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Preliminary Analysis of Trends in Australian Flood Data

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ABSTRACT
In recent years, the potential impacts of climate variability and change on the hydrologic regime have received a great deal of attention from researchers. Review of hydrological data recorded in different parts of the world has provided evidence of regime-like or quasi-periodic climate behaviour and of systematic trends in key climate variables due to climate change and/or climate variability. It has been established that a changing climate will have notable impacts on the rainfall runoff process, and thus hydrologic time series (e.g., flood data) can no longer be assumed to be stationary. A failure to take such change/variability into account can lead to underestimation/overestimation of the design flood estimate, which in turn will have important implications on the design and operation of water infrastructures.

This paper presents preliminary results from a study aimed to identify the nature of time trends in flood data in the Australian continent with the final objective of assessing the impacts of climatic change on regional floods in Australia. This research is being carried out as a part of the on-going revision of Australian Rainfall and Runoff – the national guide of design flood estimation in Australia. For this study, 491 suitable stations with flood data in the range of 30 to 97 years have been selected across the Australian continent. Two trend tests are applied: Mann-Kendall test and Spearman's Rho test to the data set. Preliminary trend analysis results show that about 30% of the selected stations show trends in annual maxima flood series data, with downward trends in the southern part of Australia and upward trends in the northern part. Further investigation is needed before any firm conclusion can be made about the trends in Australian flood data. Future work aims to address the influence of spatial correlation and autocorrelation on the ability to detect trend in annual maximum flood series data in Australia and assess the relationship between the observed trends in annual maximum flood data and other meteorological variables.

1. INTRODUCTION

In recent years, the potential impacts of climate change/climate variability on the hydrological cycle and river flow regimes have received a great deal of attention from researchers, particularly on the nature of the climate change/variability, and on the factors that contribute to it. Climate change in the context of hydrology can be defined as any change in the hydrologic cycle which is attributable to human activities, most notably those associated with increasing greenhouse gas concentrations in the atmosphere and the corresponding increases in global mean temperature. The effects of anthropogenic emission of aerosols also fall within this category, although their effects on climate are likely to be more regional and shorter-lived. Climate variability, on the other hand, is generally viewed as resulting from 'natural' sources, and may be due to internal dynamics of the climate system (e.g. ENSO/IPO) or external forcing (e.g. periodic fluctuations in solar radiation, and 'spikes' due to volcanic eruptions).

Review of hydrological records collected in different parts of the world has provided evidence of regime-like or quasi-periodic climate behaviour and of systematic trends in key climate variables due to climate change and/or climate variability (Gallant *et al.,* 2007; Fu *et al.,* 2008; Ma *et al.,* 2008; Zhang and Lu, 2009, Chowdhury and Beecham, 2009; Villarini *et al.,* 2009). As evidence, Australian average surface temperature has increased over the past 98 years, where the last two decades have been particularly warm, with the warmest year on record occurring during 2005 as shown in **Figure 1**. According to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), the climate is expected to continue to warm up over the 21st century affecting all aspects of the hydrological cycle (IPCC, 2007). The implications for flood hydrology are expected to be significant, with projections of changing mean temperature and rainfall intensities leading to a change in the flood frequency regime.

It has been established that changing climate will have notable impacts on the rainfall runoff process and thus hydrologic time series (e.g., flood data) can no longer be assumed to be stationary. A failure to take such change/variability into account can undermine the usefulness of the concept of return period, and can lead to underestimation/overestimation of design flood estimates (Khaliq *et al.,* 2006), which in turn will have important implications on the design and operation of water infrastructure. Recent research carried out in some regions of the world has questioned the validity of the traditional flood risk assumptions of stationarity and homogeneity (Power *et al.*,, 1999; Douglas *et al.*, 2000; Strupczewski *et al.*, 2001a; Franks and Kuczera, 2002; Cunderlik and Burn, 2003; Prudhomme *et al.*, 2003; Micevski *et al.*, 2006; Leclerc and Ouarda, 2007, among many others) especially with the recognition that climate naturally varies at all scales. Consequently, in the presence of trends in hydrological variables, flood estimation processes have to accommodate the changing flood regimes, e.g. by assuming time-varying parameters of the flood frequency distribution (e.g., Strupczewski *et al.*, 2001a, b).

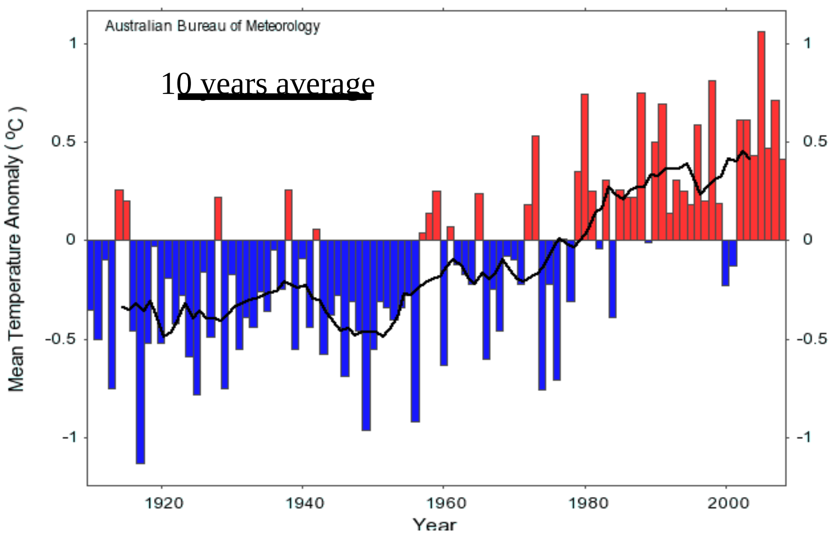

Figure 1 Annual Mean Temperature Anomalies for Australia based on 1961-2008. Source: Bureau of Meteorology Issued: 05/01/2009

Numerous studies have been undertaken in different regions of the world to investigate if abnormalities in the form of trends exist in time series of hydrological variables. Examples of such studies are: Olsen *et al. (*1999) who analysed North American flood data and reported positive trends for flood risk over time for gauged sites within the Mississippi, Missouri, and Illinois River basins. Lins and Slack (1999) studied trends in streamflows in the United States using the non-parametric Mann-Kendall (MK) test. Trends were calculated for selected quantiles of discharge to evaluate the flow regimes during the twentieth century. The outcomes indicated that the United States is getting wetter, but extreme events (e.g. flows) are not increasing in magnitude. Douglas *et al. (*2000) studied the trends in floods and low flows in the United States using a regional average Kendall's *S* trend test at two spatial scales and over two time frames. They found no evidence of trends in flood flows but they did find evidence of upward trends in low flows at larger scale in the Midwest and at a smaller scale in the Ohio, the north central and the upper Midwest regions. Results of the study carried out by McCabe and Wolock (2002) on the daily streamflow in the United States indicated a noticeable increase in annual minimum and median daily streamflow around 1970, and a less significant mixed pattern of increase and decreases in annual maximum daily streamflow. They found that the maximum number of sites with significant decrease and increase in annual maximum streamflow are 13% and 15% respectively, comparing to 51% and 55% of sites with significant increase in annual minimum streamflow and annual median streamflow. They noticed that the streamflow increase appeared as a step change rather than as a gradual trend and coincided with an increase in precipitation. Negative trends in total streamflow were most common for the analysed Pennsylvanian streamflow time series from 1971 to 2001 due to climate variability (Zhu and Day, 2005). Juckem *et al. (*2008) found a decrease in annual flood peaks for stream gauging stations in the Driftless Area of Wisconsin (southwestern part of the state).

Zhang *et al. (*2001) have investigated trends in Canadian streamflow for the past 30 to 50 years; they found that overall Canadian streamflows experienced negative trends. Burn and Elnur (2002) identified similarities in trends and patterns in the hydrological and meteorological variables at chosen locations in Canada, implying a relationship between the two groups of variables. Furthermore, trend analysis of the monthly Turkish streamflow by Kahya and Kalayci (2004) had revealed that the watersheds located in western Turkey exhibit downward trend; whereas basins located in eastern Turkey show no trend. The authors found a consistency in the conclusion drawn about trend existence among the tests used in the study. Similarly, Yenigün *et al. (*2008) detected a significant decreasing trend in the minimum streamflow in the Euphrates basin in Turkey. Birsan *et al. (*2005) have studied the trends in the Switzerland streamflows using the Mann–Kendall nonparametric test in three study periods. The main acknowledged trends from their analysis were an increase in annual runoff due to increase in the winter, spring and autumn runoff, an increase in winter maximum streamflow and an increase in spring and autumn moderate and low flows. However, they found that the behaviour in the summer period was different, with both upward and downward trends present in moderate and low flow quantiles. Furthermore, the study revealed that a strong relationship exists between streamflow trends and mean basin elevation, glacier and rock coverage (positive), and basin mean soil depth (negative).

Zhang *et al. (*2007) have reported that the eastern part of Yangtze River basin in China is dominated by decreasing extreme precipitation trends, and the western part at the upper Yangtze River basin, and middle and lower Yangtze River basin are dominated by an increasing extreme precipitation trend. Additionally, the Shiyang river basin in the arid region of northwest China was analysed by Ma *et al. (*2008) to investigate changes in annual streamflow over the past 50 years, using the Kendall and the Pettitt tests. It was found that 5 out of the 8 catchments investigated had significant downward trends, and change points were identified in 4 catchments that occurred in the year around 1961. Furthermore, it was estimated that the climate variability accounted for over 64% of the reduction in mean annual streamflow mainly due to decreased precipitation. Moreover, significant upward trends were observed in several gauge records by Jeong *et al. (*2008) after they have investigated trends in the peak flood data for the major Korean river basins. Petrow and Merz (2009) analysed the trends in the flood data in Germany using MK test. The analysis detected significant flood upward trends for a considerable fraction of basins. Also they found that most changes were detected for sites in the west, south and centre of Germany. Petrow and Merz (2009) concluded that the missing relation between significant changes and basin area suggested that the observed changes in flood behavior are climate-driven.

In Australia, Chiew & McMahon (1993) examined trends in annual streamflow of 30 unregulated Australian rivers to identify changes in streamflow related to changes in climate. The authors did not find evidence of changes in streamflow resulting from climate change. They also indicated that the detection of statistically significant trends in streamflow is largely affected by interannual variability in streamflow and to a lesser degree to the length of streamflow record. Hennessy *et al. (*1999), Plummer *et al. (*1999) and Collins *et al. (*2000) reported that Australia's continental average rainfall and temperature have an increasing trend since the beginning of the 20th century, hile Smith (2004) and Alexander *et al. (*2007) reported some decreases in the rainfall in the southeast and along the east coast of the country after 1950. Similarly, Murphy and Timbal (2008) found that the South-eastern Australia region has been experiencing an annual rainfall downward trend at the rate of 20.6 mm per decade since 1950. Taschetto and England (2008) investigated the post 1970 Australian rainfall trends, and they found an increasing trend to the west (except coastlines) and a decreasing trend on the northeast coast. This is consistent with the trend in annual total rainfall maps issued by the Australian Bureau of Meteorology and shown in **Figure 2**. In general, the spatial pattern of the trends in annual precipitation can be separated into two main regions: to the west where the rain is increasing, and the east where precipitation has been decreasing, especially during the last 30 years. Chowdhury and Beecham (2009) investigated the monthly rainfall trends and their relation to the southern oscillation index (SOI) at ten rainfall stations across Australia covering all state capital cities. The outcomes of their assessment revealed decreasing trends of rainfall depth at two stations (Perth airport and Sydney Observatory Hill), no significant trends were found in the Melbourne, Alice Springs and Townsville rainfall data, where the remaining five stations showed increasing trends of monthly rainfall depth. Furthermore, they found that SOI account for the increasing trends for the Adelaide and Cairns rainfall data and the decreasing trends for Sydney rainfall. On a short time scale, Haddad *et al. (*2008) have also reported a decreasing trend in many Victorian stations of annual maximum floods particularly after 1990.

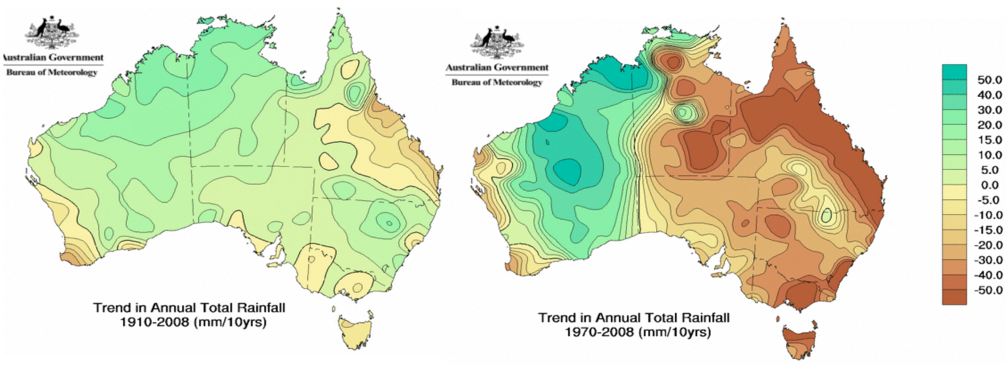

Figure 2 Rainfall trends in Australia for (a) 1910 to 2008 and (b) 1970-2008. Trends are shown in mm per decade. Source: Australian Bureau of Meteorology Issued: 05/01/2009

With respect to the Australian continent, many of the above investigations were focused on the evaluation of the trends in the Australian rainfall time series, with limited research on the impact of climate changes on flood risk assessment. This paper presents an initial assessment to identify the potential impacts of climate change on regional floods in Australia. This research is being carried out as a part of the on-going revision of Australian Rainfall and Runoff – the national guide of design flood estimation in Australia. The emphasis in the research reported herein is on the assessment of trends in the annual maximum flood time series for Australian continent. The spatial distribution of catchments exhibiting trends and not exhibiting trends is also investigated. Future work will investigate the relationship between trends in annual maximum floods and trends in meteorological parameters, and thus to attempt to establish a linkage between climate change and regional floods. This paper is organised as follow. A brief description of the statistical tests used for identifying hydrological trends at local scales is given in Section 2. This is followed by a presentation of the trend detection techniques used in this study. The methodology outlined is then applied to the annual maximum floods series in Australia. The paper ends with a summary of the results and conclusions.

2. DIFFERENT METHODS FOR TREND DETECTION

Trend analysis of observed hydro-meteorological variables such as precipitation, temperature and streamflow has been of particular interest to hydrologists and researchers for several decades. Trend analysis seeks to determine whether the probability distribution of a series of observations has changed over time (Hirsch *et al.,* 1991). Correct trend estimation is important in water resources management, as well as in the research of climate change (IPCC, 2007) especially with the recognition that observed hydro-meteorological variables can display time-dependent properties and can be affected by climate change and anthropogenic activities. A comprehensive review of statistical approaches used for trend analysis of water resources time series is provided by Helsel and Hirsch (2002). Based on the types of assumptions made during the trend investigation, trend detection analyses can be categorised into three families: design-based analyses, parametric analyses, and non-parametric analyses (McDonald *et al.,* 2003).

The design-based analyses estimate a parameter at every time period, and summarize changes in those estimates through time, with minor assumptions about the form of the trend and used properties of the sampling design (i.e., randomization) to make inferences about trend in the population. Parametric analyses (i.e., linear regression, student's *t*, cumulative deviation) assume that the time series data are independent and normally distributed. According to Khaliq *et al. (*2009) parametric tests that involve non-stationarity frequency analysis of hydrological variables are generally more powerful in modelling and investigating the trends in observations over the non-parametric tests. However, the trend analysis based on parametric process involves many assumptions about the trend behaviour - see Khaliq *et al. (*2006) for details about the parametric approaches. On the other hand, non-parametric methods (i.e., MK, Spearman's Rho) are more robust with respect to non-normality, nonlinearity, missing values, serial dependence, sensitivity to outliers (extremes), and seasonality (Yue *et al.,* 2002).

The review of literature on the identification of hydrological trends reveals that the non-parametric tests have been favoured for identifying temporal changes in observational records. Non-parametric trend tests typically have higher power than the parametric ones particularly when the probability distribution is skewed (Önöz and Bayazit, 2003; Yenigün, *et al.,* 2008)

3. STUDY AREA, DATABASE DESCRIPTION AND METHODS

The Australian annual maximum streamflow data used in this investigation have been prepared as a part of the current revision of the regional flood estimation methods in ARR. A comprehensive discussion about the data preparation technique can be found in Rahman *et al. (*2009). Streamflow variables are advocated herein as they tend to reflect climate change and can assist in comprehending the relationships between hydrology and climate. All stations have at least 30 years of streamflow record length with minor anthropogenic influences and high quality measurements, while the average record length is 38 years with the longest is 97 years. Basins sizes for the network of the 491 streamflow stations range from 1.3 km^2 to 4,360 km^2, with a median basin size is about 280 km^2. About 3% of the basins are greater than 1,000 km^2 in size; about 22% are less than 100 km^2. The geographical distribution of the selected stations is presented in **Figure 3** which reveals that most of the selected watersheds were spatially located at the coastal line, this is mainly due to the selection criteria adopted that filtered most of the inland basins from this analysis due to shorter streamflow record length.

Two rank-based non-parametric tests, MK and Spearman's Rho (SR), were selected to assess the significance of linear trend in the annual maximum streamflow (AMS) time series over Australia. Brief descriptions of the procedures are presented here; readers are referred to Helsel and Hirsch (2002) and Yue *et al. (*2002) for the details. The MK test checks whether a random response monotonically increases or decreases. SR examines whether the correlation between time steps and streamflow observations is significant. It is known that the presence of serial and spatial correlation in the data sets reduce the number of independent sites and thus affect the ability of a statistical test to assess the significance of trend (Douglas *et al.*, 2000; Burn & Elnur, 2002). As mentioned earlier, the analyses in this study are preliminary, and for simplicity AMFS data are assumed to be independent with no adjustments in the tested data to account for the serial correlation. The impact of the autocorrelations on trend analysis is left for future investigation. The outcomes of the trend analysis can be used to establish whether the observed AM time series from the study sites exhibit trends that is greater than the number that is expected to occur by chance. All the trend results in this research have been appraised using the two-tailed test at 10% level of significance that assess against the value of the standard normal distribution, to ensure an effective exploration of the trend characteristics in the study area.

4. RESULTS

The trend analysis outcomes, derived from MK and SR tests, of statistically significant trends observed at the 90% confidence level are summarised in **Table 1**. Presented is the percentage of stations with significant trend for the AM flood series; results are shown separately for positive and negative trends. Among the 491 stations, the total number of stations comprising upward and downward trend, anchored in MK and SR tests, is 156 and 172 stations respectively. Prominently, the number of trends for the AM flood variable far exceeds the critical level for establishing on site significance. Hence, the introductory conclusion is that the Australian AM flood series are exhibited substantially more trends

(32% and 35% from MK and SR correspondingly) than would be expected to occur by chance (10%). Further, **Table 1** display that the direction of the trends is, in general, downward, as established by the two tests. This result might have been affected by the shortness in record length for the majority of the tested stations (average record length of 38 years), especially by the dry period that the continent experienced in the last decade in the south-eastern and south-western parts.

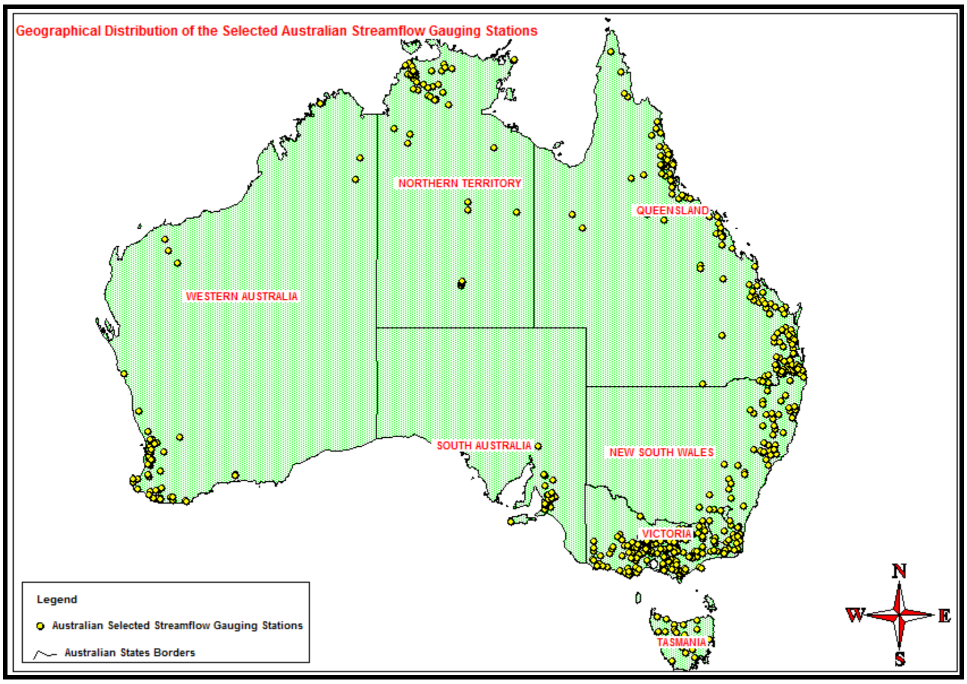

Figure 3 Geographical Distribution of the Selected Catchments

Table 1: Trend analysis results and percentage of stations with a significant trend

Trend Tests	**Number of Stations**	**Number of Decreasing Trends**	**Number of Increasing Trends**	**Percent Significant Trends (%)**
Mann-Kendall	491	127	29	32
Spearman's Rho		140	32	35

The spatial distribution of the trend results is visually scrutinized by displaying the outcomes of the AMS trends, from MK and SR tests for Australia region, in **Figures 4** and **5** respectively. Interestingly, basins located in the South-Eastern Australia display negative trends only, suggesting a decrease in the AM flood series. Similar findings appear in the south-west of Western Australia region. However, increasing trends are noted in the north-western part of the continent, suggesting increase in the AM flood series. While, combined decreasing and increasing trends pattern were detected in the north-western region mostly in Queensland. **Figures 4** and **5** substantiate that the identified AMS trend are spatially consistent with previous regional rainfall trend investigation (Murphy and Timbal, 2008; Taschetto and England, 2008) that have identified an increasing trend of rainfall in the western region (except near the coastline) and a decreasing trend along the eastern coastlines. This similarity in trends and patterns in the flow and rainfall variables for the study area implies that the trends in streamflow might be related to trends in rainfall.

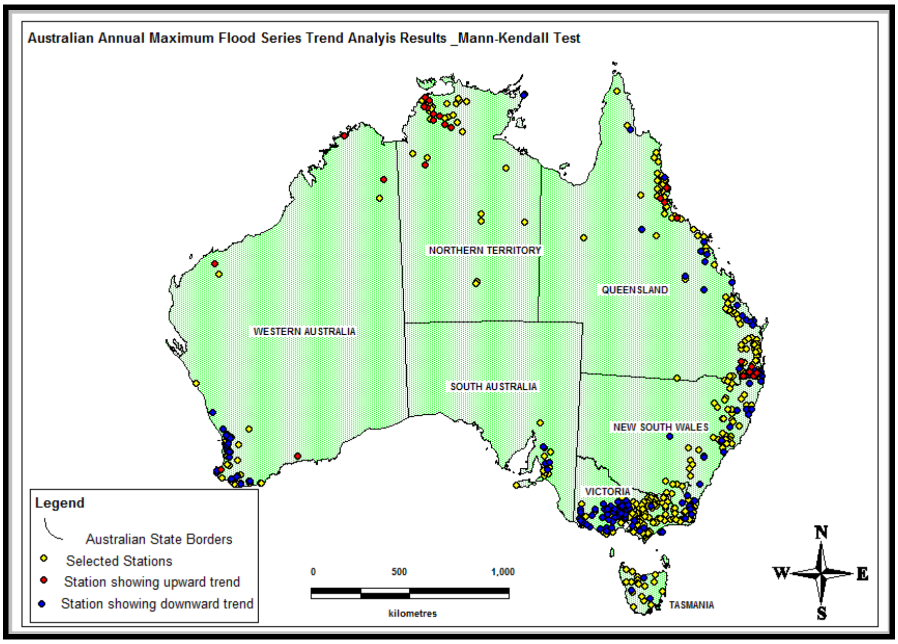

Figure 4 Results of trend analysis based on Mann-Kendall. Red and blue circles represent positiveand negative and trends, respectively

Consequently, the findings presented so far are quite convincing on the existence of linear trend in the annual maximum streamflow data over Australia tested at 10% significant level. The trend analyses and the trends spatial distribution based on the MK and SR tests display consistencies in the tests outcomes.

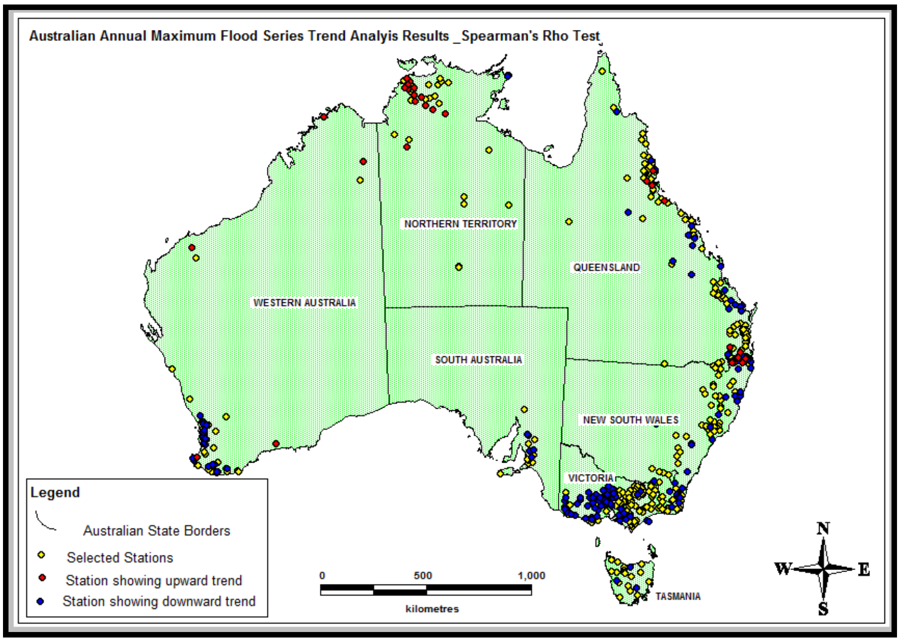

Figure 5 Results of trend analysis based on Spearman's Rho. Red and blue circles represent positive and negative trends, respectively

5. CONCLUSIONS

This paper summarises the results from the preliminary analysis of trends in flood data from Australian continent with an initial assumption that the selected stations are independent and auto-correlation in the annual maximum flood series data is negligible. The application of the preliminary trend analysis to the annual maximum flood data of 491 Australian stations using two non-parametric tests has resulted in the identification of significant trends than that are expected to occur by chance. The direction of trends is, in general, downward. Apparent is the decreasing trend in the south-west and south-east regions, while an increasing trends in the northern part of the continent. Further investigation is needed before any firm conclusion can be made about the trends in Australian flood data. Future work aims to address the influence of spatial and autocorrelation on the ability to detect trend in annual maximum flood series data in Australia and assess the relationship between the observed trends in annual maximum flood data and other meteorological variables.

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