Changes in Rainfall in New South Wales, Australia

Evan Hajani[1] and Ataur Rahman[2]

[1]Student, Western Sydney University, NSW, Australia
[2]Associate Professor, Western Sydney University, NSW, Australia
Corresponding author's E-mail: evan.hajani@gmail.com

Abstract

This study examines changes in rainfall in New South Wales (NSW), Australia using data from 200 daily rainfall stations covering the period of 1945-2014. Mann-Kendall (MK) test is applied to identify trends in the annual maximum daily rainfall (AMDR) data, while the Pettitt test is employed to determine the direction and timing of the change point along with the potential impacts of the abrupt shift in the AMDR data series. Overall, the results of the MK test do not show any consistent pattern of trends in in the AMDR data in NSW. However, southern half of NSW is dominated by decreasing trends in the AMDR data. Based on the Pettitt test it is found that 73 stations show positive trend and 127 stations show negative trend; however, only 5 stations (out of 200 stations) show a significant negative shift in the mean of the magnitude of the AMDR data.

Keywords: Mann-Kendall test, Pettitt test, trends, rainfall, change point, extreme rainfall

1. INTRODUCTION

In recent decades, climate changes resulting from increased concentration of greenhouse gases have caused notable impacts on natural and human systems around the globe. The climate change has been affecting extreme rainfalls, which is increasing the flood risk at many locations (IPCC, 2014). Many researchers have concluded that climate change is contributed by industrial revolution/anthropogenic activities since the mid-20th century (GCC, 2016). The changes in precipitation are considered to be one of the most critical factors in determining the overall impacts of climate change on the environment (Khan et al., 2015) as precipitation affects numerous facets of the environmental and agricultural systems (Haddad et al., 2011). Analysis of trends in rainfall data has been emerged as an active research area, with significant implications to environmental, agricultural and engineering activities (Williams, 1998). In the fourth assessment report, the IPCC concluded that extreme precipitation events have increased at many locations around the world during the 20th century and precipitation generally has become much heavier than the average, even in regions where the total precipitation has decreased (Trenberth et al., 2007).

Numerous studies examined trends in precipitation data across the globe. For example, Zende et al. (2012) used the MK test to examine trends in rainfall data at 10 rainfall stations in Western Maharashtra in India and found both increasing and decreasing trends in monthly rainfall data over large continuous areas. Ahmad et al. (2015) employed the MK test to detect trends in precipitation data for 15 stations in the Swat River basin, Pakistan for a period of 1961 to 2011. The results highlighted a mix of positive and negative trends in monthly, seasonal, and annual precipitation data. Some studies attempted to detect abrupt shift in mean time series data at different places around the world. For example, Vezzoli et al. (2012) presented an analysis to detect shift in annual time series of the Po River discharge in Italy by adopting Pettitt test at 5% significance level. The results show that a significance shift was found in 1962. In another study, Baddoo et al. (2015) investigated trends and change point using the Pettitt test in annual rainfall data covering a period of 1954 to 2010 for Huangfuchuan catchment in China. The results indicated that the data series were homogeneous and the change point was observed in 1979.

Climate change has been in focus in Australian continent since the beginning of the 21st century. The analysis of temperature data by both the Bureau of Meteorology (BOM) and CSIRO show further warming of the atmosphere and oceans in the Australian region. In Australia, there have been large increases and decreases in annual rainfall since 1970 in the northwest and in the southwest, respectively (BOM, 2015). Many researchers in Australia focused their attention on examining rainfall variations. They have specifically addressed trends in rainfall data and of importance; most of them had found trends in the rainfall data at varying degrees across Australia. For example, Westra and Sisson (2011) found that at 10% significance level, the number of stations showing positive trend was more than those showing negative trend in extreme precipitation data at sub-daily and daily durations in eastern Australia. Jakob et al. (2011) assessed variations in frequency and magnitude of intense rainfall events for 6 minutes to 72 hours durations using the MK test at 10% significance level using data within 31 sites located in south-east Australia. The results showed that there were considerable variations across selected sites for the period 1976 to 2005.

In order to enhance the understanding of rainfall behaviour as an indicator of climate change, it is important to examine trends in rainfall data using standard approaches and good quality and updated rainfall data so that new scientific evidence on the impact of climate change on rainfall can be established. Hence, this study is dedicated to examine the changes in rainfall data in NSW state of Australia using both the MK and Pettitt change point tests. Since rainfall is the primary input to hydrologic design, environmental processes and agricultural productivity, the results of this study would be useful to a wide range of scientific communities.

2. STUDY AREA AND DATA SELECTION

This study uses a total of 200 daily rainfall stations from New South Wales (NSW) state in Australia, each having a record length of 70 years covering the period 1945-2014. The daily rainfall data (i.e. 24-hour durations) at the selected locations were obtained from Australian Bureau of Metrology (BOM, 2015). The geographical distribution of the selected 200 daily rainfall stations is shown in Figure 1. The mean annual rainfall value for the selected 200 stations was found to be in the range of 209 mm (at Koonawarra Station, ID = 046013) and 1831 mm (at Byron Bay Station, ID = 058007), with the overall mean of 662 mm.

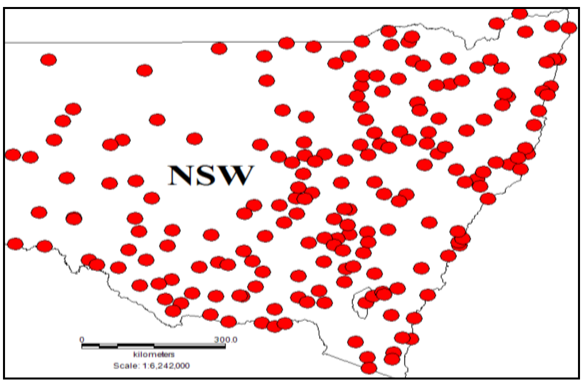

Figure 1. Locations of the selected 200 daily stations in NSW, Australia

3. METHODOLOGY

In this study, MK test (Mann, 1945 and Kendall, 1975) was adopted (at 10%, 5% and 1% significance levels) to examine trends in annual maximum daily rainfall (AMDR) data series. The AMDR series at a given station was formed by selecting the maximum rainfall values of daily duration for each of years of 1945 to 2014. Furthermore, Pettitt test (Pettitt, 1979) was applied to evaluate whether there is a shift in the mean of the AMDR data by finding the break point in the data, and re-applying the trend test for a station showing significant shift prior to and after the year that exhibited a shift. The adopted statistical techniques are described below.

3.1 Mann-Kendall (MK) Test

The null hypothesis in the MK test states that the data (X_1, X_2, ... X_n) are a sample of n independent and identically distributed random variables. The MK test statistic is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i) \tag{3}$$

where, X represents a univariate time-series, i and j denote the time indices associated with individual values, n is the number of data points and the sign is determined as follows:

$$sgn(X_j - X_i) = \begin{cases} +1 & (X_j - X_i) > 0 \\ 0 \quad if & (X_j - X_i) = 0 \\ -1 & (X_j - X_i) < 0 \end{cases} \tag{4}$$

As documented in Mann (1945) and Kendall (1975), the statistic S under the null hypothesis is approximately normally distributed for $n \geq 8$ with mean and variance as follows:

$$E(S) = 0 \tag{5}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{L} t_l(l)(l-1)(2i+5)}{18} = \sigma^2 \tag{6}$$

where, t_l indicates the number of ties of extent l, and l is the number of tied groups. Under the null hypothesis, the standardized test statistic (Z) defined in equation (7) and its corresponding p-value are approximately normally distributed as defined below:

$$Z_S = \begin{cases} \frac{S-1}{\sigma} & for \quad S > 0 \\ \frac{S+1}{\sigma} & for \quad S < 0 \\ 0 & for \quad S = 0 \end{cases} \tag{7}$$

The null hypothesis is rejected at a significance level if $|Z_S| > Z_{crit}$, where Z_{crit} is the value of the standard normal distribution with an exceedance probability of α/2.

3.2 Pettitt Change Point Test

The Pettitt test is a nonparametric approach developed by Pettitt (1979) to detect change point(s) in time series data. The test allows for detection of time t at which a possible shift in a time series data might have occurred, by determining if the two mean values prior to and after t are significantly different. The null hypothesis of this test is that no shift exists in the time series at time t and the alternative hypothesis is that change-point exists at time t. The test statistic is computed as:

$$D_{ij} = \begin{cases} +1 & (X_i - X_j) > 0 \\ 0 \quad if & (X_i - X_j) = 0 \\ -1 & (X_i - X_j) < 0 \end{cases} \tag{8}$$

where X_i and X_j are the magnitude of the rainfall data series at time *i* and *j* respectively, and X_i precedes X_j in time. To evaluate the test over the entire study period (*T*) these *D* statistics are combined as follows:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} D_{ij} \tag{9}$$

The statistic $U_{t,T}$ measures if the two samples $X_1, \ldots, X_t$ and $X_{t+1}, \ldots, X_T$ are coming from the same population. The test statistic $U_{t,T}$ is appraised for all possible values of *t* ranging from 1 to *T*. To identify the time *t* (year) which is used to represent an abrupt shift in the time series, the following statistic is used:

$$K_T = \max_{1 \le t < T} \left| U_{t,T} \right| \tag{10}$$

If K_T is significantly different from zero, a change-point occurs in the year *t* equivalent to the point in time for which the absolute value of $U_{t,T}$ is obtained.

4. RESULTS

4.1 AVERAGE RAINFALL

The spatially averaged yearly total rainfall and its 3-year moving average considering all the 200 stations are shown in Figure 2 (e.g. for Station-052021, the spatially averaged yearly total rainfall for 1945 is the sum of the total rainfall (mm) at Station 1 to Station 200 for 1945 divided by the number of stations, which is 200). It can be seen from Figure 2 that spatially averaged yearly total rainfall values in NSW range between 389 mm (year 1957) and 1050 mm (year 1950). This implies that over the entire NSW, 1957 was the driest year, and 1950 was the wettest year on average. The 3-year moving average of the spatially averaged yearly total rainfall values range from 503 mm to 828 mm.

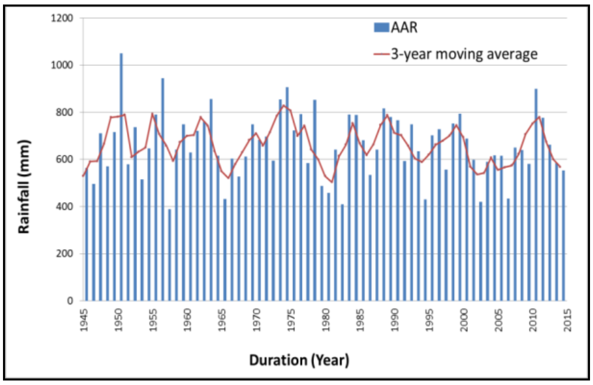

Figure 2. Spatially averaged yearly total rainfall from 1945-2014 and its 3-year moving average for NSW (considering 200 stations)

Figure 3 shows the box plot of AMDR values for all of the 200 individual stations. The upper and lower boundaries of the box represent the upper and lower quartiles, respectively, which are 398 mm and 754 mm, respectively. The median (565 mm) is represented by the line in the centre of the box. The maximum AMDR value (marked by the star in the top edge of the box plot) is 1828 (mm) (at

Station: Byron Bay-058007), and the smallest AMDR value is 184 (mm) (at Station: Wanganella-075081).

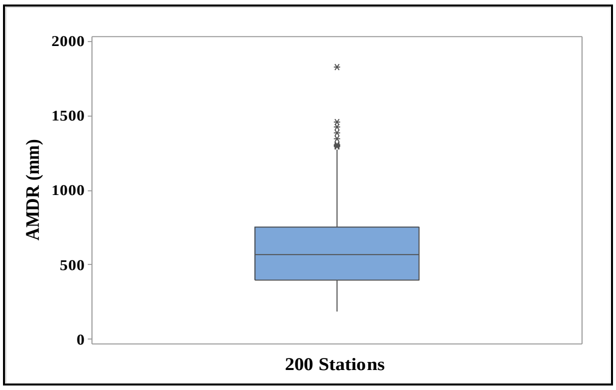

Figure 3. Box plot of annual maximum daily rainfall (AMDR) values considering the 200 stations in NSW

The variability in annual total rainfall (ATR) values at individual stations was found to be remarkably high. For example, the 10 stations (from the 200) having the 5 lowest and highest ATR values are shown in Table 1. It can be seen from Table 3 that the lowest ATR value was 30.2 mm (at Station 052021 in year 1990), and the highest ATR value was 2958.8 mm (at Station 058007), these highest and lowest ATR values represent a variation of about 9,600%.

Table 1. Five lowest and highest annual total rainfall (ATR) values from 200 stations in NSW, Australia (data period: 1945-2014)

Lowest annual total rainfall (ATR) value				Largest annual total rainfall (ATR) value		
Station ID	Year	ATR (mm)		Station ID	Year	ATR (mm)
052021	1990	30.2		058007	1999	2958.8
075166	2013	37.6		058007	1972	2888.4
047039	2002	46.2		068108	1950	2732.8
048074	1989	50.0		058012	1950	2716.8
047019	1967	51.8		058007	2006	2716.0

4.2 Trend in AMDR Time Series Data

The results of the trend analysis using the MK test for AMDR data show that when the significance level is ignored, 88 stations out of 200 show an increasing trend, while 112 stations show a decreasing trend. At the 10% significance level, 13 stations show an increasing trend and only 26 stations showing a decreasing trend. At the 5% significance level, 12 stations show an increasing trend, but 17 stations show a decreasing trend. At the 1% significance level, only 5 and 9 stations are showing increasing and decreasing trends, respectively. Overall, it can be seen that the decreasing trends are dominating the NSW rainfall regime.

Three stations are selected for in-depth analysis, which are Koonawarra-046013 (having the lowest spatially averaged annual rainfall (AAR) value), Byron Bay-058007 (having the highest spatially averaged AAR value), and Gunning Rural-070043 (which has AAR value very close to the NSW State average).

Figure 4 shows the time series plots of AMDR data for these three stations (Koonawarra-046013, Gunning Rural-070043 and Byron Bay-058007) with 3-year moving average (red line) and linear trend (black line). In general, it may be noted that the two stations (Koonawarra-046013 and Byron Bay-058007) show increasing trend, while Gunning Rural-070043 shows a decreasing trend.

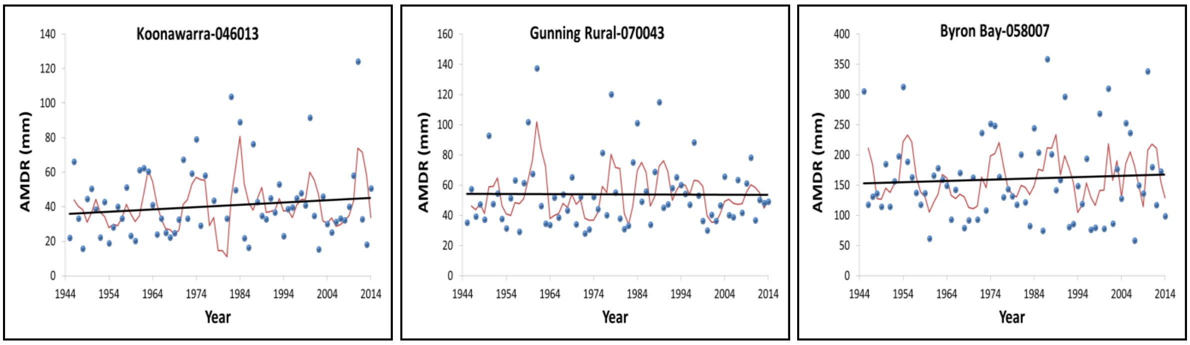

Figure 4. The AMDR data at Koonawarra-046013, Gunning Rural-070043 and Byron Bay-058007 stations for the study period 1945-2014 along with 3-year moving average (red line) and linear trend (black line)

Figure 5 shows spatial distribution of the stations showing positive and negative trends for AMDR data (considering the study period of 1945-2014) at the 10% significance level. In this Figure, it can be seen that numbers of stations showing positive trend for AMDR data are much smaller than those with negative trends. Of significance, for AMDR, the numbers of stations showing negative trends are concentrated to south-eastern NSW.

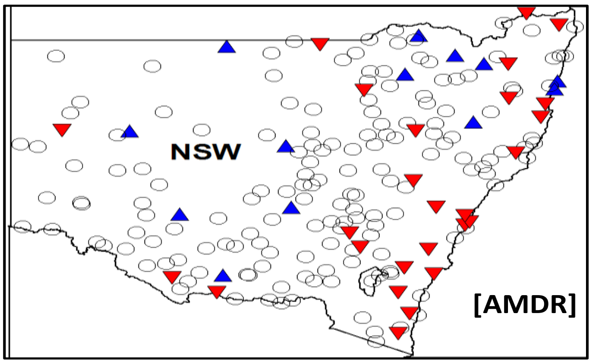

Figure 5. Spatial distribution of trends for AMDR data over NSW at 10% significance level. (Data period: 1945-2014, No. of stations: 200, blue and red triangles represent stations exhibiting significant positive and negative trend, respectively, and hollow circles represent stations indicating no significant trend)

4.3 Abrupt Shift in the Daily Rainfall Data Series

The Pettitt change-point test is employed to identify an abrupt shift in the mean of AMDR data. The direction of the shift in the mean is determined by comparing the mean of the subseries prior to the shift and that represents the mean of the subseries after the shift. From the results of the Pettitt test, it is found that 73 stations show positive trend and 127 stations show negative trend. More importantly, only 5 stations show a significant negative shift in the mean of the magnitude of the AMDR data (at the three significance levels of 10%, 5% and 1%).

Table 2 shows the results of the Pettitt test. It can be seen that only 5 stations from the 200 stations exhibit significant negative trend with a shift in the mean of the AMDR data (at the significance levels of 10% 5% and 1%) for the 70-year study period (1945-2014). These 5 stations show a shift after 1979. However, the MK test shows that these 5 stations have negative trends only for the 10% significance level. Moreover, it is found that for the 5 stations, the mean of the AMDR data prior to change point is higher than the mean after the change point and the MK test statistics prior and after the change point are smaller compared to the MK test statistic for the complete series.

Table 2. Results of Pettit (ZP) and MK (ZMK) test statistics for the AMDR data series for the five stations exhibiting a significant change-point

Station ID	K_T	t	Complete Series	Complete Series		Prior to Change-Point		After Change-point	
			Z_P statistics	Z_{MK} statistics	Mean	Z_{MK} statistics	Mean	Z_{MK} statistics	Mean
057082	355	1982	-1.706	-4.492	74.40	-0.314	91.33	-0.629	54.74
063118	330	1992	-1.702	-3.878	112.40	-0.624	126.09	-0.112	79.83
066073	364	1992	-1.877	-3.554	132.06	-0.284	149.68	0.152	87.07
068008	309	1998	-1.762	-3.194	121.70	-0.330	136.30	0.005	66.30
069016	350	1979	-1.674	-4.456	124.92	0.000	155.01	-0.897	95.83

5. CONCLUSION

This study examines changes in rainfall in New South Wales (NSW), Australia using data from 200 stations covering a record length of 1945-2014. The mean annual rainfall values over the 200 stations range 208 mm to 1,830 mm (overall mean of 662 mm, and a coefficient of variation of 0.48). Considering all the 200 stations, 1957 is found to be the driest year (for the whole of NSW) with average annual total rainfall of 389 mm, and 1950 is the wettest year (with 1050 mm rainfall). Considering the individual years and individual stations (representing 70×200 = 14,000 data points), the lowest annual total rainfall (ATR) value is found to be 30 mm and the highest value is 2,958 mm, representing a variation of about 9,600%. The results of the trend analysis using the MK test for annual maximum daily rainfall (AMDR) data shows that at the 10% significance level, 13 stations show an increasing trend and 26 stations show a decreasing trend. Overall, the decreasing trends are dominating the NSW rainfall regime. Also, the numbers of stations showing negative trends are concentrated to south-eastern NSW. From the results of the Pettitt test, it is found that 73 stations show positive trend and 127 stations show negative trend; however, only 5 stations show a significant negative shift in the mean of the magnitude of the AMDR data. Overall, the results of this study show that NSW rainfall has a high spatial and year-to-year variability. Furthermore, most of the rainfall indices examined here showing trends; however, the trends are generally mixed (both negative and positive), although negative trends is dominant for most of the rainfall indices.

REFERENCES

Ahmad I, Tang D, Wang T, Wang M, Wagan B (2015). Precipitation trend over time using Mann-Kendall and Spearman's rho tests in Swat River Basin, Pakistan, Advances in Meteorology, ID: 431860, pp. 1–15.

Australian Bureau of Meteorology, BOM (2015). State of the Climate 2014. http://www.bom .gov.au/.

Baddoo TD, Guan Y, Zhang D, Andam–Akorful SA (2015). Rainfall variability in the Huangfuchuang watershed and its relationship with ENSO, Water, 7, 3243–3262.

Jakob D, Karoly DK, and Seed A (2011). Non–stationarity in daily and sub–daily intense rainfall – Part 2: Regional assessment for sites in south–east Australia, Natural Hazards and Earth System Sciences, 11, 2273–2284.

Haddad K, Rahman A, Green J (2011). Design rainfall estimation in Australia: A case study using L moments and generalized least squares regression, Stochastic Environmental Research and Risk Assessment, 25, 6, 815–825.

Intergovernmental Panel on Climate Change, IPCC (2014). Climate change 2014: Mitigation of climate change. Working Group III contribution to the IPCC Fifth Assessment Report. Cambridge, United Kingdom: Cambridge University Press. www.ipcc.ch/report/ar5/wg3.

Global Climate Change, GCC (2016). Vital signs of the planet: A blanket around the earth. http://climate.jpl.nasa.gov/causes/

Khan MZK, Sharma A, Mehrotra R, Schepen A, Wang QJ (2015). Does improved SSTA prediction ensure better seasonal rainfall forecasts? Water Resources Research, 51, 5, 3370–3383.

Kendall MG (1975). Rank correlation methods, Griffin Publishers, London, 202.

Mann HB (1945). Non–Parametric tests against trend. Econometrical, 13, 245–259.

Pettitt A (1979). A non–parametric approach to the change–point problem, Applied Statistics, 126–135.

Trenberth KE, Jones PD, Ambenje P, Bojariu R, others (2007) Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, others (eds) Climate change (2007). The physical science basis. Intergovernmental Panel on Climate Change 4th assessment report, Cambridge University Press, Cambridge

Vezzoli R, Pecora S, Zenoni E (2012). Data analysis to detect inhomogeneity, change points, trend in observations: an application to Po River discharge extremes. Research Papers, RP0138, Technical report, Centro EuroMediterraneo Sui Cambiamenti Climatic (CMCC).

Westra S, Sisson SA (2011). Detection of non–stationarity in precipitation extremes using a max–stable process model. Journal of Hydrology, 406, 119–128.

Williams PM (1998). Modelling seasonality and trend in daily rainfall data, In Advances in Neural Information Processing Systems–Proceedings of the 1997 Conference, Jordan MI, Kearns MJ, Solla SA, MIT Press, pp. 985–991.

Zende AM, Nagarajan R, Atal K (2012). Rainfall trend in semi–arid region– Yerala River basin of Western Maharashtra, India, International Journal of Advancements in Technology, 3, 3, 137–145.