogeneous monthly trends over time is rejected, and the applicability of the seasonal MK test becomes questionable. However, the trend analysis still can be undertaken by applying the MK test for each individual month and in accounting for the serial correlation. Only 8% of the stations out of the stations exhibiting significant trend in the study area result in heterogeneity in monthly trends (e.g., monthly trends have different directions) for stations 227210, 230206, 233211 and 233223. Trend testing at these stations was undertaken for each individual month, but results are not presented in this paper. Also, in Table 1, for the stations where the value of $\chi^2_{\text{homogeneous}}$ is less than the χ^2_{critical} (with $df = 11$) value, the χ^2_{trend} is compared with the table of chi-square distribution (with $df = 1$) to find out the possibility of an appropriate test for a common trend (for all months) at a

Table 1 | Results of homogeneity of trends between months based on Van Belle and Hughes' homogeneity of trend test

Station No.	$\chi^2_{\text{homogeneous}}$	χ^2_{trend}	Station No.	$\chi^2_{\text{homogeneous}}$	χ^2_{trend}
221209	9.74	55.49[a]	238208	8.80	47.44[a]
221210	8.12	43.95[a]	238223	5.21	54.80[a]
223204	13.95	25.32[a]	238229	9.01	48.28[a]
226204	11.11	34.65[a]	238230	4.64	51.44[a]
227200	13.40	36.54[a]	238235	7.66	60.73[a]
227210	21.80[b]		402213	5.21	21.94[a]
227213	15.62	20.39[a]	404207	2.61	22.80[a]
227225	14.30	19.86[a]	404208	18.17	36.98[a]
227231	7.21	19.73[a]	405226	6.76	34.19[a]
229216	13.33	2.60	405228	6.27	25.34[a]
230202	19.83[b]		405238	6.67	36.21[a]
230204	8.844	51.63[a]	405240	9.38	35.38[a]
230205	13.91	46.07[a]	405251	6.82	18.46[a]
230206	20.18[b]		406213	8.27	55.73[a]
230211	7.34	67.27[a]	406214	7.61	57.73[a]
231213	10.02	38.11[a]	406215	6.64	55.78[a]
231225	16.20	15.59	407213	6.01	118.36[a]
232200	14.80	31.79[a]	407214	11.34	49.85[a]
232210	13.70	67.86[a]	407217	5.18	38.36[a]
233211	21.33[b]		407220	10.84	71.93[a]
233215	12.00	6.46	407221	12.53	22.19[a]
233223	20.78[b]		407222	7.79	62.20[a]
234200	13.47	46.50[a]	407227	7.81	57.08[a]
236204	8.66	70.60[a]	407230	8.88	57.79[a]
236205	3.09	52.34[a]	408202	16.22	73.85[a]
237200	3.95	31.14[a]	415207	9.73	43.98[a]
237205	6.58	78.80[a]			
238204	6.50	67.95[a]			

[a] Trends in months having same direction.

[b] Trends in months having different direction.

The critical values of $\chi^2_{\text{homogeneous}}$ and χ^2_{trend} at $\alpha = 0.05$ significant level equal to 19.68 and 3.84, respectively.

station. The results of this option are demonstrated in the third column of Table 1, which are completely consistent with the finding of the second column. Therefore, it is concluded that a common trend is present in all months in streamflow data, having a significant trend at the significance level of 5%. Figure 2 shows the outcomes of testing the homogeneity of monthly trends in graphical form.

Autocorrelation in annual flood series

The outcomes of the serial-correlation analysis of the annual flood series recommended that for the majority of the selected stations a block size of one should be sufficient to account for the serial dependency in the time series. This was therefore used in the BBS approach when estimating the significance levels of trends. An example of the calculated autocorrelation coefficients at different lag time for the AM flood data series is presented in Figure 3. In addition, the significance of the lag-1 serial correlation for the chosen catchments was tested at the significance level of 5%. The results show that 11 and 18% of the AM flood and *POT3 mag.* data series exhibit significant lag-1 serial correlation, respectively, while 7% of each of the *POT1 mag.* and *POT2 mag.* time series show significant lag-1 serial correlation. For the stations where the serial correlation was found significant for more than a one-year lag, the significance levels for the trend analysis were estimated using the longer blocks. These stations are marked and footnoted in Table B1 in Appendix B (available online at http://www.iwaponline.com/nh/046/064.pdf). It is also noted that when a longer block size was needed for the AM flood data series, the same block size was used to determine the significance levels of trends for the POT magnitude series.

Trends in flood index series

For each of the 131 selected stations, the significance of the trends, in terms of TI, in the seven flood flow index series estimated using the MK test associated with the bootstrap resampling approach is presented in Table B1, Appendix B. As described before, when the trend is negative the significance level (*TI*) is shown in negative and in italic bold. Also, absolute values of significance levels exceeding 95% are shown in bold font in Table B1. These values relate to trends significant at the 5% level. The resemblance between the columns in Table B1 can be evaluated using correlation analysis. This shows that there is generally reasonable agreement between the outcomes from the different flood indices. Apart from the significance level, the results display more stations with negative trends compared with stations with positive trends for the tested flood indices and over the selected study period. The percentage of stations with

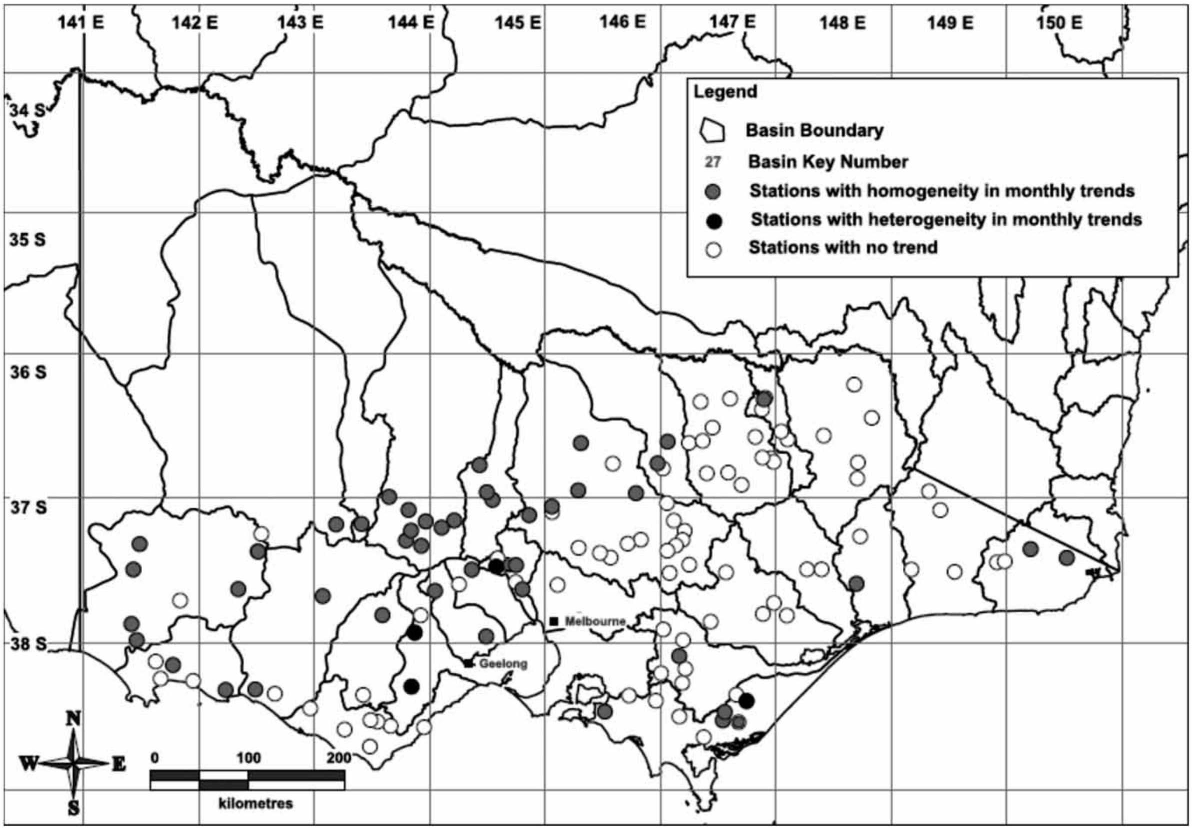

Figure 2 | Homogeneity of monthly trends based on Van Belle and Hughes' homogeneity of trend test. Stations in grey circles have homogeneous monthly trends opposite to the stations in black circles. Stations in white circles indicate no trend.

positive trends varies from 8 to 53%, while the percentage of stations with negative trends varies from 47% to 92% over the study period. Overall, these results show that the selected Victoria catchments are mainly dominated by negative trends in the flood data series with at least 47% (*POT1 mag.*) and at most 92% (AM) of stations showing negative trends. This conclusion tallies with the finding documented in Ishak *et al.* (2013).

Table B1 shows very good agreement between the first two columns of the flood magnitude indices (i.e., AM and monthly maximum) and generally between the different flood indices. The *TI* results show that 42% of the stations with significant trend are common between the first two columns of Table B1 (MK and seasonal MK tests). Similar results are also found between the three POT flood frequency indices, and between the AM, monthly maximum and *POT3 mag.* flood magnitude indices. However, the columns showing the POT flood frequency indices are not significantly correlated with their related POT flood magnitude indices. This contradiction in the outcomes can be explained by the fact that a decrease (increase) in the magnitude of floods is not necessarily related to a decrease (increase) in the frequency of floods with which they occur. A comparable conclusion has also been reported in Svensson *et al.* (2005).

The trend analysis results show that for both the flood magnitude and frequency index series, there are generally slightly more stations exhibiting significant negative trends than significant positive trends. The percentage of stations with significant negative trends ranges from 4 to 35%, while the percentage of stations with significant positive trends varies from 1 to 5%. It is noticeable from Table B1 that more significant negative trends may transpire in the AM flood data series than in the POT flood magnitude series, particularly when a sequence of low flood peaks appear at the end of a time series with trend. These flood peaks may be too low to be chosen for the POT analysis,

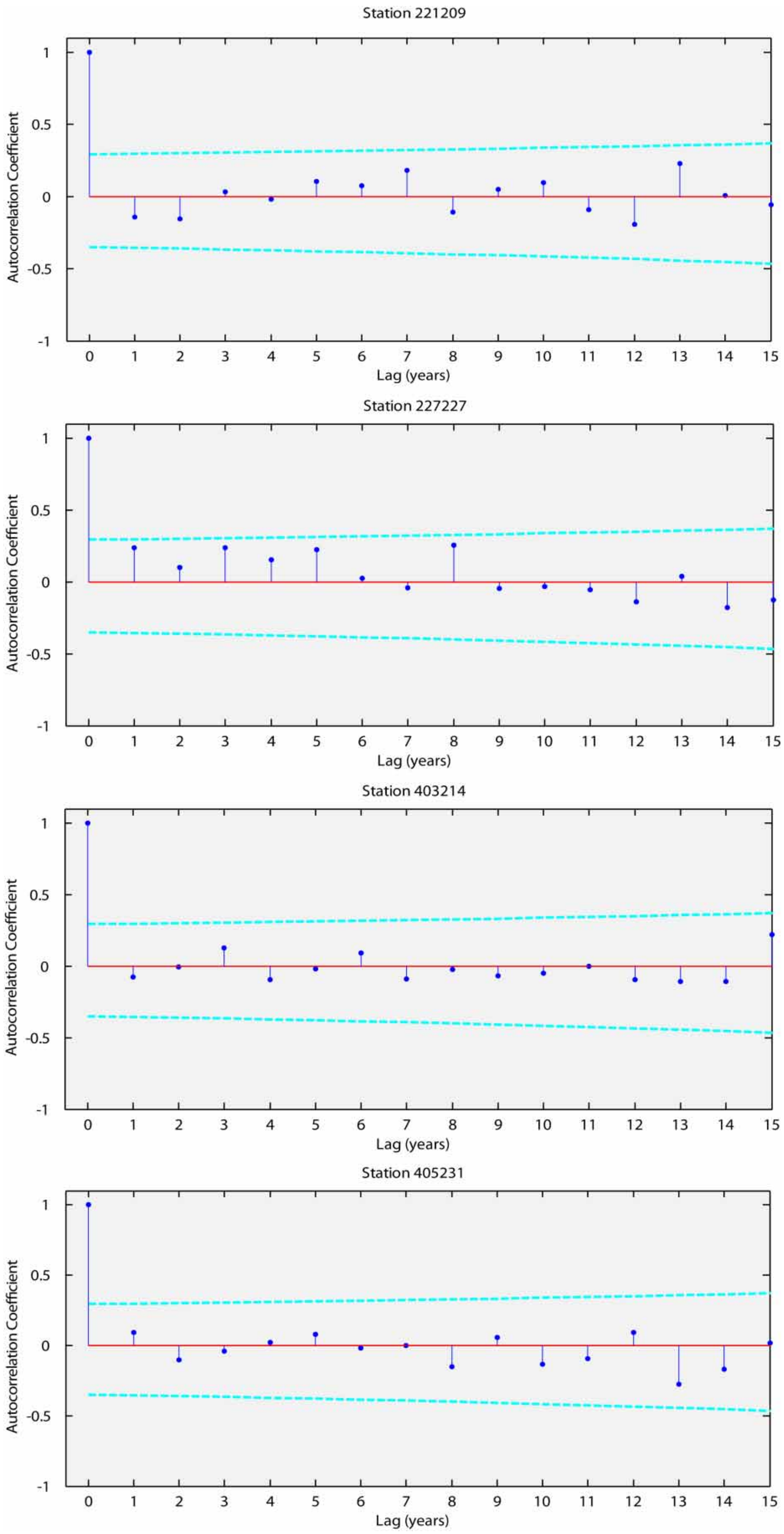

Figure 3 | Sample of autocorrelation of (AM) flood data series for four different stations.

whereas one event per year is included in the AM flood data series, which occasionally result in steeper slope and longer time series. A comparison of the AM flood and *POT1 mag.* time series plots for stations 236204 and 405238 is presented in Figure 4 for illustration purpose. Due to this difference in significant trends between the POT and AM flood series, it possibly would be more useful to include a larger amount of data into the trend analysis in some other way than through the simple POT approach used in this paper.

Moreover, the numbers of stations exhibiting significant negative trends for the AM, monthly maximum and *POT3 mag.* flood magnitude series, which are 18%, 35% and 8%, respectively, are higher than the number expected to have occurred by chance at the significance level of 5%. For instance, for the *POT3 mag.* flood data series, ten stations out of 131 (8%) show a significant downward trend. This is greater than the around six stations which would be expected to exhibit a trend by chance at the significance level of 5%. Similarly, the numbers of stations exhibiting significant negative trends for POT flood frequency indices are also judged to be statistically significant at the same significance level. In contrast, the trends in the *POT1 mag.* and *POT2 mag.* indices (4% for each) are judged to be statistically insignificant at the significance level of 5%. Also, the

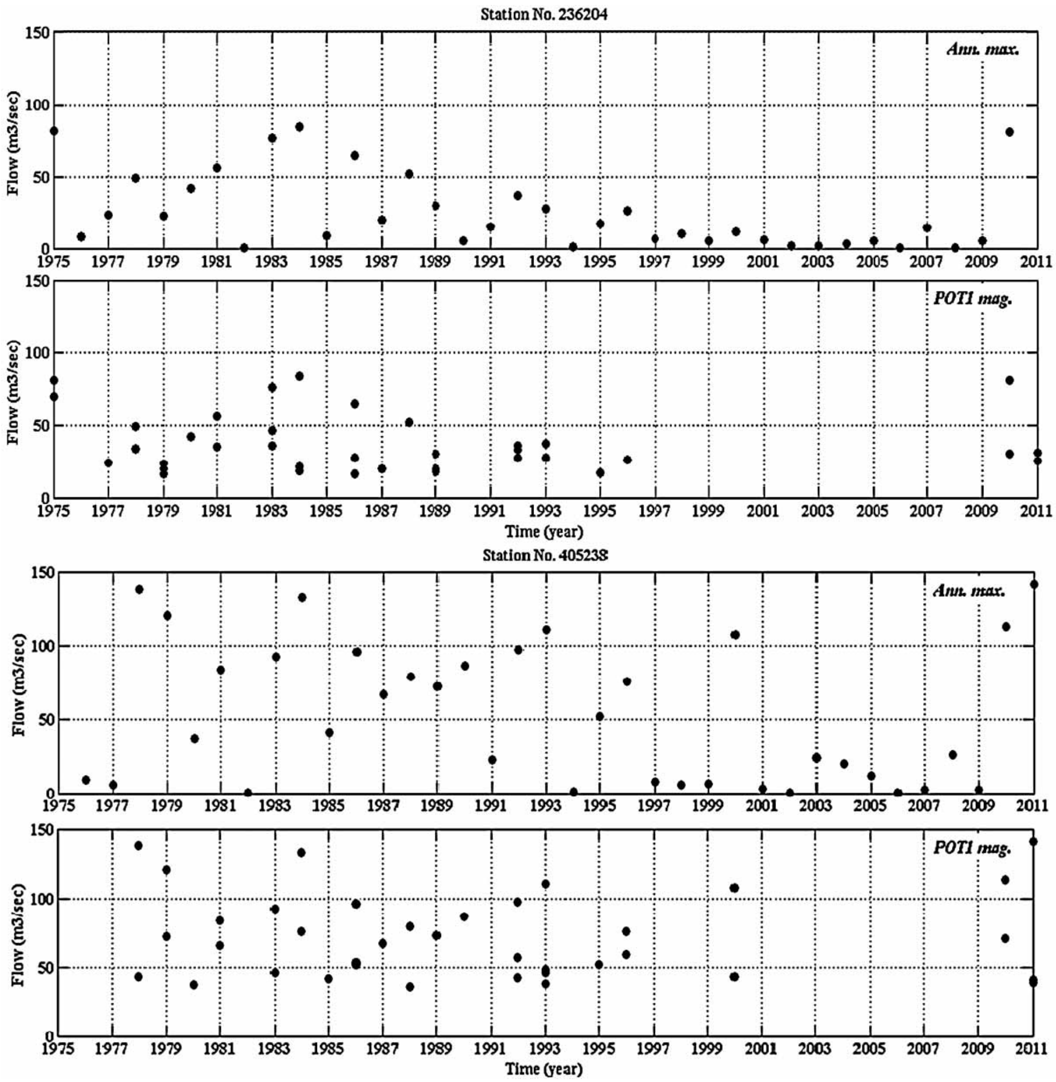

Figure 4 | Comparison of AM (*Ann. max.*) and POT1 magnitude (*POT1 mag.*) flow time series for stations 236204 and 405238.

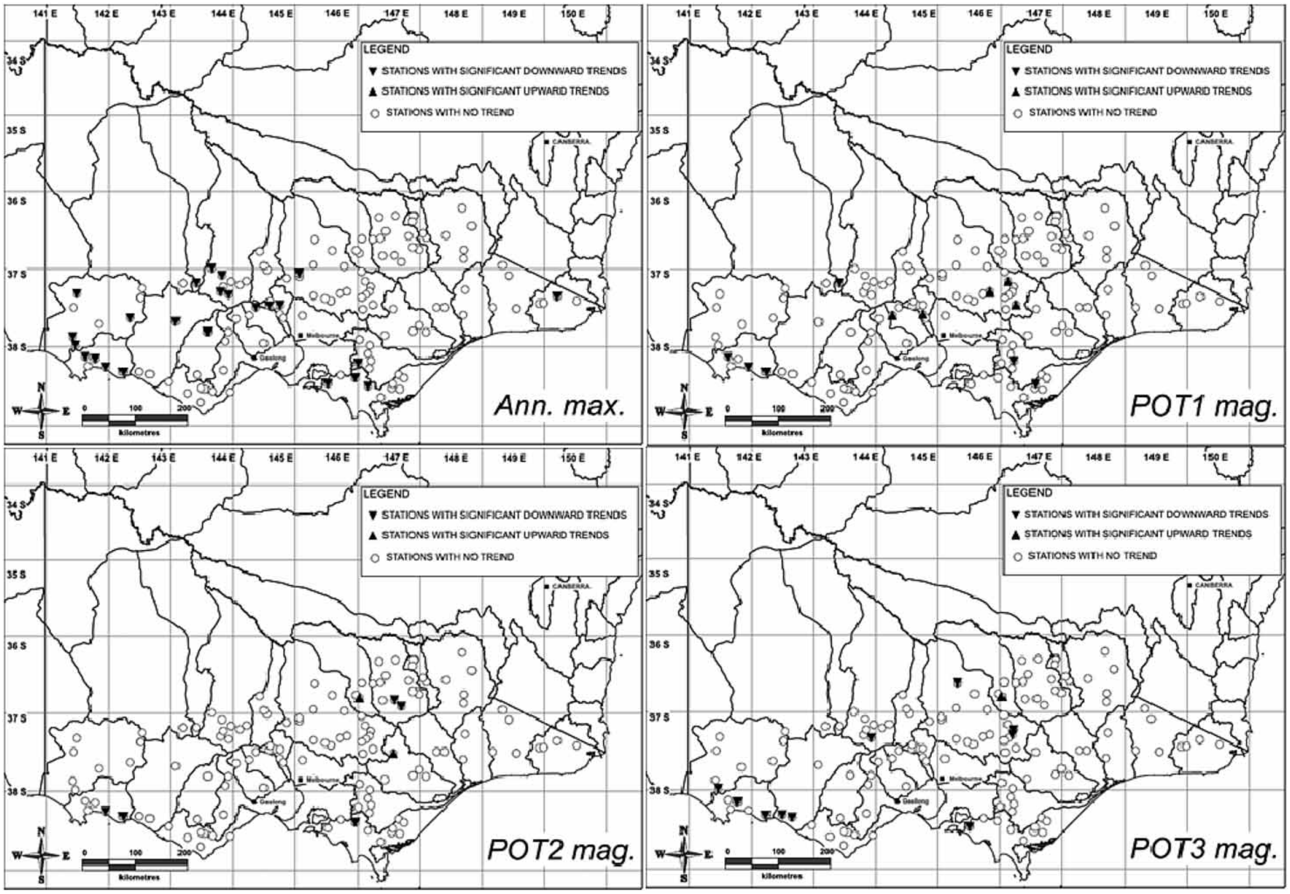

Figure 5 | Spatial distribution of the stations exhibiting significant trends for the four flood magnitude indices using MK test and BBS. Negative trends are shown in flipped black triangles, positive trends in black triangles and no trends in white circles.

percentages of stations with significant positive trends are judged to be statistically insignificant at the significance level of 5% for the different flood indices.

The spatial distribution of stations showing significant trends for the different flood magnitude indices over the study period are shown in Figure 5, whereas Figure 6 presents the graphical distribution of the significant trends in monthly maximum streamflow data series. When inspecting the results given in the second column of Table 1, the reliability of the trend indications in Figure 6 is shown by another approach since seasonal trends in most stations turn out to be homogeneous. Out of 131 catchments, 15 stations exhibiting significant negative trends have been detected by both MK and seasonal MK tests. The resemblance between Figures 6 and 3 suggests that the results obtained in this section for the monthly maximum flood data series and for the POT indices (as they are based on the monthly maximum series) do not need to be revised. This assessment is predictable, because of the strong similarity in the results between both the MK and seasonal MK tests for most of the catchments.

CONCLUSION

This study examines trends in the flood data at 131 catchments, mainly located in Victoria in southeast Australia. This considers the monthly maximum, POT and AM flood data. The trends in monthly maximum flood data have been found to have the same direction (in all months) for the majority of the tested catchments, based on Van Belle and Hughes' approach, and hence the monthly streamflow

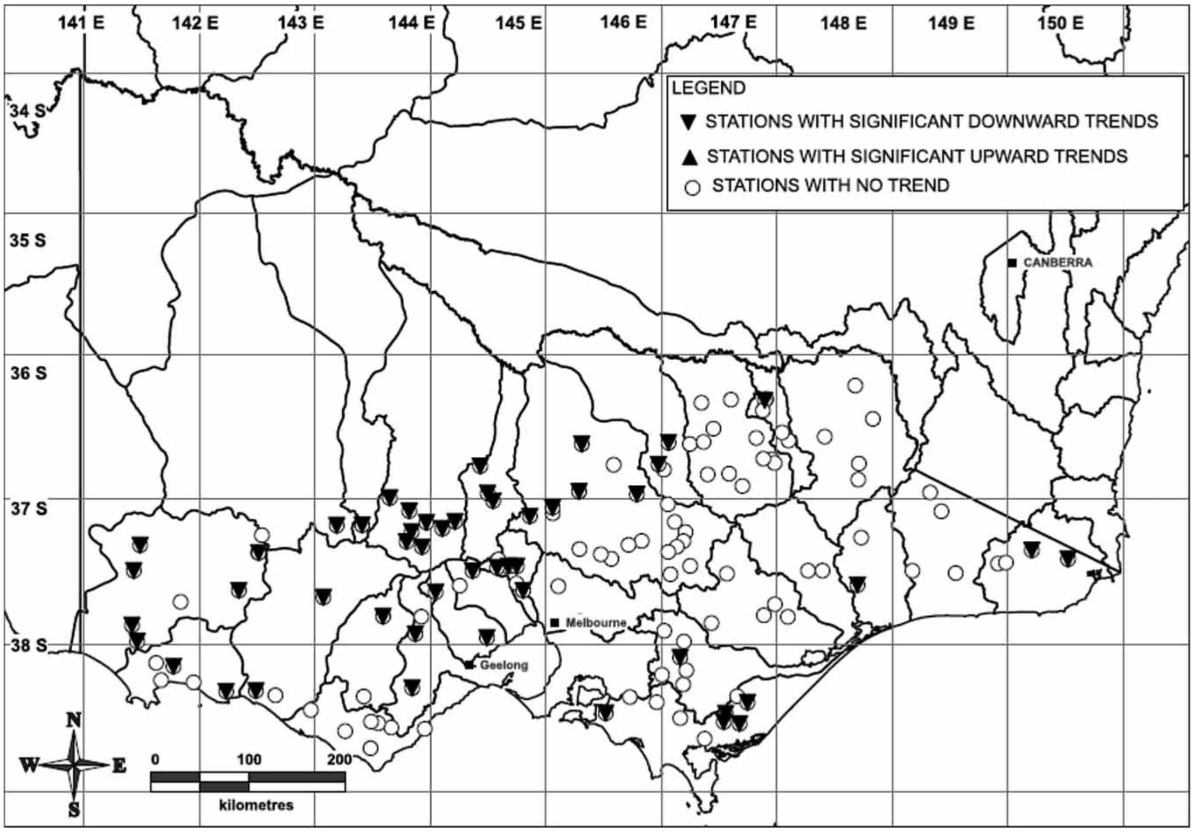

Figure 6 | Seasonal MK trend test results for monthly maximum flood data series; stations exhibiting significant trend are represented by flipped black triangles.

trends are considered homogeneous for the monthly maximum streamflow time series. It has been found that the selected Victoria catchments are mainly dominated by negative trends in the flood data series with at least 47% (POT data series) and at most 92% (AM data series) of stations showing negative trends.

The trend analysis results reveal that the numbers of stations exhibiting significant negative trends for the AM, monthly maximum and *POT3 mag.* flood magnitude series are higher than the number expected to have occurred by chance at the significance level of 5%. Similarly, the numbers of stations exhibiting significant negative trends for POT flood frequency indices are also judged to be statistically significant at the same significance level. Conversely, the trends in the *POT1 mag.* and *POT2 mag.* indices are considered to be statistically insignificant at the significance level of 5%. Positive trends have not been noted to be detected at the significance level of 5% for the different flood indices.

The trends analyses in this paper provide evidence of existing downward trends in the floods for the state of Victoria over the 1975–2011 study period. The presence of trends in streamflow patterns over the state of Victoria may be attributed to the observed decreases in rainfall (Alexander *et al.* 2007) and, to some extent, to increases in temperature (Alexander & Arblaster 2009), or due to climate change anthropogenic activities (Milly *et al.* 2005). Therefore, it is plausible to investigate the interconnection between the trends in rainfall, temperature and streamflow variables in considering Australia as one study domain, prior to assessing the potential impact of climate change on these observed trends in floods.

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REFERENCES

Alexander, L. V. & Arblaster, J. M. 2009 Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. *Int. J. Climatol.* **29**, 417–435.

Alexander, L. V., Hope, P., Collins, D., Trewin, B., Lynch, A. & Nicholls, N. 2007 Trends in Australia's climate means and extremes: a global context. *Aust. Meteorol. Mag.* **56**, 1–18.

Birsan, M. V., Molnar, P., Burlando, P. & Pfaundler, M. 2005 Streamflow trends in Switzerland. *J. Hydrol.* **314**, 312–329.

Burn, D. H. & Hag Elnur, M. A. 2002 Detection of hydrologic trends and variability. *J. Hydrol.* **255**, 107–122.

Ehsanzadeh, E., Ouarda, T. B. M. J. & Saley, H. M. 2011 A simultaneous analysis of gradual and abrupt changes in Canadian low streamflow. *Hydrol. Process.* **25**, 727–739.

Franks, S. W. & Kuczera, G. 2002 Flood frequency analysis: evidence and implications of secular climate variability, New South Wales. *Water Resour. Res.* **38** (5), 1062.

Groisman, P. Y., Knight, R. W. & Karl, T. R. 2001 Heavy precipitation and high streamflow in the contiguous United States: trends in the twentieth century. *Bull. Am. Meteor. Soc.* **82**, 219–246.

Haddad, K., Rahman, A., Weinmann, P. E., Kuczera, G. & Ball, J. E. 2010 Streamflow data preparation for regional flood frequency analysis: lessons from south-east Australia. *Aust. J. Water Resour.* **14** (1), 17–32.

Hirsch, R. M., Slack, J. R. & Smith, R. A. 1982 Techniques of trend analysis for monthly water quality data. *Water Resour. Res.* **18**, 107–121.

Hu, Y., Maskey, S., Uhlenbrook, S. & Zhao, H. 2011 Streamflow trends and climate linkages in the source region of the Yellow River, China. *Hydrol. Process.* **25**, 3399–3411.

Intergovernmental Panel on Climate Change (IPCC) 2007 Climate Change 2007: Mitigation of Climate Change. In: *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (B. Metz, O. Davidson, P. Bosch, R. Dave & L. Meyer, eds). Cambridge University Press, New York, USA.

Ishak, E., Rahman, A., Westra, S., Sharma, A. & Kuczera, G. 2010 Preliminary analysis of trends in Australian flood data. In: *World Environmental and Water Resources Congress 2010, May 16–20*, Providence, RI, USA, pp. 115–124.

Ishak, E. H., Rahman, A., Westra, S., Sharma, A. & Kuczera, G. 2013 Evaluating non-stationarity of Australian annual maximum flood. *J. Hydrol.* **494**, 134–145.

Ishak, I., Rahman, A., Westra, S., Sharma, A. & Kuczera, G. 2011 Trends in peak streamflow data in Australia: impacts of serial and cross-correlation. In: *34th IAHR World Congress, 26 June–1 July 2011*, Brisbane, Australia, pp. 766–773.

Kahya, E. & Kalayci, S. 2004 Trends analysis of streamflow in Turkey. *J. Hydrol.* **289**, 128–144.

Khaliq, M. N., Ouarda, T. B. M. J., Gachon, P., Sushama, L. & St-Hilaire, A. 2009 Identification of hydrological trends in the presence of serial and cross correlations: a review of selected methods and their application to annual flow regimes of Canadian rivers. *J. Hydrol.* **368**, 117–130.

Kiem, A. S. & Verdon-Kidd, D. C. 2009 Climatic drivers of Victorian streamflow: is ENSO the dominant influence? *Aust. J. Water Resour.* **13**, 17–30.

Kundzewicz, Z. W. & Robson, A. J. 2000 *Detecting Trend and Other Changes in Hydrological Data. Word Climate Program-Data and Monitoring*. World Meteorological Organization, Geneva, Switzerland (WMO/TD-No. 1013).

Kundzewicz, Z. W., Graczyk, D., Maurer, T., Pińskwar, I., Radziejewski, M., Svensson, C. & Szwed, M. 2005 Trend detection in river flow series: 1. Annual maximum flow. *Hydrol. Sci. J.* **50**, 797–810.

Lindström, G. & Bergström, S. 2004 Runoff trends in Sweden 1807–2002. *Hydrol. Sci. J.* **49**, 69–83.

Madsen, H., Pearson, C. P. & Rosbjerg, D. 1997 Comparison of annual maximum series and partial duration series methods for modeling extreme hydrologic events: 2. Regional modeling. *Water Resour. Res.* **33**, 759–769.

Micevski, T., Franks, S. W. & Kuczera, G. 2006 Multidecadal variability in coastal eastern Australian flood data. *J. Hydrol.* **327**, 219–225.

Milly, P. C. D., Dunne, K. A. & Vecchia, A. V. 2005 Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **438**, 347–350.

Mudelsee, M., Borngen, M., Tetzlaff, G. & Grunewald, U. 2003 No upward trends in the occurrence of extreme floods in central Europe. *Nature* **425**, 166–169.

Murphy, B. F. & Timbal, B. 2008 A review of recent climate variability and climate change in south-eastern Australia. *Int. J. Climatol.* **28**, 859–879.

Petrow, T. & Merz, B. 2009 Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002. *J. Hydrol.* **371**, 129–141.

Salas, J. D., Delleur, J. W., Yevjevich, V. & Lane, W. L. 1980 *Applied Modeling of Hydrologic Time Series*. Water Resources Publications, Littleton, CO, USA.

Small, D., Islam, S. & Vogel, R. M. 2006 Trends in precipitation and streamflow in the eastern U.S.: paradox or perception? *Geophys. Res. Lett.* **33**, L03403.

Svensson, C., Kundzewicz, Z. W. & Maurer, T. 2005 Trend detection in river flow series: 2. Flood and low-flow index series. *Hydrol. Sci. J.* **50** (5), 811–824.

Topaloğlu, F. 2006 Regional trend detection of Turkish river flows. *Nord. Hydrol.* **37**, 165–182.

Van Belle, V. G. & Hughes, J. P. 1984 Nonparametric tests for trends in water quality. *Water Resour. Res.* **20** (1), 127–136.

von Storch, H. 1995 Misuses of statistical analysis in climate research. In: *Analysis of Climate Variability: Applications of Statistical Techniques* (H. von Storch & A. Navarra, eds). Springer-Verlag, Berlin, Germany, pp. 11–26.

Wang, W., Van Gelder, P. H. A. J. M. & Vrijling, J. K. 2005 Detection of changes in streamflow series in western Europe over 1901–2000. *Water Supply* **5** (6), 289–299.

Xu, C. Y., Gong, L. B., Jiang, T., Chen, D. L. & Singh, V. P. 2006 Analysis of spatial distribution and temporal trend of reference evapotranspiration in Changjiang (Yangtze River) catchment. *J. Hydrol.* **327**, 81–93.

Yue, S., Pilon, P. J., Phinney, B. & Cavadias, G. 2002 The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrol. Process.* **16**, 1807–1829.

Zhang, Q., Jiang, T., Germmer, M. & Becker, S. 2005 Precipitation, temperature and discharge analysis from 1951 to 2002 in the Yangtze River basin, China. *Hydrol. Sci. J.* **50** (1), 65–80.

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