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Trend analysis of rainfall losses using an event-based hydrological model in eastern NSW

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Abstract: Climate change is likely to impact on the magnitude and frequency of extreme flow events. Whilst flood data have traditionally been assumed to remain stationary, this may no longer be the case due to the effects of climate change. A number of studies have demonstrated trends and variability in annual maximum flood data across Australia. These findings have been supported by Australian climate change studies, which predict increases in extreme rainfalls, increasing evaporation and changes to soil moisture conditions. However, what it is more uncertain is the magnitude of these changes, the specific changes at a regional scale and the impact on catchment characteristics at the local scale and how this affects catchment response when a hydrologic model is to be developed.

This study investigates trends in loss parameters using an event-based rainfall-runoff model, for four catchments across eastern New South Wales. These catchments include the Orara River, Ourimbah Creek, Currambene Creek and Pambula River. The analysis explores three loss models, the initial loss-continuing loss (IL-CL) model, initial loss-proportional loss (IL-PL) model and Soil Water balance MODel (SWMOD). Trends were investigated for the loss parameters of all three loss models, including the initial loss (IL), continuing loss (CL), proportional loss (PL) and initial moisture (IM, from SWMOD). The relationship between trends in loss parameters and trends in the annual maximum flow series, antecedent precipitation index, annual runoff totals, annual rainfall totals, number of rainy days and inter-event duration are also examined.

In this study, four tests were adopted to test for trends, namely the Mann-Kendall, linear regression, CUSUM and cumulative deviation tests. Results from the tests of change and visual analyses show that for two of the four catchments there is strong evidence of an upward trend in the IL data, strong evidence of a downward trend in the IM data and strong evidence of a downward trend in the API data (28 days). The changes in the initial condition for rainfall-runoff modelling (IL and IM) correspond well to the trends in the API, as surrogate for the antecedent moisture content. Only one of the catchments saw a change in the continuing loss measures (CL and PL), however, this is also the only catchment that shows evidence of trends in the annual flood series.

Keywords: *Trend analysis, Mann-Kendall test, RORB, initial loss, continuing loss, floods.*

1. INTRODUCTION

Flooding is a major concern in Australia. Records dating back to the end of the 18^{th} century show that there have been over 2300 fatalities due to flooding alone (Blong 2005). It has been estimated that flooding causes 31% of the mean annual damages due to natural disasters and cost around \$376.9 million per annum over the 39-year period leading up to 2005 (BITRE 2008). This makes flooding the most expensive natural disaster in Australia. New South Wales is the most populous state in Australia, with some 34% of the entire population in Australia. Much of the development in NSW is susceptible to flooding, due to historical settlements on floodplains; a key example being the Hawkesbury-Nepean basin west of Sydney. As the population surges and the density of living grows, the risk of flooding will increase due to further development on these floodplains.

Climate change, whether a result of human activities or natural variability, is a critical issue facing the world's population. The fourth assessment report of the IPCC (Pachauri & Reisinger 2007) states that "warming of the climate system is unequivocal and is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level."

Many studies have focused on Australia and are consistent in finding that there will most likely be an increase in the intensity of extreme rainfalls, whilst at the same time these events will become less frequent (Cleugh *et al.* 2011, Jakob *et al.* (2011), Westra 2011, Westra and Sisson (2011), DECCW 2010, CSIRO & BOM, 2007). As floods in Australia are predominately caused by heavy rainfall, the risk of flooding is expected to increase with climate change. Floods are not solely influenced by rainfall intensities, other factors that affect flood behaviour include antecedent moisture conditions and level of water storages. A number of studies suggest that there is likely to be a decrease in antecedent moisture conditions due to changes in rainfall intermittency and evapotranspiration (Cleugh *et al.* 2011).

Climate change projections show that there is likely to be increases to the mean annual runoff in northern NSW, whilst there will be a decrease in southern NSW (DECCW 2010). A number of studies have attempted to detect changes in annual maximum flood data: an early study by Chiew & McMahon (1993) found no clear evidence of trends in streamflow volumes, however, since then several studies have detected changes in Australian flood data, including those by Franks & Kuczera (2002) and Ishak *et al.* (2010, 2013). It has been found that the trends found in annual maximum flood data cannot solely be attributed to changes in annual maximum rainfall (Cai & Cowan, 2008; Westra 2011), as the BOM (2010) have shown that the annual maximum rainfall to be approximately stationary at a daily time scale.

As shown previously, there has been much research into the effects of climate change on streamflow data; however, there is currently limited research on how changing antecedent moisture conditions could affect design flood estimates. Several studies, largely interested in the effect of climate indices on flood frequency, have found that floods are primarily affected by the variability in antecedent moisture conditions, as opposed to the extreme rainfall events alone. In one particular study by Chiew *et al.* (2008) it was found that the intensification of rainfall and increases in losses (i.e. the decline in antecedent moisture conditions) had an almost equal but opposite effect on the flood magnitudes.

In current climate conditions flooding poses a significant risk to society, in terms of the cost of damages and intangible effects (e.g. loss of life). Climate change has the potential to increase the risk of flooding, therefore it is crucial to investigate the full range of flood scenarios for flood risk analyses. In order to do so, it is first necessary to determine the potential impact of climate change on various inputs needed for hydrological modelling. This study therefore seeks to identify the causes of recent trends found in annual maximum flood series for 4 catchments in eastern NSW. In particular, we attempt to quantify trends in loss parameters, antecedent precipitation index (API), annual maximum flood series, annual runoff total, annual rainfall total, number of rainy days and inter-event duration and investigate the relationship between any potential trends.

2. STUDY AREA AND DATA

Several factors were considered when selecting the study catchments along the east coast of NSW; including, the catchment size, daily rain gauge density and long periods of concurrent hourly rainfall and streamflow data. It is also crucial that a catchment does not have any significant regulation or diversion and that the catchment is 'pristine', in that no major land-use changes have occurred throughout the period of the streamflow record. Based on the aforementioned criteria, a total of four catchments were selected from NSW: Orara River, Ourimbah Creek, Currambene Creek and Pambula River. The catchments ranged in size from 83 km^2 to 135 km^2 and an annual average rainfall varying from 903 mm to 1793 mm. The data period adopted for each catchment range from 18 years to 41 years, with both streamflow and hourly rainfall data available for the entire period. Table 1 shows some important characteristics for the study catchments.

Table 1. Important characteristics for the four study catchments along the eastern coast of NSW

	Orara River at Karangi	Ourimbah Ck Upstream Weir	Currambene Ck at Falls Ck	Pambula River at Lochiel
Station number	204025	211013	216004	220003
Catchment area (km^2)	135	83	95	105
Mean annual rainfall (mm)	1793	1230	1199	903
Adopted pluviograph	59026	61351 / 61029	68076 / 568086	69066
Adopted data period	1970 - 2009	1976 - 2010	1970 - 2011	1993 - 2011
# storm events selected	43	39	32	23

3. METHODOLOGY

3.1. Rainfall-runoff modelling

In order to investigate potential trends in the time series data, rainfall-runoff models need to be developed and calibrated for each catchment. The lumped conceptual rainfall-runoff model, namely RORB, is adopted as it is simple and has relatively few parameters. Three loss models were adopted; the initial loss-continuing loss (IL-CL) and initial loss-proportional loss (IL-PL) models due to their extensive use in the Australian water industry, and SWMOD as it has been found to be very effective in Western Australian catchments.

For the IL-CL model, the initial loss (IL) occurs prior to the commencement of surface runoff, whilst the continuing loss (CL) is the average rate of loss throughout the remainder of the storm. In the IL-CL model, the initial loss (IL) occurs prior to the start of surface runoff and the continuing loss (CL) is the average rate of loss throughout the remainder of the storm. Similarly in the IL-PL model, the IL is followed by a proportional loss (PL), which is the average proportion of loss for the remainder of the storm. Unlike the previous two models, SWMOD is a distributed storage capacity model, where the initial moisture (IM) is the saturation of the soil at the start of the event.

Storm events were selected based on rainfall bursts of 12 hour duration. The rainfall spatial pattern for each event was produced using ordinary kriging, with daily rainfall stations in and around the study catchment. The contribution of baseflow to each event was removed using a recursive digital filter with 9 passes and a filter factor of 0.925.

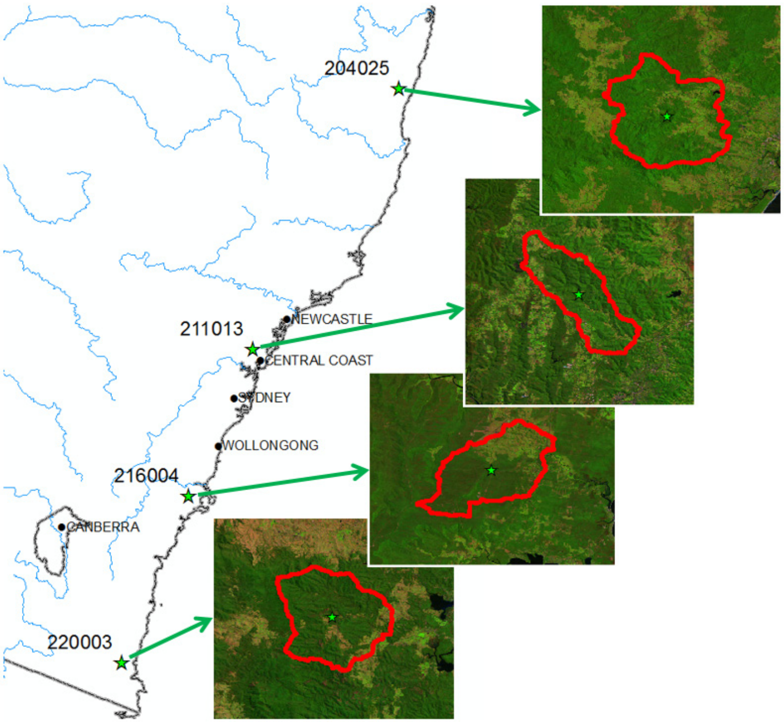

Figure 1. Location and detail of the four study catchments along the east coast of NSW

3.2. Rainfall-runoff inputs

Trends were investigated for the selected loss parameters of all three loss models, including the IL, IM, CL and PL. Any relationships between the trend in the losses and trends in other variables were also investigated; the variables that were chosen include the annual maximum discharge, annual runoff total, annual rainfall total, number of rainy days, inter-event duration (IED) and antecedent precipitation index for 28 days prior to the start of the event (API 28d).

3.3. Tests for detecting trend and step-changes

Numerous approaches can be used to detect trend. Parametric tests, such as linear regression, assume an underlying distribution and also make an assumption that the data are independent of one another. Alternatively, non-parametric tests make fewer assumptions; however they still rely on the assumption of independence. Different tests detect different types of trends, the two most common types being: tests for trend and tests for a step-change in the mean. In this study, four tests were adopted, namely the Mann-Kendall (MK), linear regression (LR), CUSUM and cumulative deviation (CD) tests. The non-parametric MK test is rank-based test that determines whether there is a trend in the data. LR is a common test for trend and assumes that the data is normally distributed. The distribution-free CUSUM test is a rank-based test that determines whether there is a step-change in the data. Lastly, the CD assumes data is normally distributed and determines whether the mean in two parts of the data are significantly different.

Table 2. Trend results for the selected catchments for all ten variables

Catchment	Trend Test	IL	IM	CL	PL	API (28d)	Flow Max	Flow Total	Rain Total	Rain Days	IED
Orara River	MK	3.202	-1.706	0.217	-1.051	-2.355	-1.138	-0.209	-0.992	-0.921	-0.728
		1%	10%	NS	NS	5%	NS	NS	NS	NS	NS
	LR	3.888	-1.698	-0.347	-0.603	-2.100	-1.143	-0.212	-1.162	-1.357	0.233
		1%	10%	NS	NS	5%	NS	NS	NS	NS	NS
	CU-SUM	15	5	4	4	6	4	6	7	7	5
		1%	NS	NS	NS	NS	NS	NS	NS	NS	NS
	CD	2.150	0.991	0.660	0.909	1.024	0.874	0.731	0.995	1.139	0.509
		1%	NS	NS	NS	NS	NS	NS	NS	10%	NS
Ourimbah Creek	MK	-1.548	1.645	0.697	-0.728	0.798	-1.138	-2.073	-0.442	0.085	2.055
		NS	10%	NS	NS	NS	10%	5%	NS	NS	5%
	LR	-0.937	0.750	0.105	-0.822	0.418	-1.272	-2.058	-0.184	0.144	1.889
		NS	NS	NS	NS	NS	NS	5%	NS	NS	10%
	CU-SUM	5	6	5	5	7	6	6	8	5	7
		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	CD	0.614	0.568	0.412	0.676	0.709	1.154	1.482	0.745	0.786	1.397
		NS	NS	NS	[illegible]	NS	10%	1%	NS	NS	5%
Currambene Creek	MK	2.270	-2.173	1.782	-2.082	-2.043	-1.138	-3.181	-0.442	1.087	1.288
		5%	5%	10%	5%	5%	1%	1%	NS	NS	NS
	LR	2.545	-2.646	1.455	-2.371	-1.602	-3.535	-3.527	-0.184	0.940	1.378
		5%	5%	NS	5%	NS	1%	1%	NS	NS	NS
	CU-SUM	8	6	9	7	5	9	10	8	9	8
		5%	NS	1%	10%	NS	5%	5%	NS	10%	NS
	CD	1.304	1.267	0.959	1.652	1.225	1.516	1.824	0.745	1.300	1.146
		5%	5%	NS	1%	10%	1%	1%	NS	5%	10%
Pambula River	MK	-1.400	2.007	0.038	-0.227	1.162	-1.138	-1.516	-0.442	-1.664	-0.667
		NS	5%	NS	NS	NS	NS	NS	NS	10%	NS
	LR	-0.229	0.593	-0.011	-0.314	1.559	-1.101	-1.926	-0.184	-1.723	-0.374
		NS	NS	NS	NS	NS	NS	10%	NS	10%	NS
	CU-SUM	4	9	2	4	4	10	6	8	11	6
		NS	1%	NS	NS	NS	5%	NS	NS	10%	NS
	CD	0.533	0.613	0.702	0.868	0.897	1.096	1.365	0.745	1.668	0.885
		NS	NS	NS	NS	NS	NS	5%	NS	1%	NS

4. RESULTS AND DISCUSSION

The trend analysis results are summarised in Table 2; this table presents the test statistic and significance level for each trend test (where NS indicates not significant). Fairly strong evidence of an increasing change in the IL data were found for two of the four catchments (Orara and Currambene), which was also reflected by evidence of a gradual downward trend in the IM data for the same catchments. The IL and IM should theoretically reflect the antecedent conditions; this can be seen by a gradual downward trend in the API data for the Orara River catchment and possible evidence of a change for the Currambene Creek catchment. There was also weak evidence of a step-change in the number of rainy days for these two catchments. Currambene Creek also shows strong evidence of change in the max and total flow series, which may be the cause of changes in the loss data, as this catchment is the only catchment to detect any trends in the CL and PL data.

A visual analysis was conducted for the IL, IM and API data given the strong evidence of change from the tests for change. The time series plots for each data series and each catchment are shown in figures 2, 3 and 4. Similar to the test results, the Orara River and Currambene Creek catchments were found to have a strong positive linear trend in the IL data (see Figures 2a & 2c), a strong negative trend in the IM data (see Figures 3a & 3c) and correspondingly a strong negative trend in the API data (see Figures 4a & 4c). The other two catchments (Ourimbah Creek and Pambula River) were found to have a slight positive linear trend in the IM data (see Figures 3b & 3d). Pambula River is seen to have a strong positive linear trend in the API data (see Figure 4d), however, as there are three outliers and due to the short time series, this may not be representative.

It should be noted that Currambene Creek has a lack of suitable events in the 10 year period from 1983 to 1993. Events that were found to be suitable during this period either had missing data or had little to no streamflow. Another note is that Pambula River has a relatively short time series, this could mean that trend results for this catchment may be different than if a longer record had been available. The data for this catchment does not begin until 1993, whilst records for the three remaining catchments began in the early- to mid-1970's.

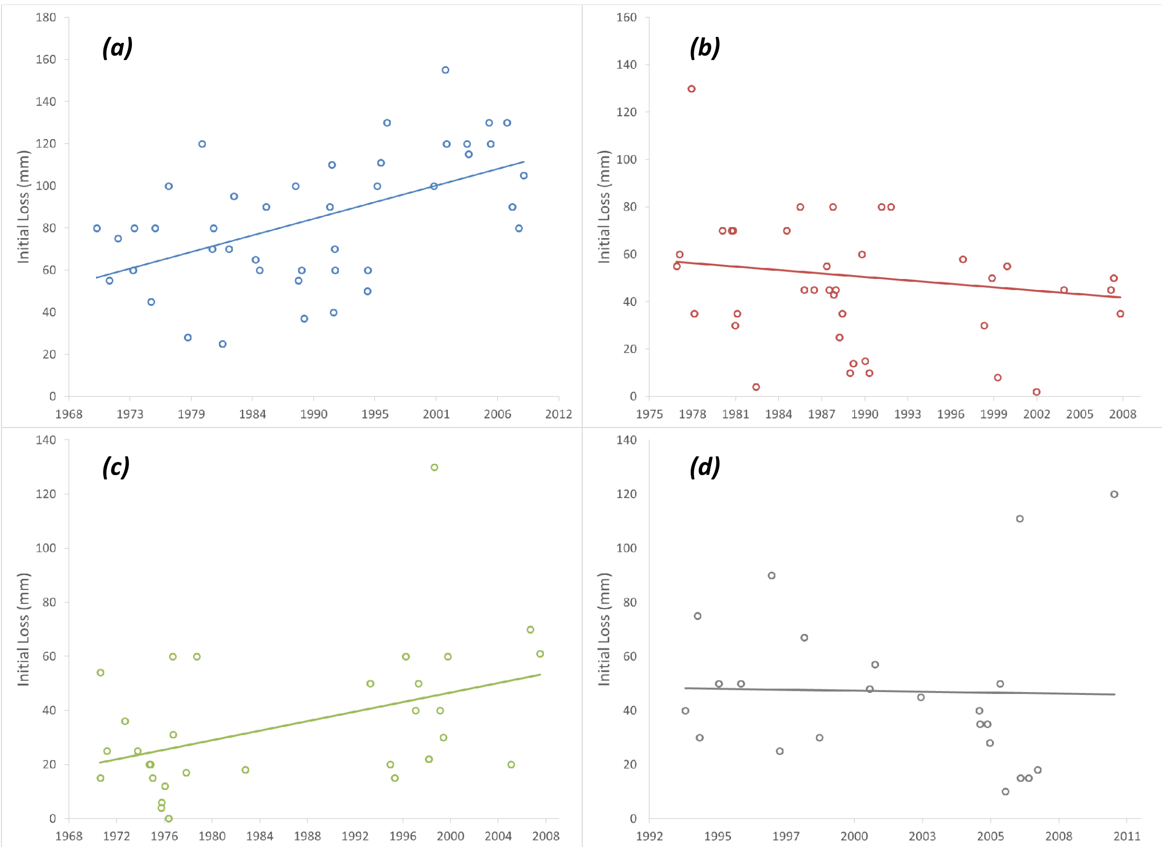

Figure 2. Linear trend for the initial loss data for the (a) Orara River, (b) Ourimbah Creek, (c) Currambene Creek and (d) Pambula River

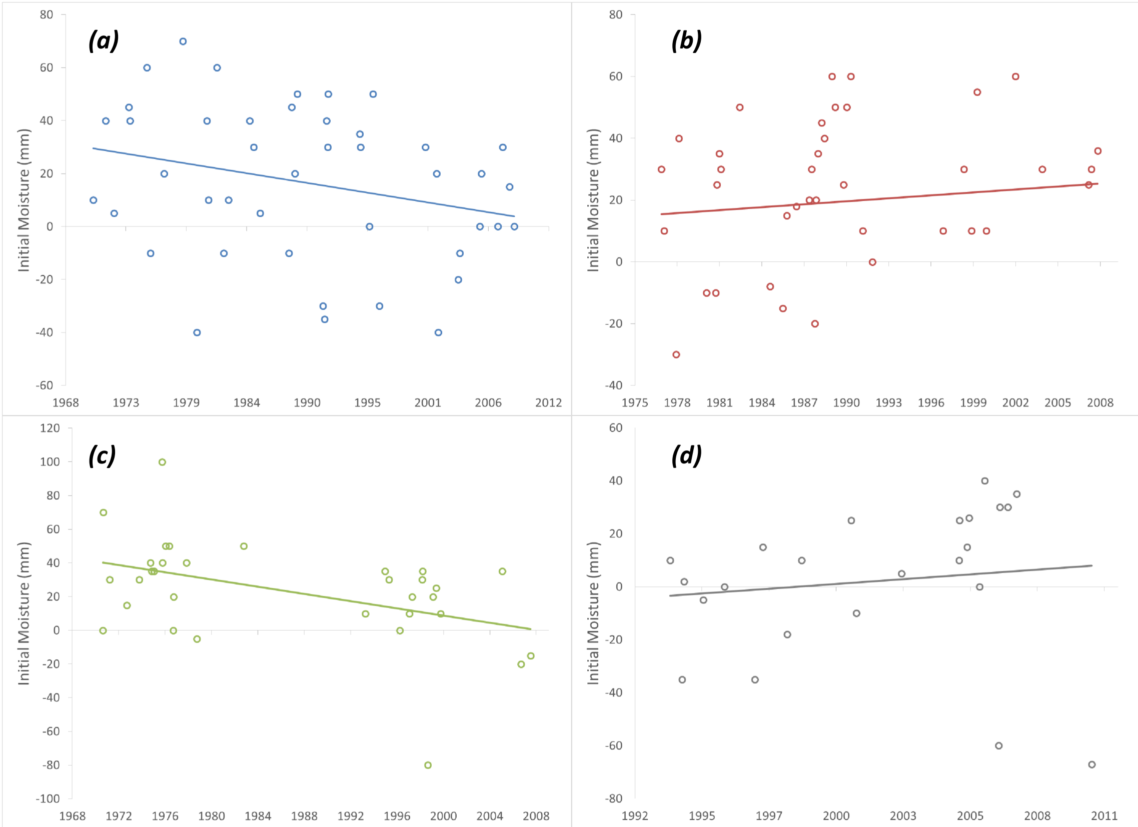

Figure 3. Linear trend for the initial moisture (SWMOD) data for the (a) Orara River, (b) Ourimbah Creek, (c) Currambene Creek and (d) Pambula River

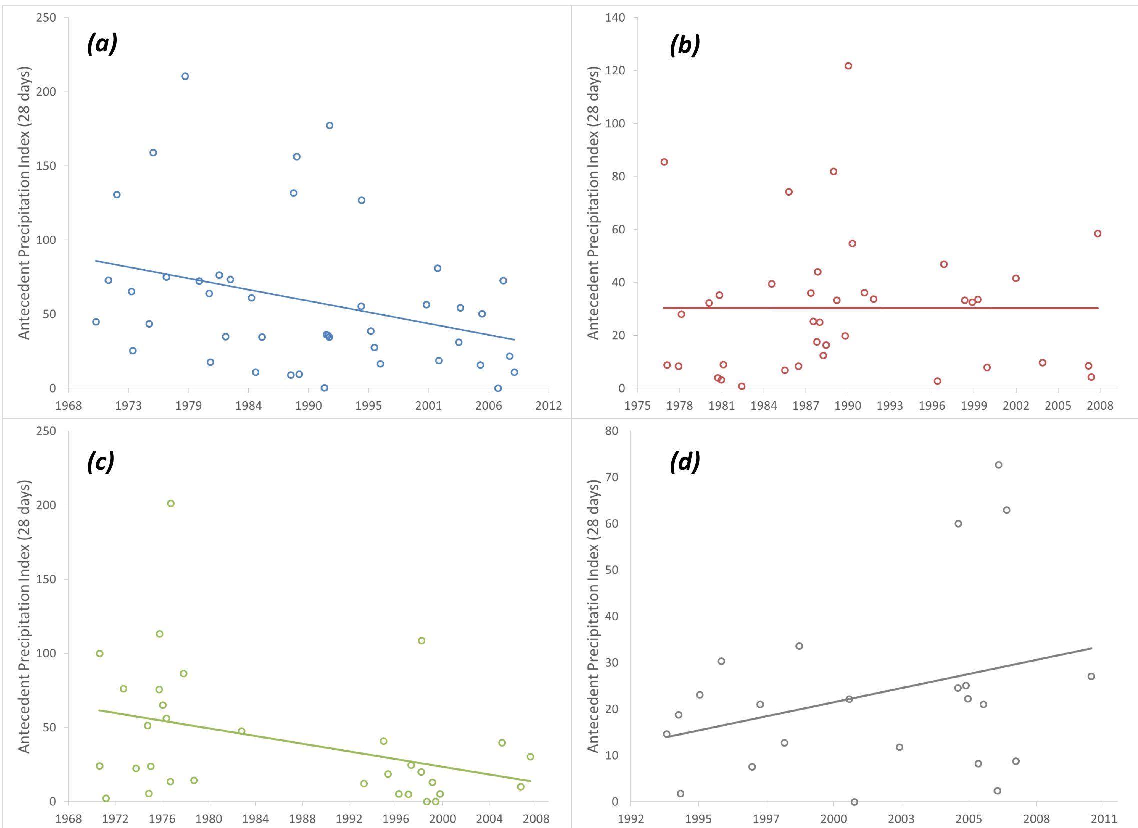

Figure 4. Linear trend for the antecedent precipitaion index (API, 28 days) data for the (a) Orara River, (b) Ourimbah Creek, (c) Currambene Creek and (d) Pambula River

5. CONCLUSIONS

Climate change is likely to impact on the magnitude and frequency of extreme flow events. A number of studies have demonstrated trends and variability in annual maximum floods across Australia. However, changes to design losses (as a surrogate for soil moisture conditions) have seen little research. This study therefore investigated trends in loss parameters and explored the relationships between these trends and trends in the annual maximum flood series, API, annual runoff totals, annual rainfall totals, number of rainy days and IED.

Results from the tests of change and visual analyses show that for two of the four catchments there was strong evidence of an upward trend in the IL data, strong evidence of a downward trend in the IM data and strong evidence of a downward trend in the API (28 days). The changes in initial conditions for rainfall-runoff modelling (IL and IM) correspond well to the trends in the API, as a surrogate for the antecedent moisture content. Only one of the catchments saw a change in the continuing losses (CL and PL); however, this was also the only catchment that showed evidence of trends in the annual maximum flood series.

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