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An Analysis of Abrupt Change in Rainfall and the Occurrence of Extreme Events

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Abstract: Extreme events are normally apparent as they considerably and deviate from the normal condition. In some parts of the world increases in extreme events are apparent, while in others there appears to be a decline. It is of great attention to explore and understand the changes (if any) for an area from the previous history before undertaking any further studies. These abrupt changes may indicate a shift into another rainfall regime. In the current study, abrupt changes in historic rainfall variability were investigated using Sequential Mann-Kendall test at five (5) selected stations. Four out of the five stations (Edenhope, Kerang, Malmsbury and Yanac) selected showed significant abrupt increases in rainfall. The Melbourne Regional Office (MRO) station identified an abrupt increase in 1916, however, it was not significant. In addition, Standardised Precipitation Index (SPI) was applied to identify the historical extreme events, namely droughts and floods. It is observed that the annual rainfall had an increasing change in early 1990s due to flood events. The floods of 1946 was one of the worst events recorded in history and most of the stations undergone large increases in rainfall. This study reveals that the Sequential Mann-Kendall test detected the change point well and the results were consistent with the SPI.

Keywords: Abrupt change, extreme events, sequential Mann Kendall test, standardised precipitation index

1. Introduction

The study of trend or identifying abrupt change is essential when examining the resilience of receptors. Abrupt change involves a sudden jump from one value to a much greater (increase) or lower value (decrease) of rainfall and deviate significantly from the normal historical level. Understanding abrupt change poses special challenges in climate discipline. Few methods have been applied to identify abrupt change or the year when the trend begins, including the Wilcoxon-Mann-Whitney test, Pettitt's test [1], Cumulative Summation (CUSUM) test, and the Sequential Mann-Kendall test. The Sequential Mann-Kendall test is the most widely used as it is reputed to have an advantage over other methods in terms of accuracy [2]. This method has been successfully applied in a number of studies in China [3], Turkey [4] and India [5].

Monitoring extreme events (i.e. floods and droughts) is a real challenge as they are becoming more recurrent due to climate change. Standardised Precipitation Index (SPI) was selected in the current study as it has been shown to be the most appropriate index for assessing floods and droughts [6] in Victoria. To date, there have been limited studies on the sudden climatic shift in the country. It is necessary to explore the related change points in rainfall time series data by a proper and reliable statistical method which is capable of indicating the abnormalities in a time series. Moreover, any possible causes or reasons of increasing or decreasing trends that are identified could be investigated. Therefore, in the

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current study, we try to link the identified abrupt changes with the historical extreme events that have occurred (see Fig. 1). This paper is organised as follows. In section 2, a brief description of the selected stations and the climatic data used are provided. The statistical and SPI methods are also presented. The results of the abrupt changes and the simulated SPI are presented in section 3. Finally, the conclusions from the study are summarised in the last section.

2. Data and Methods

Victoria is a State in the south-east Australia. A part of the Murray-Darling Basin which is one of the most important agricultural districts is in the State of Victoria. Furthermore, the Yarra River catchment, which supplies drinking water for metropolitan Melbourne is a very productive catchment. The catchment water resources support urban water supply, and the agricultural and horticultural industries. The five (5) selected rainfall stations and the descriptions for this study are shown in Fig. 1 and Table 1. Rainfall data for the period considering from 1900 to 2015 was taken from the Australian Bureau of Meteorology (BoM) web site for analysis. Victoria has experienced a number of extreme events, namely the extreme heat waves, flooding and bush fires. Some of the significant floods and droughts that have occurred in this state are highlighted in Fig. 1.

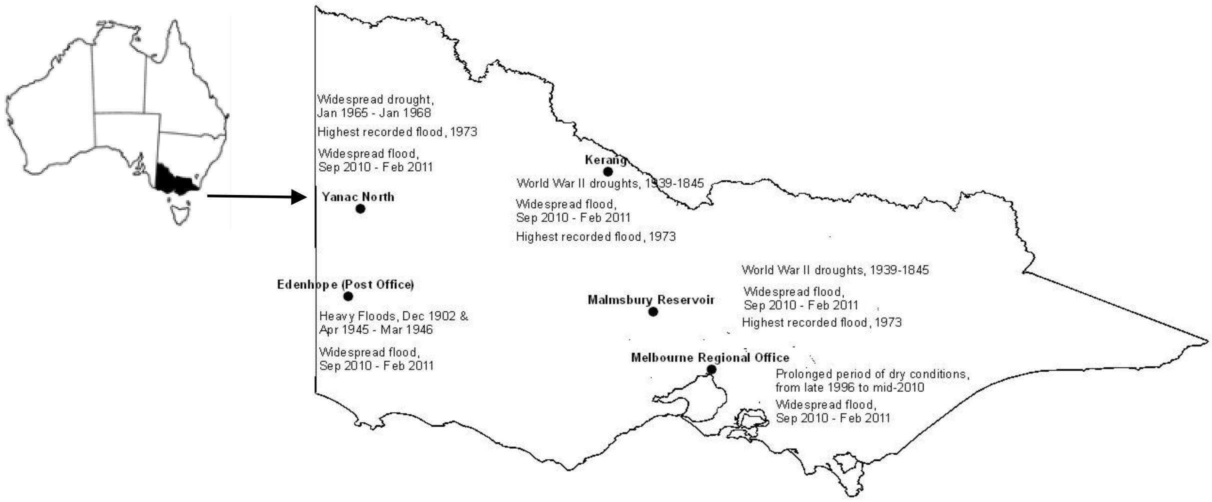


Fig. 1 - Some of the significant historical events occurred at the selected stations.

Table 1 – Description of rainfall stations.

Station No.	Station Name	Long. (^{0}E)	Lat. (^{0}S)	Missing monthly rainfall (%)	No of years of data
1	Yanac North	141.42	-36.11	-	115
2	Edenhope (Post Office)	141.3	-37.04	1.4	123
3	Kerang	143.92	-35.72	-	132
4	Malmsbury Reservoir	144.37	-37.2	-	140
5	Melbourne Regional Office	144.97	-37.81	-	157

2.1 Sequential Mann-Kendall Test

The sequential of the Mann Kendall test is used to detect the change points that may occur in a long data series, especially these points at which the trend changes upward to downward or the other way round [7]. A detailed description of the steps followed to apply the test is presented below. The magnitudes of x_i annual mean time series, (i = 1, . . ., n) are compared with x_j, (j = 1, . . ., i - 1). For each comparison, the cases where $x_i > x_j$ are counted and denoted by n_i. A statistic t_i can therefore, be defined as:

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

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

$$E_{(t)} = \frac{i\left(i-1\right)}{4} \tag{2}$$

$$var\left(t_i\right) = \frac{\left[i\left(i-1\right)\left(2i+5\right)\right]}{72} \tag{3}$$

The forward sequential statistic, *u*(*t*) values of a standardized variable is computed.

$$u_{(t)} = \frac{t_i - E\left(t\right)}{\sqrt{var\left(t_i\right)}} \tag{4}$$

Using the original time series, values of the backward sequential statistic, *u′*(*t*) are estimated.

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

When *u*(*t*) and *u′*(*t*) curves are plotted, the intersection point provides approximate potential trend turning point within the time series. If intersection of *u(t)* and *u′*(*t*) occur beyond ±1.96 of the standardized statistic, a detectable change at that point in the time series can be established. The separation point of the upward and downward curves indicates the starting point of abrupt rainfall change at each station.

2.2 Standardised Precipitation Index (SPI)

The SPI was designed by McKee *et al.* [8] and his colleagues at Colorado State University to quantify the precipitation deficit for multiple time scales (i.e. 1, 3, 6, 12, 24 and 48 months). The equations and methods are widely discussed in other research papers [6, 9]. The computation of the SPI index requires the following steps:

Step 1:
A cumulative probability distribution function (PDF) (gamma distribution) was fitted on aggregated monthly (*k*) precipitation series (say *k* = 12 months in this study). The gamma PDF (*g*(*x*)) is defined as:

$$g\left(x\right) = \frac{1}{\beta^{\alpha}\Gamma\left(\alpha\right)} x^{\alpha-1} e^{-x/\beta} \tag{6}$$

where β is a scale parameter; α is a shape parameter, which can be estimated using the method of maximum likelihood; *x* is the precipitation amount; and $\Gamma(\alpha)$ is the gamma function at α. The estimated parameters can be used to find the cumulative probability distribution function of observed precipitation events for the given month and particular time scale. The cumulative distribution function (CDF), *G(x)* is obtained by integrating Eq. (6) and given in Eq. (7).

$$G\left(x\right) = \int_0^x g\left(x\right)dx = \int_0^x \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma\left(\hat{\alpha}\right)} x^{\hat{\alpha}-1} e^{-x/\hat{\beta}} dx \tag{7}$$

where,

$$\hat{\alpha} = \frac{1}{4A}\left(1+\sqrt{1+\frac{4A}{3}}\right) \tag{8}$$

$$\hat{\beta} = \frac{\hat{x}}{\hat{a}} \tag{9}$$

$$A = \ln\left(\overline{x}\right) - \frac{\sum \ln\left(x\right)}{n} \tag{10}$$

where *n* is the number of precipitation observations and $\bar{x}$ refers to the sample mean of the data.

Step 2:
The cumulative distribution function (CDF) was transformed to the CDF of the standard normal distribution with zero mean and unit variance, which is given as follows:

$$SPI = \psi^{-1}\left[G\left(x\right)\right] \tag{11}$$

This transformed probability is the SPI. A positive value for SPI indicates that precipitation is above average and a negative value denotes below average precipitation. Based on the classification of the SPI, flood (drought) may be defined, as the period during which the SPI is continuously positive (negative) and reaches a value of +1 (-1) or higher (lower).

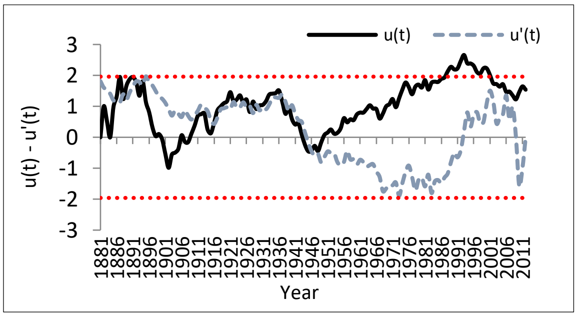
3. Results and Discussion

3.1 Identifying the Abrupt Change

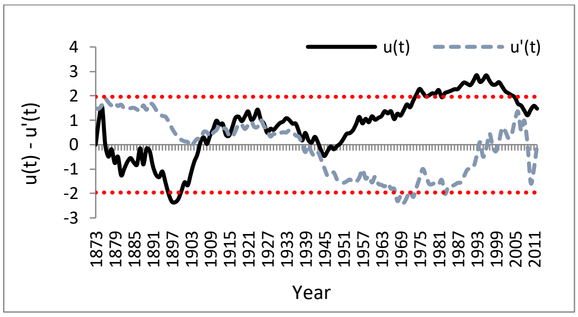
The results of Sequential Mann-Kendall test for yearly rainfall data set are tabulated in Table 2. Of all stations, three (3) (Kerang, Malmsbury and Yanac) show significant abrupt changes in 1946. The sequential values of the statistics *u(t)* and *u′(t)* are illustrated by solid and dotted lines, respectively, and the horizontal dotted lines correspond to the confidence limit at ±5% significance level (Fig. 2). The intersection point is significant at the 5% level, hence the critical point of change is in 1946. It was recorded on March 10, 1946, parts of the western district of Victoria were under floodwaters due to a tropical cyclone (Fig. 3). On 11 March, the previous forty-eight hours had produced 52 mm of rain. During that event, some of the areas received 221 mm of rain over four days between 16 and 19, March. Much devastation and loss of life have accompanied the worst floods in the history of the western district of Victoria, also known as the *Big Flood*.

Table 2 - Sequential Mann-Kendall test results.

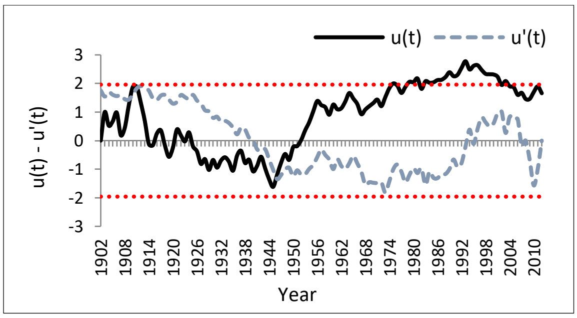
Station	Sequential Mann-Kendall test	
	Abrupt change	Significant trend
Edenhope (Post Office)	1902 1930	1910(↑) 1973 (↑)
Kerang	1946	1988 (↑)
Melbourne Regional Office (MRO)	1916 2000	No No
Malmsbury Reservoir	1946	1974 (↑)
Yanac North	1946	1993 (↑)



(a) Kerang station



(b) Malmsbury station



(c) Yanac station

Fig. 2 - Sequential Mann Kendall test values and the SPI 12-month time scale plot for all stations.

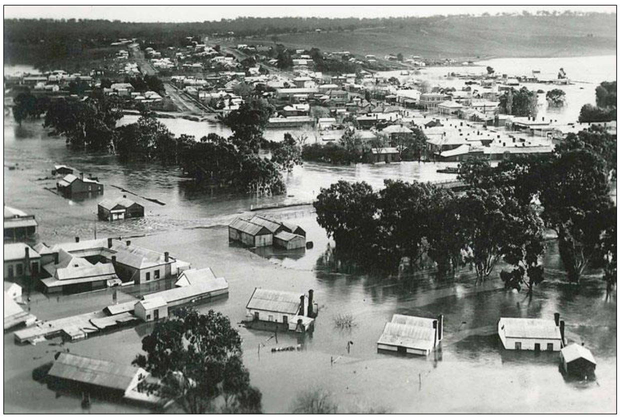
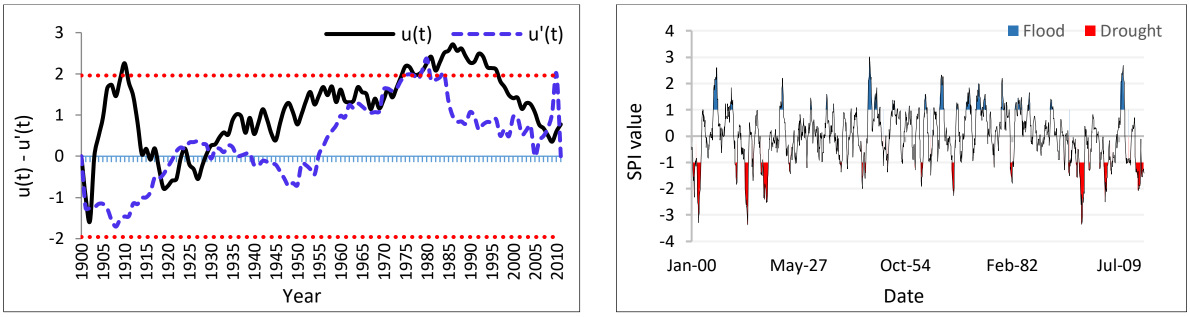
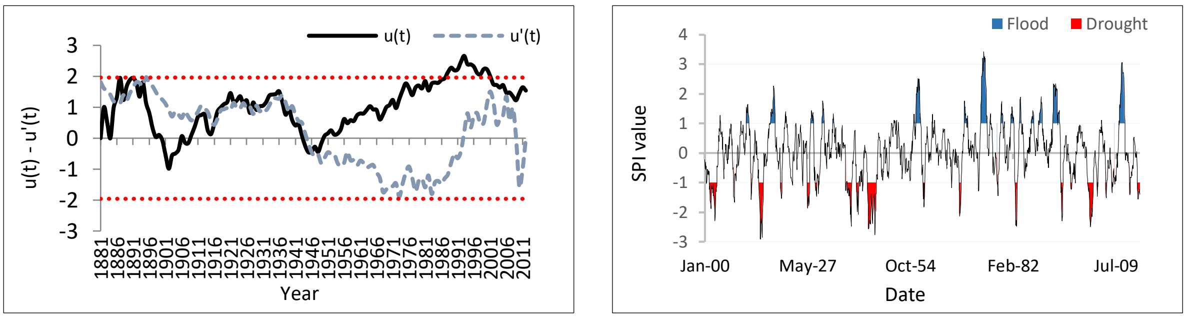


Fig. 3 - View of one of the towns during the 1946 floods.

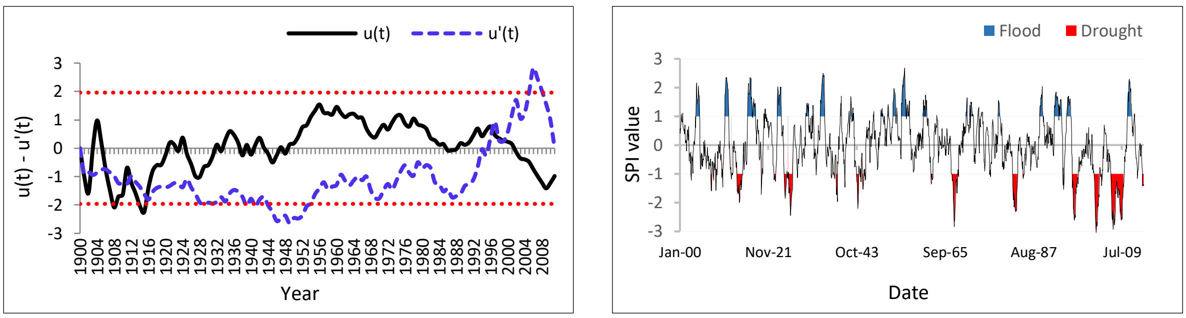
While for the Edenhope station, there are two significant change points (increases) in 1902 and 1930. Again this is related to the heavy floods events occurred in December 1902 and early 1930s [10]. In contrast, the MRO station shows abrupt change (decrease) in 2000 though not significant. This station was badly effected with the prolonged drought. Fig. 4 presents the plots of the Sequential Mann- Kendall test using the annual precipitation data series and the SPI values for all selected stations. The Edenhope station shows an abrupt change in 1902 with a significant increasing trend initiating in 1910. The SPI plot shows one of the most severe flood events recorded in December 1902 due to heavy rain continued for two days throughout the state [11]. Dams and reservoirs were filled to overflowing, and many were burst. Again this station shows an abrupt change in 1930 and a significant increasing trend since 1973. The highest flood event recorded was from April, 1945 to March, 1946.



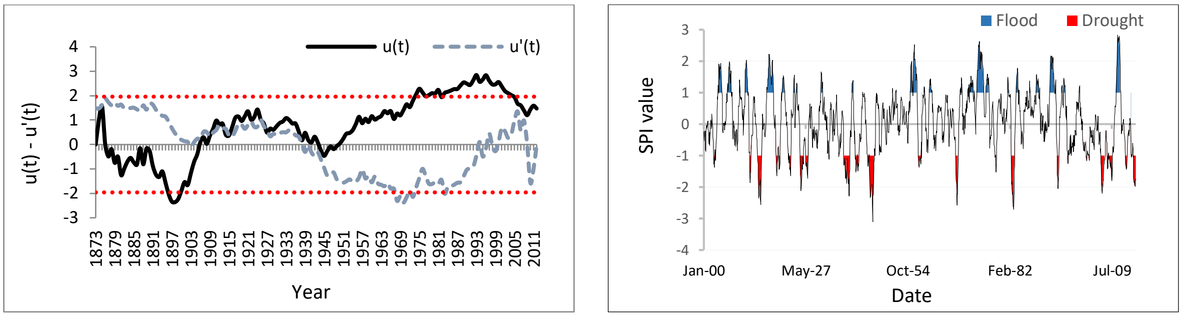
(a) Edenhope station



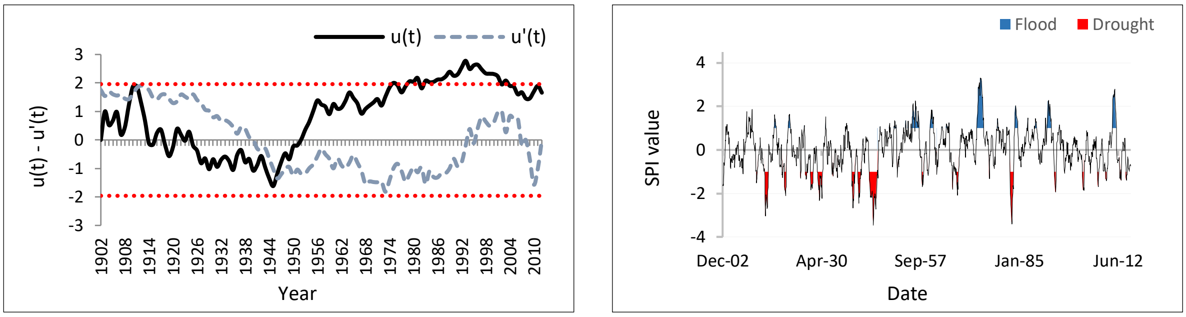
(b) Kerang station



(c) MRO station



(d) Malmsbury station



(e) Yanac station

Fig. 4 - Sequential Mann Kendall test values and the SPI 12-month time scale plot for all stations.

As shown in Fig. 4(b), Kerang exhibits an abrupt change starting in 1946 and a statistically significant increase in 1988. This station was just recovered from a very severe drought initiated from May 1943 to September 1945. Using the SPI, four (4) extreme flood events are identified (refer Fig. 4(b)) in 1955-57, 1973-75, 1992-94 and 2010-11. The La Nina event since 1973 brought more rainfall across eastern Australia. This region experienced one of the most extensive and damaging storms and flood events in its history throughout the period from September 2010 to March 2011. $u(t)$ and $u'(t)$ curves for the MRO station (see Fig. 4(c)) display two points of intersection at 1916 and 2000. However, they are not significant. Overall, for this time series, both extreme floods and droughts have occurred at this station. A record continuous rainfall was experienced throughout Victoria in September 1916. While the rain was very beneficial from an agricultural point of view, it caused serious floods in Melbourne and several parts of the state. The Yarra at several places rose as much as 15 ft. and in many residential districts on low ground houses were flooded. It can be observed that downward abrupt changes in 2000 has led to occurrence of persistent droughts.

Similar to the Kerang station, the Malmsbury and Yanac stations (refer Fig. 4(d) and Fig. 4(e)) experienced floods in 1946 and shifted into another rainfall regime. It is interesting to note that strong and persistent droughts are identified using the SPI at most of the stations from 1997 to 2009. It is also known as the Big Dry [12]. Fig. 5 illustrates rainfall from October 1996 to September 2010 which was the lowest on record for areas shaded in solid red. Another widespread event was the 2010 Victorian floods (see Fig. 6). The floods, which followed heavy rain across south-eastern Australia in early September 2010. Again, major parts of Victoria received high intensity of rainfall between 12 and 14 January, 2011 caused major flooding.

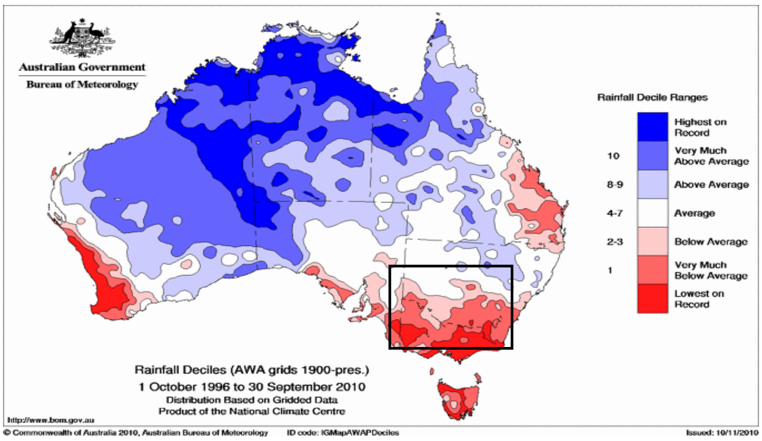


Fig. 5 - Australian rainfall deciles from October 1996 to September 2010 [13].

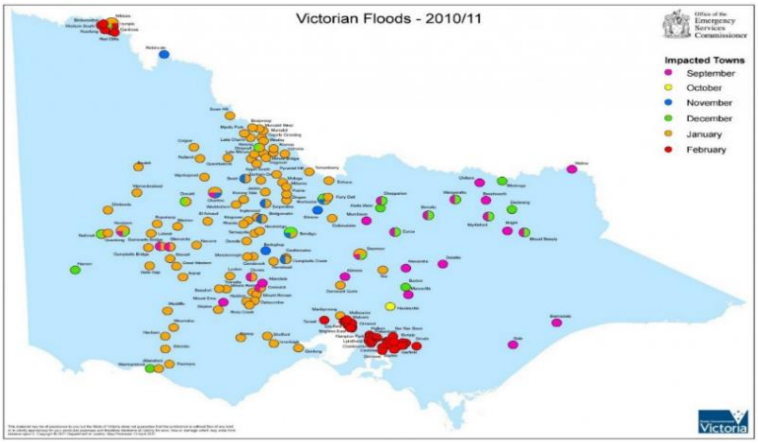


Fig. 6 - Victorian floods from September 2010 to February 2011
(Courtesy of Office of the Emergency Services Commissioner, Victoria, Australia).

4. Conclusions

The historical precipitation data from 1900 to 2015 was analysed. The study revealed that there were abrupt increases in annual rainfall for most of the stations in the early 90s. Only one station identified abrupt decrease but not significant. The significant finding of this analysis was that, the Sequential Mann Kendall test detected the change points well and the SPI was found to be very useful in monitoring floods and droughts. Several significant extreme events were identified and mostly related to the changes detected earlier. It is recommended to apply these methods to other stations to cover the state of Victoria and the results can be used to develop a map of potential regions of abrupt rainfall changes.

Acknowledgement

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