Rainfall trend analysis of Sydney's drinking water catchments

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Abstract

The Warragamba catchment, which supplies about 80% of Greater Sydney's drinking water, reached an all time low of 32.4% in February 2007. Questions were raised about the adequacy of the water infrastructure to meet the water needs of Sydney and whether the reduction in storage was a result of decreasing rainfall trend in the region. This paper attempts to answer these questions by investigating the long-term rainfall pattern in the Warragamba catchment area and investigates the seasonal and annual changes in rainfall patterns. Statistical analysis of available rainfall data indicates a trend of decreasing rainfall of 2.52*mm*/*year* between the period of 1945 and 1998 whereas between 1890 and 2003, a linear increasing trend of 0.32*mm*/*year* was observed. Three substantial drought periods have occurred over the study period. These periods were identified as 1901-1910, 1939-1948 and 2000-2006. Out of these, the 1901-1910 drought was the most severe one, followed by the 1939-1948 drought. The most recent drought (2000-2006) was the least severe among the three recorded. However, it is the only drought of significant duration that has occurred since the completion of construction of Warragamba Dam in 1960.

Keywords: Warragamba, rainfall trend, breakpoint analysis.

1 Introduction

Sydney's water supply system relies heavily on storages provided by a network of dams. Warragamba dam, located in the western region of Sydney is the largest of these dams and supplies about 80% of Sydney's water requirements [1].

In recent years, the lack of rainfall in the Warragamba catchment has raised concerns about adequacy of water infrastructure in Greater Sydney. While the

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water crisis has been a result of multiple factors (e.g., strong population growth rate of 1.2% per annum [2], high per capita water demand [3, 4], environmental flow requirements [5]), a dry spell that began in 2000 which continued until 2007 is one of the major causes. The dry spell combined with other factors earlier mentioned resulted in the storage level to drop to a record low of 32.4% in February 2007 (Fig. 1). The result was the implementation of various levels of water restrictions in addition to the development of a metro water plan by the state government.

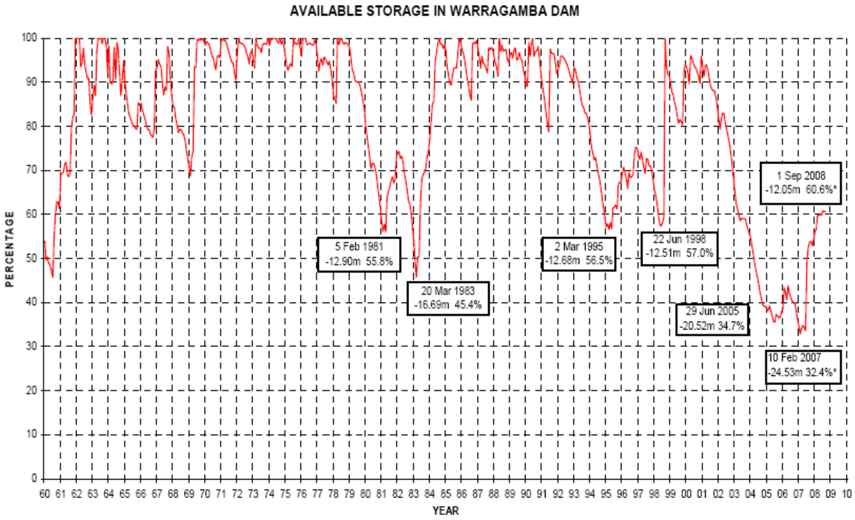

Figure 1: History of available storage, Warragamba Dam (source: *SCA* [1]).

The adverse impacts of inadequate water supply need not be overstressed [6, 7]. Adequate water supply requires an accurate estimation of water availability. As the main sources of water supply for Sydney are surface storages in dams which depend upon rainfall, it is of utmost importance that a thorough understanding of rainfall pattern is known. Such an understanding will assist planners to reliably predict future rainfall trends and what current water infrastructure can yield in future. This paper is based on a study carried out as a result of this recognition. The principal objective is to evaluate long-term rainfall trends in the Warragamba catchment area. This is achieved through statistical analysis of long-term rainfall data in the Warragamba catchment area. Analyses were performed (a) to determine whether annual and seasonal rainfall has increased or decreased over the analysis period, (b) to identify and compare drought periods that have occurred over the catchment area, and (c) to identify whether a breakpoint occurs in the trend of annual rainfall.

2 Study area

The Warragamba catchment area is located inland to the west of the Sydney. The catchment covers an area of 9050km^2 and encompasses the townships of

Lithgow, Katoomba, Goulburn and Bowral [1]. Fig. 2 shows the location of the Warragamba catchment area as well other drinking water catchments in the Greater Sydney region. The catchment consists of a series of sub-catchments, namely Mulwaree River, Upper Wollondilly, Wollondilly River, Warragamba River, Nattai River, Kowmung River, Wingecarribee River, Little River, Werriberri Creek, Upper Cox River, Mid Cox's River and Lower Cox's River [8]. The dam across the Warragamba River forms Lake Burragorang.

3 Data collection

A total of 24 gauging stations (Table 1) were selected for this study from among the 295 gauging stations identified within or in close proximity of the study area. The stations were selected based on length of data availability, data quality and spatial locations.

It is interesting to note that the density of gauging stations varies throughout the catchment. The Blue Mountains and the Wollondilly regions have relatively denser raingauge network whereas the number of gauging stations around Lake Burragorang is relatively sparse. Area weighting was used to minimise the effect of raingauge density variation.

In addition to density variation, length of observation and data quality also vary between stations. While complete records of rainfall data were available for some gauging stations, records for some gauging stations were missing. Missing records were filled in using the inverse distance method [9, 10]. It is also noted that Picton (68052) has the longest record (1880 – 2008) and Big Hill (70119) has the shortest record (1944 – 2004). Completeness of record was relatively high with the exceptions of Wombeyan Caves (63093) (79% complete), Chatsbury (70020) (81% complete) and Mittagong (68044) (86% complete). Blackheath (63009) and Bundanoon (68008) were identified as the two stations with the highest levels (4%) of suspect data.

4 Rainfall analysis

Annual and seasonal rainfall trend analyses were performed using the data from the 24 gauging stations. In addition, drought analysis was performed using five of the 24 gauging stations. This was followed by breakpoint analysis, utilising the cumulative deviations tests.

4.1 Annual trend analysis

The record length was divided into two different series lengths. The medium term record covered the period between 1945 and 1998 and included all 24 gauging stations. The long-term record covered the period between 1890 and 2003 and included 17 selected gauging stations (selection was based on availability of data of desired length). Descriptive statistics of annual rainfall for medium term and long term periods are presented in Table 2.

Figure 2: Warragamba Catchment Area (source: *SCA* [1]).

It is apparent that medium-term statistics are significantly higher than the long-term statistics. This may be due to higher rainfall values during the latter part of the 19th century (Fig. 3). It is also interesting to note that the long-term trend shows an increase in rainfall trend at 0.32*mm*/*year* (Fig. 3) whereas the

Table 1: Gauging Stations.

Station No.	**Station Name**	**Data Period**	**Station No.**	**Station Name**	**Data Period**
63009	Blackheath (Lawrence St)	1898-2008	68062	High Range (Wanganderry)	1945-2008
63033	Gurnang State Forest	1890-2003	70002	Bannaby (Hillasmount)	1890-2003
63036	Jenolan Caves	1890-2003	70020	Chatsbury (Maryland)	1890-2004
63039	Katoomba (NarrowNeck Rd)	1890-2003	70036	Lake Bathurst (Somerton)	1931-2008
63062	Newnes Forest Centre	1938-1999	70055	Goulburn (Kippilaw Stn)	1886-2008
63079	Sunny Corner (Snow Line)	1890-2003	70063	Marulan (George St)	1890-2003
63093	Wombeyan Caves	1942-2008	70080	Taralga Post Office	1882-2008
63095	Yerranderie (Private Town)	1890-2003	70088	Yarra (Rowe's Lagoon)	1890-2003
63224	Lithgow (Birdwood St)	1890-2003	70105	Mount Fairy (Merigan)	1890-2003
68008	Bundanoon Bowling Club	1902-2007	70119	Big Hill (Glen Dusk)	1944-2004
68044	Mittagong (Beatrice Street)	1886-2008	70131	Woodhouselee (Leeston)	1890-2003
68052	Picton Council Depot	1880-2008	568045	Warragamba Met. Stn	1890-2003

Table 2: Descriptive statistics – annual rainfall (area weighted).

	1945-1998	***1890-2003***
Mean	921.0	815.5
Median	916.2	787.9
Standard Deviation	241.4	203.0
Lower Quartile	781.2	672.4
Upper Quartile	1039.3	929.6

medium-term trend shows a decrease in rainfall trend at 2.52*mm*/*year* (Fig. 4). Both these trends were found not to be statistically significant at 95% confidence level using Kendall-Tau rank correlation test (Table 3).

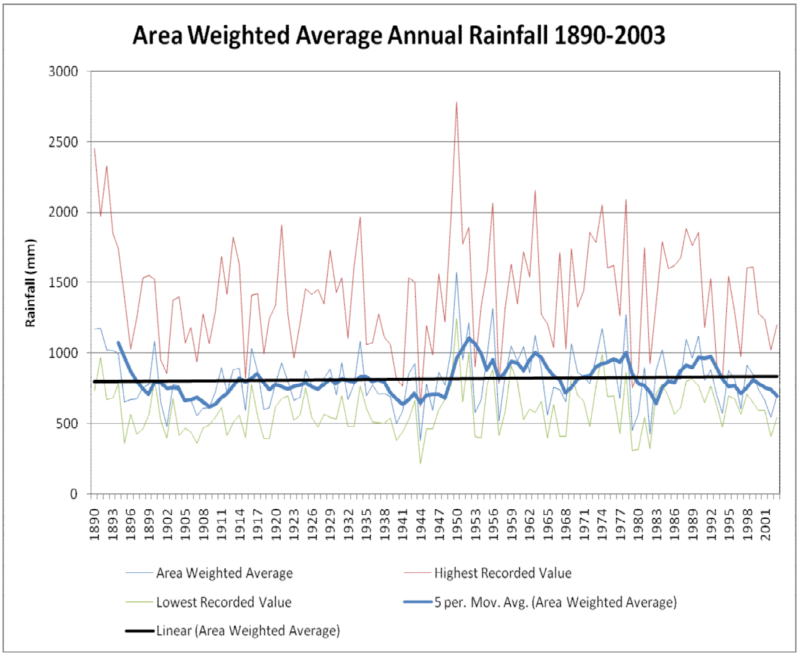

Figure 3: Long-term area weighted average annual rainfall.

Figures 3 and 4 show occurrence of high rainfall in 1890, followed by a dry spell between 1901 and 1910. The figures also show occurrence of second dry spell between 1939 and 1948, followed by above average rainfall for a number of years. This includes 1950 which has the highest area weighted average of any period at 1662.5*mm* of rainfall. From the 1950's to 1985 the data shows a high degree of variability, annual rainfall remaining generally above the mean although two troughs occur in 1968 and 1983. Between 1985 and 1992 is another period of above average annual rainfall. Rainfall starts to taper off from this point onwards followed by the drought between 2000 and 2006.

4.2 Seasonal trend analysis

The medium-term and long-term rainfall were divided into four seasons – autumn, winter, spring and summer – and the resulting data were analysed for trends. Mean, median and standard deviations for different seasons are presented in Table 4. Similar to the annual trend, the medium-term statistics are significantly higher than the long-term statistics for each season.

The autumn rainfall shows a mix of both increasing and decreasing rainfall trends. The decreasing trends occur mostly at stations with shorter data lengths. The result of long-term analysis shows a trend of increasing rainfall at 0.1*mm/year* whereas the medium-term analysis shows a trend of decreasing rainfall of 0.1mm/year. Both these trends were found to be statistically insignificant. Hence, it was concluded that no trend exists in both the long and

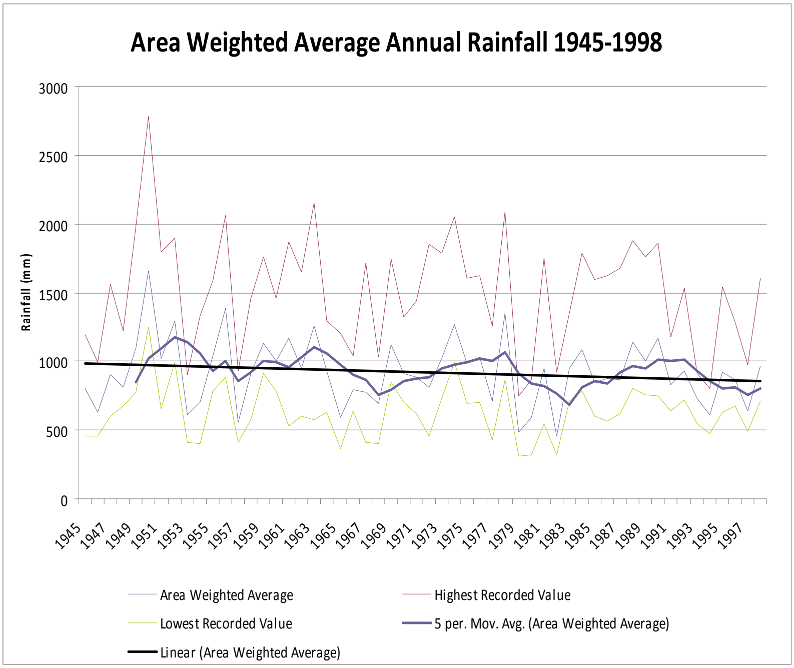

Figure 4: Medium-term area weighted average annual rainfall

the medium term data. Similarly, an analysis of summer rainfall shows no specific trend.

The winter rainfall data shows a decreasing trend in rainfall. Analysis of medium term data shows a decreasing trend at 0.99*mm/year* whereas the long-term data shows rainfall decreasing at 0.5*mm/year*. The long-term trend was found to be statistically significant at the 95% confidence level while the 1945-1998 study was found not to be statistically significant at 95% confidence level.

Analysis of spring rainfall shows a trend of increasing rainfall. The long-term area weighted average shows a trend of increasing rainfall at 0.35*mm/year*. The medium term data shows a trend of decreasing rainfall at 0.05*mm/year*. Both the long and the short-term rainfall trends were found not to be statistically significant at 95% confidence level.

4.3 Drought analysis

Five rain gauge stations (located at Blackheath, Goulburn, Mittagong, Picton and Taralga) spread across the catchment and covering the period between 1898 and 2007 were selected for drought analysis. Five year moving averages were computed and are shown in Fig. 5. The plot shows three significant drought periods - (a) 1901-1910, (b) 1939-1948 and (c) 2000-2006. Of these three periods, the drought of 1901 to 1910 is the severest one. The drought has the lowest recorded five-year running mean value of 621.2*mm*. The drought lasts for

Table 3: Trend analysis – annual rainfall.

Name	**Period**	**Trend (*mm/yr*)**	**Kendall's Tau**	**Significant at 95% Confidence Level**
Sunny Corner	1890-2003	0.57	0.079	No
Newnes Forest	1939-1998	1.64	0.086	No
Lithgow	1890-2003	0.38	0.056	No
Katoomba	1890-2003	-0.22	0.011	No
Blackheath	1898-2007	0.86	0.07	No
Jenolan Caves	1890-2003	0.95	0.098	No
Warragamba	1890-2003	1.80	0.141	Yes
Gurnang	1890-2003	-0.03	0.026	No
Yerranderie	1890-2003	0.27	0.022	No
Picton	1880-2007	0.77	0.072	No
Wombeyan Caves	1943-2007	-2.76	-0.138	No
High Range	1945-2007	-4.31	-0.192	Yes
Mittagong	1886-2007	-0.60	-0.052	No
Taralga	1883-2007	0.82	0.126	Yes
Bannaby	1890-2003	-0.09	0.022	No
Woodhouselee	1890-2003	0.25	0.037	No
Chatsbury	1891-2003	-0.29	-0.024	No
Big Hill	1945-2004	-3.90	-0.199	Yes
Bundanoon	1902-2003	1.16	0.069	No
Marulan	1890-2003	0.46	0.032	No
Yarra	1886-2007	1.09	0.146	Yes
Rowe's Lagoon	1890-2003	1.18	0.148	Yes
Lake Bathurst	1932-2007	-0.15	0.017	No
Mt Fairy	1890-2003	0.78	0.098	No

ten years in length making it the equal longest recorded drought period. The severity of the drought is most evident in the five year running means for the years 1905 to 1910. It is interesting to note that six of the ten lowest recorded five year running means occur consecutively during this period.

The drought of 1939-1948 is the second most severe drought of the three. This drought also lasted for ten years. The drought reaches its five-year running mean trough in 1944. This year also recorded the lowest average annual rainfall at 412.2*mm*. The drought has three of the ten lowest recorded five-year running means. It is also noted that this drought period does have some relief mid period with high rainfall occurring in 1943.

Table 4: Descriptive statistics – area weighted rainfall.

Term	Descriptive Statistics	Autumn	Winter	Spring	Summer
Medium-Term (1945 – 1998)	Mean	231.0	203.7	214.3	272.2
	Median	199.3	184.9	213.3	268.5
	Std. Dev.	118.4	104.6	76.6	111.6
Long-Term (1890 – 2003)	Mean	206.2	190.5	187.3	231.0
	Median	177.3	174.9	175.8	222.3
	Std. Dev.	106.9	91.3	75.0	104.1

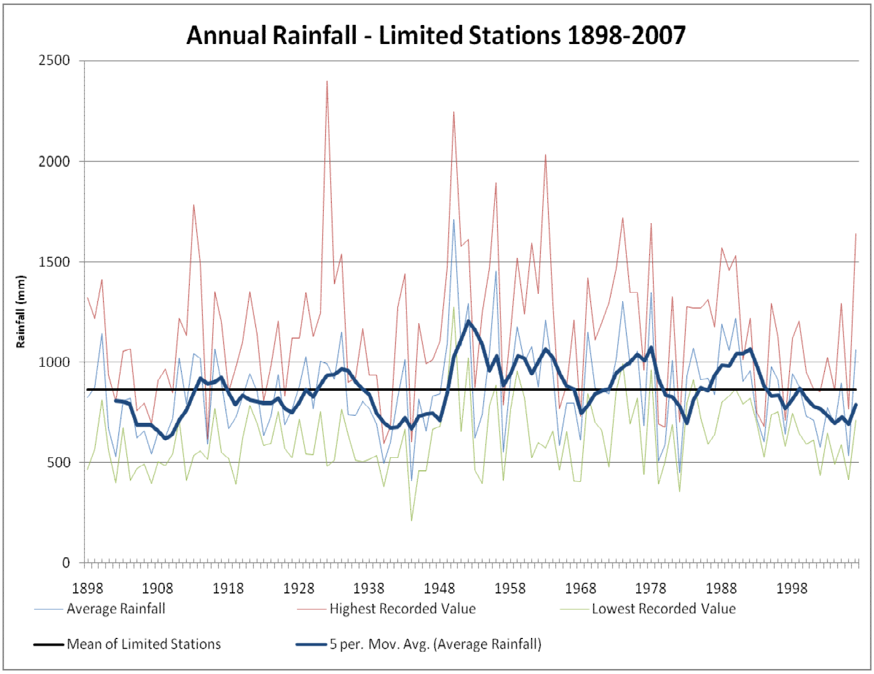

Figure 5: Annual rainfall – drought analysis.

Of the three droughts, the drought of 2000-2006 is the mildest. The drought lasts for 7 years, reaching the lowest point in 2006. The drought's severity is largely influenced by low rainfall in 2002 and 2006 which are within the ten lowest average annual rainfalls recorded.

4.4 Breakpoint analysis

Breakpoint shows an abrupt change within a set of data and aids in identifying changes in rainfall pattern from natural fluctuations. This study uses the cumulative deviations test [11] to identify breakpoint in the rainfall data set. Results of the test for all stations are shown in Fig. 6.

Fig. 6 indicates three breakpoints in the data. From the beginning of the data to 1894, the annual rainfall data shows a positive cumulative deviation. This is indicative of above mean rainfall occurring during this time. In 1894 the first breakpoint occurs in the data series. At this time the cumulative deviation changes from a positive trend to a negative trend. The negative trend continues until the occurrence of the second breakpoint sometime between 1946 and 1948. During this period, annual rainfall is generally below the mean. It is also noted that at the second breakpoint there is a change from negative cumulative deviation to positive deviation. This indicates a change from below average to above average rainfall. The last breakpoint is less clear from available data. While some gauging stations show a breakpoint occurring in 1978, others show a change occurring in 1992. From the third breakpoint to 2007 there has been a negative cumulative deviation.

5 Results and discussions

Annual rainfall trend analysis shows a marginal trend of increasing annual rainfall over the long term, while in the medium term a trend of decreasing rainfall is observed. This study confirmed the results of the previous studies [12–14] that show annual rainfall trend decreasing as longer data lengths become available.

The difference between long term and medium term mean and median values is largely the result of high rainfall periods from the 1950's to the 1980's. Preceding this period, a lengthy period of lower rainfall was observed. More recently the rainfall has resembled previously experienced (before the 1950's). It is therefore appropriate that a long-term data set be used to generate a mean or median value for the purpose of estimating future inflows. Any data set which limits data to a medium term period (1950>) is likely to bias the result.

No distinctive pattern was observed in autumn or summer rainfall. The results of winter rainfall pattern indicate decreasing rainfall over time whereas the spring rainfall pattern shows mixed results.

The results of the drought analysis show a historical trend of droughts occurring over the catchment area. The most recent drought (2000 to 2006) is the least severe of the droughts recorded since 1898. The drought periods and the subsequent high rainfall periods that follow are the likely result of changes from El-Nino to La-Nina conditions. However the relationship between rainfall, El-Nino and La-Nina events is more complex than a direct correlation and needs further study before a correlation can be drawn.

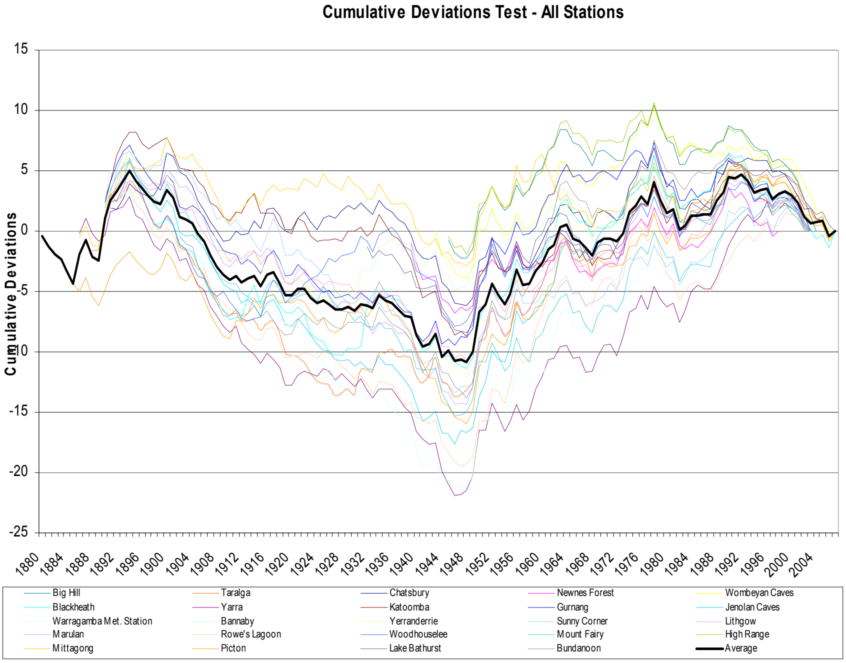

Figure 6: Cumulative deviations – all stations.

The breakpoint analysis shows a trend of changes to mean rainfall occurring over time. This has important implications as it indicates that mean rainfall changes over time. Therefore previous rainfall may not be a good indicator of mean rainfall in the future. Under the assumption that the last breakpoint occurred in 1992, the time between breakpoints is approximately 50 years; indicating 50 year cycles of wet and dry periods.

These changes in rainfall and associated flood patterns have been noted by Warner, Riley and others, and identified as flood- and drought-dominated regimes [15, 16].

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