Trend Analysis for Extreme Rainfall Events in New South Wales, Australia

Evan Hajani, Ataur Rahman, Khaled Haddad

***Abstract*—**Climate change will affect the hydrological cycle in many different ways such as increase in evaporation and rainfalls. There have been growing interests among researchers to identify the nature of trends in historical rainfall data in many different parts of the world. This paper examines the trends in annual maximum rainfall data from 30 stations in New South Wales, Australia by using two non-parametric tests, Mann-Kendall (MK) and Spearman's Rho (SR). Rainfall data were analyzed for fifteen different durations ranging from 6 min to 3 days. It is found that the sub-hourly durations (6, 12, 18, 24, 30 and 48 minutes) show statistically significant positive (upward) trends whereas longer duration (sub-daily and daily) events generally show a statistically significant negative (downward) trend. It is also found that the MK test and SR test provide notably different results for some rainfall event durations considered in this study. Since shorter duration sub-hourly rainfall events show positive trends at many stations, the design rainfall data based on stationary frequency analysis for these durations need to be adjusted to account for the impact of climate change. These shorter durations are more relevant to many urban development projects based on smaller catchments having a much shorter response time.

***Keywords*—**Climate change, Mann-Kendall test, Spearman's Rho test, trends, design rainfall.

I. Introduction

TREND detection is an active area of interest for both hydrologists and climatologists in order to investigate climate change scenarios and enhance climate impact research to identify impacts of climate change on hydro-meteorological time series data [1]. Trend detection in rainfall time series is crucial for planning and designing many regional water resources management projects. The trend in rainfall pattern has been examined extensively using different methods by many researchers from various parts of the world (e.g. Ashley et al. [2] and Haylock et al. [3] in USA, Burgueno et al. [4] in Spain, Odekunle et al. [5] in Africa, Zhai et al. [6] in China, Fujibe [7] in Japan, Hannaford and Buys [8] in UK, , Nikhil Raj and Azeez [9] in India, Hanif et al. [10] in Pakistan and Burn and Taleghani [11] in Canada). For example, Hamdi et al. [12] adopted several statistical approaches including Mann-Kendall, Linear Regression, CUSUM, Rank Sum, Student's t-test, Rank Difference, Auto Correlation and Skewness-Kurtosis Normality test to detect trends and quantify evidences of climatic change by analyzing data from six meteorological stations around Jordan. The results indicated that there were no visible trends indicating an increase or decrease in the annual precipitation and maximum temperature. Karpouzos et al. [1] analysed trends of precipitation data covering a 30 year period for six stations located within the prefecture of Pieria in Northern Greece. Various statistical techniques such as the Mann-Kendall test, Sequential version of the Mann-Kendall test and Sen's estimator of slope were adopted to detect possible changes in precipitation in annual, monthly and seasonal basis. Furthermore, CUSUM test was used for evaluating a step change in the precipitation data. Results showed that more significant trends were related to seasonal time series than to annual ones.

In another study, Clarke et al. [13] investigated trends of 5 minutes to 24 hours duration rainfall data from 13 Canadian stations and found that about 30% of the cases demonstrated a statistically significant trend. Rana et al. [14] analyzed trends in precipitation of accumulated daily rainfall data of 48 stations covering 60 years of data during the period from 1951 to 2004 in the cities of Delhi and Mumbai in India. The Mann-Kendall test and linear regression were adopted to evaluate long term trends in rainfall. The analysis revealed great degree of variability in precipitation in the study area. Also it was found significant increasing trends in the higher latitudes and decreasing trends along coastal areas for seasonal rainfall. Mondal et al. [15] analysed the trends using daily rainfall data of 40 years from 1971 to 2010 to find out the monthly variability of rainfall in Birupa River basin located in the north-eastern part of Cuttack district in Orissa state of India. The modified Mann-Kendall test was used for the determination of the spatial variation and temporal trends. The results showed that there were increasing and decreasing trends in monthly data in the study area.

In Australia, many researchers have investigated trends in rainfall data (e.g. Yu and Neil [16], Plummer et al. [17], Haylock and Nicholls [18], Groisman et al. [19], Gallant et al. [20], Alexander et al. [21], Hardwick Jones et al. [22], Li et al. [23], and Chen et al. [24]). Most of these studies have found trends in Australian rainfall data, the common findings are that the northwest had experienced an increase in rainfall over the last 50 years, while much of eastern Australia and the far southwest have experienced a decrease. For example, Chowdhury and Beecham [25] investigated the monthly rainfall trends at ten rainfall stations across Australia covering all state capitals. They found a decreasing trend of June and

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July rainfall depth at two stations (Perth Airport and Sydney Observatory Hill), while no significant trends in Melbourne, Alice Springs and Townsville rainfall stations, whereas five stations showed an increasing trend on monthly rainfall depth. In another study, Jacob et al. [26] evaluated changes in sub-daily extreme rainfalls, and found that changes in short duration rainfall data are in greater magnitude than the longer duration ones. Chen et al. [24]) suggested that for six minutes duration, rainfall intensity would increase despite a decrease in the mean annual rainfall.

Loveridge and Rahman [27] adopted four tests (Mann-Kendall, linear regression, CUSUM and cumulative deviation) to investigate trends in loss parameters using an event-based rainfall-runoff model for four catchments. The results showed that there was strong evidence of an upward trend in the initial loss data for two catchments. Also, Yilmaz and Perera [28] investigated the heavy rainfall trends for storm durations of 6 minutes to 72 hours. The statistical tests used were the Mann-Kendall and Spearman's Rho tests to detect trends in annual maximum rainfall intensities of the selected storm durations. The results of the data sets of hourly storm indicated increasing trends, but for 6 to 72 hours heavy rainfall data sets showed statistically insignificant decreasing trends.

The objective of this study is to investigate trends in sub-hourly, sub-daily and daily rainfall events in New South Wales (NSW), Australia using the latest rainfall data, to compare trends in shorter and longer duration events using two different non-parametric trend tests and the spatial variability of the identified trends.

II. Method and Data

There are many non-parametric and parametric trend tests available that can be adopted to investigate trends in rainfall data. Non-parametric trend tests were adopted in this study since this is robust with respect to non-normality, nonlinearity, missing values, serial dependency and outliers in the data [16]. The most frequently used non-parametric test for identifying trends in hydrological time series data is the Mann-Kendall (MK) test ([29], [30]), which is a rank-based distribution-free method for identifying trends. In this study, in addition to the MK test, Spearman's Rho (SR) test was also adopted so that the results can be compared by two different tests.

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:

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

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 sign is determined as follows:

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

As documented in Mann [29] and Kendall [30], the statistic S under the null hypothesis is approximately normally distributed for $n \geq 8$ with mean and variance as follows:

$$E(S) = 0 \tag{3}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{L} t_l(l)(l-1)(2i+5)}{18} = \sigma^2 \tag{4}$$

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 (5) and its corresponding p-value are approximately normally distributed as defined below:

$$Z_S = \begin{cases} \frac{S-1}{\sigma} & for \quad S > 0 \\ \frac{S+1}{\sigma} & for \quad S < 0 \\ 0 & for \quad S = 0 \end{cases} \tag{5}$$

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 $\alpha/2$. In our analysis, the statistically significant trends are evaluated at the 10%, 5% and 1% significance levels (two-tailed test).

In the SR test, the null hypothesis (H_0) is that all the data X_i in the time series are independent and identically distributed, while the alternative hypothesis (H_i) is that X_i increases or decreases with i, that is trend exists [16]. The SR test statistic D is given by:

$$D = 1 - \frac{6\sum_{i=1}^{n}(R_i - i)^2}{n(n^2-1)} \tag{6}$$

$$Z_{SR} = D\sqrt{\frac{n-2}{1-D^2}} \tag{7}$$

where, R_i is the rank of i observation X_i in the time series and n is the length of the time series. A positive value of Z_{SR} indicates an upward trend; while negative Z_{SR} indicate a downward trend in the time series. When $Z_{SR} > t_{(n-2,1-\alpha/2)}$, the null hypothesis is rejected indicating a significant trend in the time series data. Here, $t_{(n-2,1-\alpha/2)}$ is the critical value of t distribution.

The selected study area covers New South Wales (NSW) state in Australia (Fig. 1). The pluviograph stations were selected which have a recorded length of greater than 10 years, 30 stations with data ranging between 1932 to 2012 were retained which had less than 20% gaps in the annual maximum rainfall series. Rainfall events of six sub-hourly durations (6, 12, 18, 24, 30 and 48 minutes), six sub-daily durations (60 min, 2, 3, 6, 8 and 12 hours), and three daily durations (24, 48 and 72 hours) were extracted from each of the selected 30 pluviograph stations. The geographical distributions of the selected 30 pluviograph stations are shown in Fig. 1 which shows a uniform density of selected stations over NSW. Table I lists the selected pluviograph stations with record lengths, period of data and latitudes and longitudes. The record lengths of the annual maximum rainfall events series range from 12 to 72 years (average: 36 years) and the mean annual rainfalls in this region are in the range of 183 mm to 1439 mm (average: 580 mm).

TABLE I
SELECTED PLUVIOGRAPH STATIONS AND RECORD LENGTHS

Station ID	Station	Data Period	Length (Years)	Latitude (Degree)	Longitude (Degree)
46012	Wilcannia	2001-2012	12	-31.5194	143.3850
46037	Tibooburra	1985-2012	28	-29.4345	142.0098
47058	Menindee	1994-2011	18	-32.3902	142.4164
48015	Brewarrina	1997-2012	16	-29.9614	146.8651
48027	Cobar Mo	1966-2011	49	-31.484	145.8294
48031	Collarenebri	1977-2011	35	-29.5407	148.5818
49000	Ivanhoe	2001-2012	12	-32.8831	144.3088
51049	Trangie	1969-2012	44	-31.9861	147.9489
55054	Tamworth	1959-1992	34	-31.0867	150.8467
56018	Inverell	1948-2010	63	-29.7752	151.0819
56041	Bonshaw	1955-1969	15	-29.1333	151.4500
57033	Wollomombi	1960-1982	23	-30.5112	152.0427
58044	Nimbin	1964-2009	46	-28.5966	153.2233
58099	Whiporie	1974-2010	37	-29.2823	152.9886
61151	Chichester	1961-2012	52	-32.2426	151.6830
61174	Millfield	1959-1980	22	-32.9000	151.2667
61309	Milbrodale	1970-2012	43	-32.6881	150.9728
61351	Peats	1982-2010	29	-33.3102	151.2443
63023	Cowra	1942-2010	69	-33.8087	148.7071
63063	Oberon	1989-2012	24	-33.6682	149.8348
64046	Coonabarabran	1972-2011	40	-31.2886	149.0687
65035	Wellington	1962-2004	43	-32.5059	148.9708
67035	Liverpool	1966-2001	36	-33.9272	150.9128
69049	Nerriga	1972-2010	39	-35.1165	150.0847
70014	Canberra	1938-2009	72	-35.3049	149.2014
72091	Tooma	1957-1973	17	-35.9111	148.2167
74114	Wagga Wagga	1947-2003	57	-35.1311	147.3091
74128	Deniliquin	1978-2002	25	-35.5269	144.9520
75028	Griffith	1932-1988	57	-34.2487	146.0695
75050	Naradhan	1971-2012	42	-33.6104	146.3161

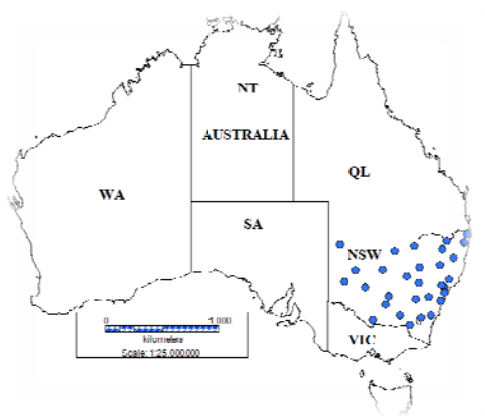

Fig. 1 Selected pluviograph stations in NSW, Australia

III. RESULTS AND DISCUSSION

The results from the trend analysis are presented in Figs. 2 and 3 (for 5% level of significance) and in Figs. 4 and 5 (for 10% level of significance) by both the MK and SR tests. In Fig. 2, it is found that for the MK test (5% level of significance), the percentages of stations with statistically significant positive trends are notably higher for sub-hourly durations (6 to 48 minutes), for 1 hour the positive and negative trends are very similar, for 2 hours to 1 day, the negative trends are much higher and for 2 and 3 days, positive trends are higher than the negative ones.

In Fig. 3, it is found that the SR test (at 5% level of significance) shows all positive trends for 6 minutes to 48 minutes durations and 1 hour to 6 hours durations, and for 8 hours to 1 day there are more positive trends than the negative ones. In Fig. 4, the MK test results (at 10% significance level) show that 6 minutes to 48 minutes durations have more positive trends than the negative ones, for 1 hour to 1 day, there are more negative trends than the positive ones. In the case of SR test at 5% significance level (Fig. 5), there are more positive trends, in particular for shorter durations.

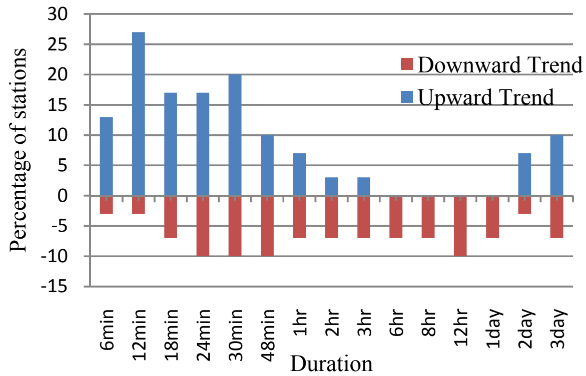

Fig. 2 Percentage of stations with positive and negative trends (at 5% level) for MK test

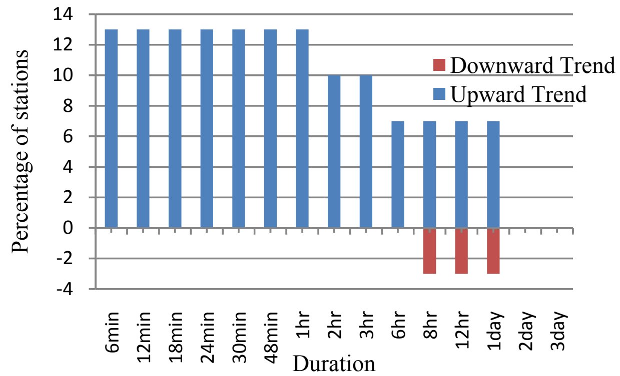

Fig. 3 Percentage of stations with positive and negative trends (at 5% level) for SR test

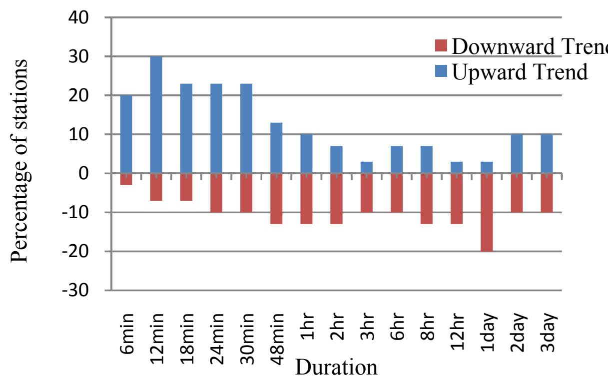

Fig. 4 Percentage of stations with positive and negative trends (at 10% level) for MK test

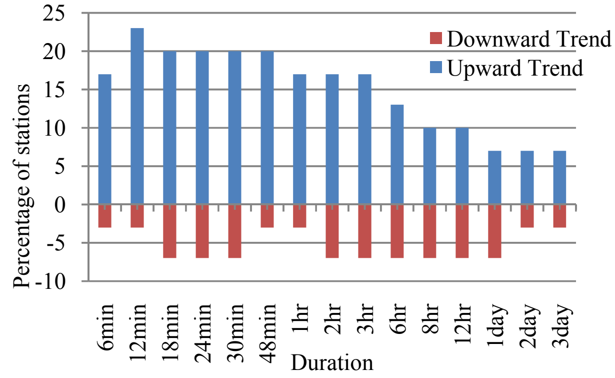

Fig. 5 Percentage of stations with positive and negative trends (at 10% level) for SR test

Table II shows the percentage of stations showing significant positive and negative trend at 1%, 5% and 10% significance levels. This shows that at 1% level of significance, the percentages of stations indicating positive trend vary from 0% to 10% for the MK and SR tests for different durations. However, the percentages of stations indicating negative trend vary from 0% to 7% for the MK test and for SR test, there is no trend.

TABLE II
PERCENTAGE OF STATIONS SHOWING SIGNIFICANT POSITIVE AND (NEGATIVE) TRENDS AT 1%, 5% AND 10% SIGNIFICANCE LEVELS

Significance level	1%		5%		10%	
Duration	MK test	SR test	MK test	SR test	MK test	SR test
6 min	10 (0)	10 (0)	13 (3)	13 (0)	20 (3)	17 (3)
12 min	10 (0)	10 (0)	27 (3)	13 (0)	30 (7)	23 (3)
18 min	10 (3)	10 (0)	17 (7)	13 (0)	23 (7)	20 (7)
24 min	10 (3)	10 (0)	17 (10)	13 (0)	23 (10)	20 (7)
30 min	7 (0)	7 (0)	20 (10)	13 (0)	23 (10)	20 (7)
48 min	3 (0)	3 (0)	10 (10)	13 (0)	13 (13)	20 (3)
1 hr	3 (0)	3 (0)	7 (7)	13 (0)	10 (13)	17 (3)
2 hr	3 (7)	3 (0)	3 (7)	10 (0)	7 (13)	17 (7)
3 hr	3 (3)	0 (0)	3 (7)	10 (0)	3 (10)	17 (7)
6 hr	0 (7)	0 (0)	0 (7)	7 (0)	7 (10)	13 (7)
8 hr	0 (7)	0 (0)	0 (7)	7 (3)	7 (13)	10 (7)
12hr	0 (7)	0 (0)	0 (10)	7 (3)	3 (13)	10 (7)
24 hr	0 (0)	0 (0)	0 (7)	7 (3)	3 (20)	7 (7)
48 hr	0 (0)	0 (0)	7 (3)	0 (0)	10 (10)	7 (3)
72 hr	0 (0)	0 (0)	10 (7)	0 (0)	10 (10)	7 (3)

For the 5% significance level, the percentage of stations with positive trend vary from 0% to 27% and 0% to 13% for the MK and SR tests, respectively for different durations and the percentages of stations indicating negative trend vary from 0% to 7% and 0% to 3% for different durations for MK and SR tests, respectively. While for the 10% significance level, the percentage of stations with positive trend vary from 0% to 30% and 0% to 17% for the MK and SR tests, respectively for different durations and the percentages of stations indicating negative trend vary from 0% to 20% and 0% to 7% for different durations for both the tests. Overall, the numbers of stations indicating positive trends are greater than negative trends for shorter duration events by both the tests and three significance levels considered in this study.

Fig. 6 shows the spatial distributions of the pluviograph stations showing positive and negative trends for 6 minutes and 48 hours durations for the MK test. This figure shows that there are a greater number of stations in NSW state that show positive trends than negative trends for 6 minutes duration.

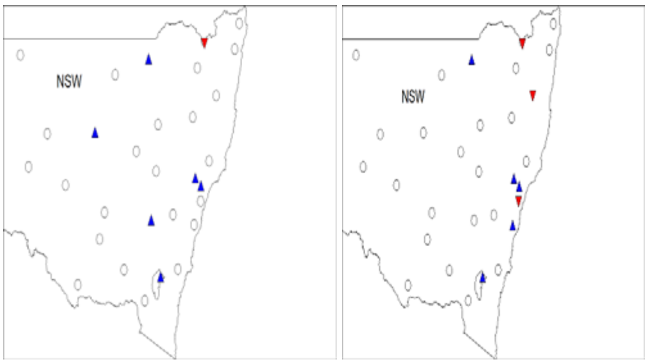

Fig. 6 Spatial distributions of stations showing positive, negative and no trends (at the 10% level of significance) for 6 minutes (left) and 48 hours (right) durations using MK test. Blue and red triangles represent stations exhibiting significant positive and negative trends respectively and the hollow circles represent stations indicating no trend

IV. Conclusion

This paper examines the trends of sub-hourly, sub-daily and daily extreme rainfall events from 30 rainfall stations across NSW state in Australia. Two non-parametric tests (MK and SR) are applied to detect trends at 1%, 5% and 10% significance levels. It is found that the sub-hourly durations (6, 12, 18, 24, 30 and 48 minutes) show statistically significant positive (upward) trends whereas longer duration (sub-daily and daily) events generally show a statistically significant negative (downward) trend. It is also found that the MK test and SR test provide notably different results for some rainfall event durations considered in this study. Since shorter duration sub-hourly rainfall events show positive trends at many stations, the design rainfall data based on stationary frequency analysis for these durations need to be adjusted to account for the impact of climate change. These shorter durations are more relevant to many urban development projects based on smaller catchments having a much shorter response time.

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