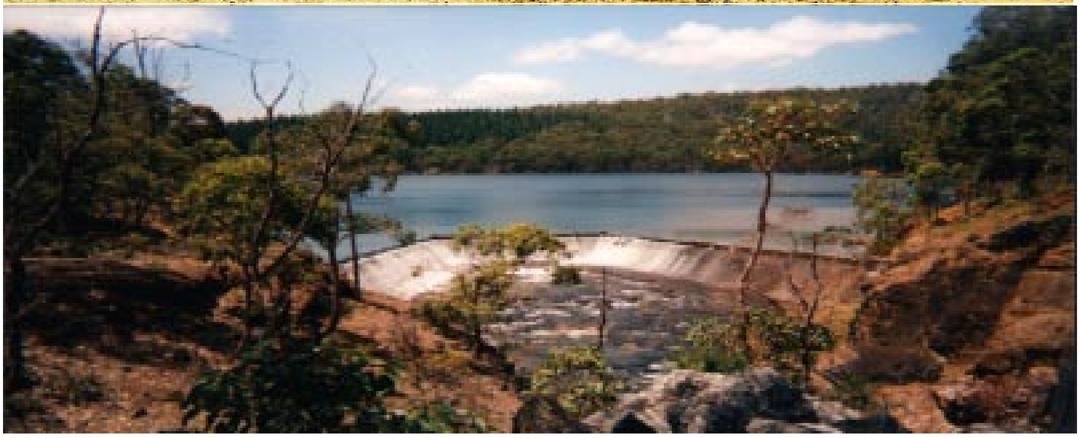
THE EFFECT OF CLIMATE VARIABILITY ON STREAMFLOW IN SOUTH WESTERN AUSTRALIA



SURFACE WATER HYDROLOGY SERIES

UNPUBLISHED REPORT

SWH 25 1999

WATER AND RIVERS
COMMISSION

WATER AND RIVERS COMMISSION
HYATT CENTRE
3 PLAIN STREET
EAST PERTH
WESTERN AUSTRALIA 6004
TELEPHONE (09) 278 0300
FACSIMILE (09) 278 0301

Yenyenning Lakes Outflow channel (top)
Stirling Dam (bottom)

The Effect of Climate Variability on Streamflow in the South-west of Western Australia

S.J. Rodgers & J.K. Ruprecht
Surface Water Hydrology
Resource Investigation Division
Water and Rivers Commission

WATER AND RIVERS COMMISSION
SURFACE WATER HYDROLOGY REPORT SERIES
REPORT NO SWH 25

Contents

SUMMARY v

1. INTRODUCTION **9**

1.1 GENERAL 9
1.2 SOUTH WEST 9
1.2.1 Catchment and Data Description *9*
1.2.2 Vegetation *9*
1.2.3 Climate *10*

2. METHOD OF ANALYSIS **13**

2.1 AUTOCORRELATION FUNCTION 13
2.2 STATISTICAL TREND TESTS 13
2.2.1 Distribution -free CUSUM Test *13*
2.2.2 Brillinger Trend Test *14*

3. TRENDS IN ANNUAL STREAMFLOW **15**

3.1 GAUGED DATA 15
3.1.1 Annual Streamflow *15*
3.1.2 Sample Autocorrelation *18*
3.1.3 Loess and Alternative Smoothers *20*
3.1.4 Trend Tests *22*
3.2 MODELLED DATA 23
3.2.1 Annual Variation *24*
3.2.2 Sample Autocorrelation *24*
3.2.3 Loess and Alternative Smoothers *25*
3.2.4 Trend Tests *26*

4. TRENDS IN FLOW DURATION **28**

4.1 FLOW DURATION 28
4.2 MONTHLY STREAMFLOW 29

5. TRENDS IN FLOODFLOWS **32**

5.1 GAUGED DATA 32
5.1.1 Annual floodflow *32*
5.1.2 Loess Regression *34*
5.1.3 Design Floodflows *34*
5.1.4 Trend Analysis *35*
5.2 MODELLED DATA 36
5.2.1 Annual Floodflows *36*
5.2.2 Loess and Alternative Smoothers *37*
5.2.3 Design Floodflows *37*
5.2.4 Trend Analysis *38*

6. RELATIONSHIP OF STREAMFLOW WITH CLIMATE **39**

6.1 STREAMFLOW AND RAINFALL IN THE SOUTH-WEST 39
6.2 STREAMFLOW AND THE SOUTHERN OSCILLATION INDEX (SOI) 39

7. CONCLUDING DISCUSSION 41
7.1 CLIMATE VARIABILITY 41
7.2 IMPLICATIONS FOR WATER RESOURCE MANAGEMENT 41
7.3 IMPLICATIONS FOR FLOOD MANAGEMENT 41
7.4 SOI RELATIONSHIP 41
7.5 FURTHER INVESTIGATIONS 42
8. REFERENCES 43

Appendices

APPENDIX A: ANNUAL AND SEASONAL VARIATION IN STREAMFLOW 44
APPENDIX B: DECADAL VARIATION IN STREAMFLOW 56
APPENDIX C: SAMPLE AUTOCORRELATION 58
APPENDIX D: LOESS AND ALTERNATIVE SMOOTHING 65
APPENDIX E: STATISTICAL TESTS 73

Summary

Climate variability is a major concern for water resource managers in Western Australia, given the run of below average rainfall and consequently streamflow which has been observed over the last twenty years.

This report has undertaken rigorous statistical analysis applied to quantify the trends in streamflow for the south west for Western Australia.

Of the 33 rivers analysed: 15 had statistically significant trends of decreasing streamflow and 3 had a statistically significant trends of increasing streamflow. Those rivers with an increase in streamflow all had major areas of clearing within their catchments.

To obtain long term streamflow records for the water supply dams for the Perth metropolitan area a Sacramento model incorporating rainfall, evaporation, soil type parameters was used. The modelled monthly inflows were converted to annual values which were then used to test for a trend or a change in mean. The total mean annual inflows to the metropolitan sources since 1974 is just under 200 GL while the mean for the period of 1950 - 1994 was in excess of 280 GL, a 30 % reduction in the mean annual inflows. The combined mean annual inflow for the entire period from 1912 to 1994 is greater than 315 GL. The mean combined annual inflow between 1974 and 1994 is in excess of 37 % less than the long term mean (1912-1994). There has been an extended period of below average annual inflows to the metropolitan reservoirs about since 1974.

The reduction in streamflow observed at the gauging stations since 1976 in the high rainfall areas (mean annual rainfall >1,100 mm) has resulted in a significant change in the flow duration of the streams. The flow duration, in the streams of the high rainfall areas flow, at various flow rates has typically decreased by between 10 and 25 %. This is most evident by the 25 % reduction in the period of time during which the Yarragil Brook streamflow gauging station has recorded flow since 1975 compared to prior to 1975 (Figure 4.1).

The gauged streams draining catchments with lower mean annual rainfalls do not exhibit a similar response in flow duration since 1976 as observed in the higher rainfall areas. Flow duration at various flow rates has changed only slightly since 1975 at high and medium flows, while the duration of the very low flows (<1 m^3/s) has typically increased. This is evident at the Thomson Brook gauging station where an approximate 10% increase in flow duration is observed at these very low flow rates. The relatively high degree of clearing which is commonplace in the lower mean annual rainfall catchments, including Thomson Brook, may be altering the hydrologic characteristics of the catchments. The high degree of clearing may also indirectly alter the flow in streams due to the construction of small farm dams and embankments, to irrigate crops and provide a drinking supply for stock. A number of the larger catchments in these lower rainfall, largely cleared catchments exhibit very little change in the flow duration between the period prior to 1976 and since this date. The catchments which receive the least rainfall of those studied, Williams and Murray Rivers in Basin 614, both show that a decrease in the flow duration has taken place since 1976. This may imply that the increase in runoff resulting from a high degree of catchment clearing may be more than negated by the impact on runoff resulting from a decrease in annual rainfall.

The floodflow analysis emphasised the importance of incorporating long term datasets of flood analysis. The Avon and Blackwood Rivers given completely different results. For the Avon River there were reducing values for the 1-in-100 year Average Recurrence Interval value with reduced period of record for analysis. Conversely the Blackwood river should the opposite result with an increasing estimate for the 1-in-100 ARI floodflow with reduced period of record.

The lack of major floods in the areas from the Murray to Avon Rivers in the south west of Western Australia has significant environmental and social impacts. The environmental impacts are that there is substantial quantities of river sediment which in a major flood could be mobilised and impact on river pools along the Avon River and into a the Swan estuary. The social impacts are that the communities along the rivers, particularly the Swan, Avon, and Murray Rivers have not experienced flooding for many years, at least since 1964. The decline in the level of preparation of a community for flooding with duration after flooding is substantial. The percentage of a community prepared for flooding deteriorates to less than 10% 30 years after the last flood (Lustig and Maher, 1997).

There was found to be a clear relationship between streamflow and the concurrent value for the Southern Oscillation Index (SOI). For both the North Dandalup and Frankland Rivers, when the SOI for May to October is above 5, then there is about a 50% increase in the median streamflow volume for this period, compared to when the SOI is below 5. The current inter-government initiative into understanding the climate variability and seasonal forecasting for the south west should provide more insight into this interesting relationship.

Decadal to multi-decadal variability in climate has been well documented.

Recent modelling suggests that interdecadal (~15-35 years) period and century-scale (~(50-150 years period) climate variability may be intrinsic to the climate system (Mann et al, 1995).

Ware (1995) has identified four dominant time series:

- 2-3 year (quasi-biennial oscillation)
- 5-7 year (El Nino - SO)
- 20-25 year (bidecadal oscillation)
- 50-75 year (poorly resolved, low frequency oscillation)

Studies in North America of instrumental climate data and isolated long-term proxy records suggest that interdecadal climate variability is closely related to a pressure anomaly pattern called the “Pacific Pan American”. Connections have also been found with low-frequency changes such as ENSO.

The relatively recent climate history is considered to be part of the natural climate variability.

Allocations for water abstraction should take into account the lower streamflow observed in the last two decades, particularly for the Perth water supply. However the long term sustainable yield should be based on long periods of data which incorporate the extended dry periods observed in the last 25 years. Additional performance criteria need to be developed to incorporate the impact of sustained periods of time when streamflow is below average and consequently the water supply system is under some sort of restriction. The most useful terms are resiliency and vulnerability. Where resiliency is the ability of a system to recover from a failure and vulnerability is a measure of the likely severity of a failure. In the case of the Perth water supply system the resiliency of the system to recover from a failure is considered low given the period of restrictions observed in the last 30 years.

The impact of the interdecadal period of low streamflow on the ecology of our rivers needs to be understood. Many rivers, particularly in the Northern Jarrah Forest have had reduced streamflow are now reducing to no flow much earlier than in the period prior to 1975. The ecological impact of this change is uncertain and needs to be understood.

If greater understanding of the climate variability is to be achieved investigations with the following major objectives should be undertaken:

1) to better our understanding of mechanisms that lead to multi-year persistence of climate anomalies in the south west of WA;
2) to supplement the modern climate record by using carefully selected proxy records, such as tree rings; and
3) to improve estimates of the return periods of significant dry and wet regimes over the south west of WA by incorporating paleoclimate data.

Questions to be addressed about decadal scale variations include:

1) what are the spatial scales of multi-year fluctuations, and how do they compare with those of shorter period fluctuations?,
2) is the variability of precipitation independent from that of temperature on these multi-year time scales?, and
3) is there greater persistence in factors that drive winter wet/dry precipitation or in factors that drive summer warm/cool temperatures?

Extension of the hydroclimatological indices may provide insight into several questions:

a) are climatological shifts such as those witnessed in the mid-1970's seen in the pre-instrumental period?
b) in the long term, how prominent is decadal variability? and
c) how stable are the long-term statistics of droughts and wet periods in south west WA?

A basin-specific tree-ring reconstruction of streamflow in the south west would be useful to link our findings on large-scale patterns of hydroclimatic variability to the history of persistent flow anomalies in the critical water supply region.

Questions still unanswered include, are the climate anomaly patterns evident during the past couple of decades in the south west of WA unique? Are the observed recent large-scale patterns of hydroclimatic variability unusual in relation to past ENSO and hemispheric circulation patterns.

1. Introduction

The current low rainfall and streamflow sequence being experienced in many parts of the south-west of Western Australia is of major concern to the Water and Rivers Commission as the state water resource manager. The low rainfall and streamflow has implications on agriculture and industries throughout the south-west and into the eastern goldfields. The restrictions in water use in Perth are also a symptom of this sequence of low rainfall and streamflow. In addition to the economic implications of the low rainfall and streamflow sequence there is also considerable implications from a social and environmental perspective. Some of the impacts on the environment include river beds being drier for longer, some of the social impacts include the lack of overflowing dams. The large crowds that came to watch the relatively minor overflows at Mundaring Weir in 1996 are an example of this.

1.1 General

The effect of climate variability on water resources can be extremely severe. Burroughs (1992) states that the lake level of Lake Victoria, in Africa, is believed to have declined by nearly 2.5 metres between 1876 and 1898, mainly between 1893 and 1898. However, a second change in the Lake Victoria level was observed in 1961 (Burroughs, 1992) when a two metre increase in the lake level was observed.

The earliest known direct measurement of annual water levels is for the Nile River in northern Africa (Burroughs, 1992). The annual flood levels for the Nile have been recorded as far back as around 3090 BC, but the most reliable annual flood level records date from 622 AD onwards. The records show major long term fluctuations with periods of low and high discharge over periods of between 110 and 170 years (Burroughs, 1992).

The analysis of indirect information about the weather and flow conditions of the past, often termed proxy data, have been useful in establishing a case for shifts in the climate. Such data includes tree-rings, ice cores and lake sediments. All of which provide some indication of annual variation in weather conditions. Correlations of tree-ring data with streamflow for the rivers of the west coast of the USA, chiefly the Colorado River, indicate that there have been periods of up to 20 years of very low streamflow (Ruprecht et al. 1996). Another example of longer term climate variability is on the Burdekin River, in Queensland. Ruprecht et al. 1996 state that the Burdekin River had a period of 70 -100 years when there was no significant flows. This finding was based on the presence of annual florescent bands in coral growth rings over the last 400 - 500 years.

1.2 South West

1.2.1 Catchment and Data Description

The geographic scope of the study is defined by the Australian Water Resources Council (AWRC) Basins 602 to 616. The data analysed in this study were selected from the XX streamflow gauging stations located within these south-west Basins. The analysis was carried out for only 34 of the gauged rivers and streams which were free from significant regulation by dams, no significant land-use change had occurred in the catchments and an available data set of more than 28 years. A summary of the catchment and data characteristics of the gauged streams examined in the study is shown in Table 1.1.

1.2.2 Vegetation

The south-west is dominated by karri and jarrah forests which form part of the broad-leaved evergreen forests of Australia (Ovington and Pryor, 1983). On the basis of canopy density and height the jarrah forest is classified as open forest in the north and tall forest in the south. As rainfall decreases towards the north and east the trees decrease in stature thus forming woodland or low forest. There has been significant amount of clearing of the natural vegetation in the south-west to enable a relative intensive agricultural industry to develop. The replacement of the deep rooted natural vegetation with shallow rooted, annual crops has resulted in greatly increased runoff rates and possibly increased the potential floodflows.

Table 1.1 Summary of the catchment and data characteristics for gauged streams in the south-west.

Station No.	Stream	Period of Record	Area (km^2)	Catchment R/fall (mm/yr)	Clearing (%)	Mean Ann. Flow (GL)	CV*
602 199	Goodga River	1964 -	49.1	870	10	4.13	0.38
602 031	Waychinicup Creek	1964 -	230.8	760	5	8.6	0.63
603 190	Yate Flat Creek	1963-	57	780	60	5.28	0.60
603 003/173	Denmark River	1964-	239.8	760	32	12.2	0.79
603 136	Denmark River	1940-	532.3	800	20	35.2	0.66
604 010/053	Kent River	1940-	1,831	800	40	87.2	0.66
605 012	Frankland River	1940-	5,762	600	56	169	0.67
606 185	Shannon River	1964-	407	1,230	2.5	80.7	0.47
606 195	Weld River	1964-	250	1,275	0	53.6	0.41
607 144	Wilgarup River	1961-	461.2	950	33	33.2	0.49
607 220	Warren River	1966-	4,023	800	40	320	0.47
607 009/013	Lefroy Brook	1940-	253.7	1,170	30	54.1	0.44
607 004/145	Perup River	1961-	658.3	750	18.5	18.7	0.67
607 155	Dombakup Brook	1961-	118.1	1,430	16	39.6	0.36
608 151	Donnelly River	1940-	780	1,110	22	134	0.44
608 148/001	Barlee Brook	1962-	158.9	1,160	0	28.4	0.44
608 171	Fly Brook	1962-	63.4	1,420	25	21.8	0.33
609 025	Blackwood River	1956-	20,370	550	85	582	0.71
610 128/001	Margaret River	1940-	390.8	1,055	16	88.6	0.48
611 111	Thomson Brook	1957-	102.2	960	30	12.8	0.57
612 014/037	Bingham River	1953-	369.3	750	10	10.0	1.10
612 034	Collie River South	1952-	660.4	780	27	35.4	0.77
612 001	Collie R. East Trib.	1967-	1,340	710	28	45.3	0.73
612 017/036	Harris River	1952-1995	383	1,000	5	35.5	0.68
613 013/007	Bancell Brook	1940-	14	1,225	20	5.16	0.35
614 196	Williams River	1966-	1,437	600	80	72.6	0.64
614 006	Murray River	1966-	6,840	650	50	265	0.36
614 047	Davies Brook	1954-	67.1	1,215	5	7.09	0.64
614 016	North Dandalup River	1952-1992	153	1,300	0	28.3	0.54
614 044	Yarragil Brook	1951-	72.5	1,090	0	3.22	0.87
616 001	Wooroloo Brook	1963-	536	900	40	50.5	0.48
616 216	Helena River	1966-	585	680	10	6.51	0.67
616 165	Lennard Brook	1962-	62	730	60	6.09	0.18
617 058	Gingin Brook	1957-	120	715	75	14.1	0.25

***** coefficient of variation (standard deviation divided by the mean)

1.2.3 Climate

The climate of the south-west is typically Mediterranean with mild, wet winters and hot, dry summers. The mean annual rainfall has a distinct gradient from 1100-1400 mm, down the Darling Range in the west and extending south east to Denmark, to less than 500 mm at the inland and eastern extremities. The rainfall on the coastal plain, west of the Darling Range to south of Busselton, averages around 900 mm per year. About 80% of the annual rainfall occurs in the six months from May to October.

The evaporation in the south-west of Western Australia increases from less than 100 mm/year in the Cape Leeuwin area to in excess of 2000 mm/year in an approximate north-easterly direction (Luke et al. 1988). While greater than 80 % of annual rainfall typically occurs between May and October, about 80% of the annual pan evaporation (which is an approximate measure of potential evaporation) occurs during the alternate six months from November to April.

A summary of the changes in climate observed during the 1970's, as cited in Ruprecht et al (1996) is given below.

Through analysis of high quality rainfall and temperature data sets for Australia, Nicholls et al. (1996) demonstrate that during the 1970s a jump-like change occurred in the relationship between ENSO and Australian climate. In particular, annual rainfall and maximum temperature tend to be greater for a given value of the Southern Oscillation Index (SOI) now than for that value of the SOI in earlier years. Similar jumps occur in the amplitudes of the first two principal components of the SST distribution in the Indian-Pacific region. (Allan and Haylock (1993) also note a change in the large-scale winter circulation across Australia since 1971.) Using results from the Bureau of Meteorology Research Centre (BMRC) climate model, it was found that the observed changes in rainfall and temperature can be simulated when the model is forced by the observed global SST distribution. While climate models are able to simulate some changes like the jump in the 1970s, they have mixed success in simulating the observed interannual variability (Frederiksen et al., 1995).

An analysis by Roger Tapp (Bureau of Meteorology), based largely on high quality rainfall records for the period 1910-1989 (see Lavery et al., 1992), shows a sizeable decrease in annual rainfall over almost all of the South-West, west of Albany. Strongest percentage decreases were in an area just inland from the Lower West Coast and extending south to a maximum near Walpole (see Fig. 1). Not surprisingly, the trend in May-October rainfall closely matched the annual rainfall trend. November-April trends were weaker and more varied. Within the wet season it was the later months that showed the strongest downward trend.

Such analyses obviously depend strongly on the chosen starting and finishing dates. The records for individual stations, such as those in Fig. 2, give another perspective. Many south-west stations experienced an increasing trend late last century and early in this century.

Similar upward and downward rainfall trends, on scales of decades to centuries and beyond, can be found in many other long-term rainfall records. They are regarded as part of the natural variability of the climate system and may be linked to subtle variations in atmospheric circulation patterns.

Human activities can also affect rainfall, through changes to land surface and atmospheric composition. Any human-induced trends are usually very difficult to detect above the 'noise' of natural variability. Improved modelling should enable better definition of rainfall changes that might be expected from such processes, for comparison with records from high quality stations.

Five simulations have been undertaken using the CSIRO9 GCM forced at the surface by historically observed SSTs from 1871 to 1991. Multiple simulations have been done with slightly different initial conditions to allow for the so-called chaotic behaviour of the atmosphere, meaning that different weather sequences can occur for the same average climatic state. It is planned at present to analyse daily weather sequences from four of these simulations, from 1955 to 1990, essentially for studies over eastern Australia. With supplementary funding, the analysis could be extended to include weather over the South-West. This would see if the GCM simulations reproduced the observed behaviour during the period of rapid decline in rainfall over the region, and could help identify the cause. It would also be a guide as to whether GCM simulations could be used for seasonal forecasting in the region, given accurate forecasts of SSTs. BMRC GCM runs forced by observed SSTs for the periods 1950-1990 and 1880-1990 have reproduced trend/jump in 1970s.

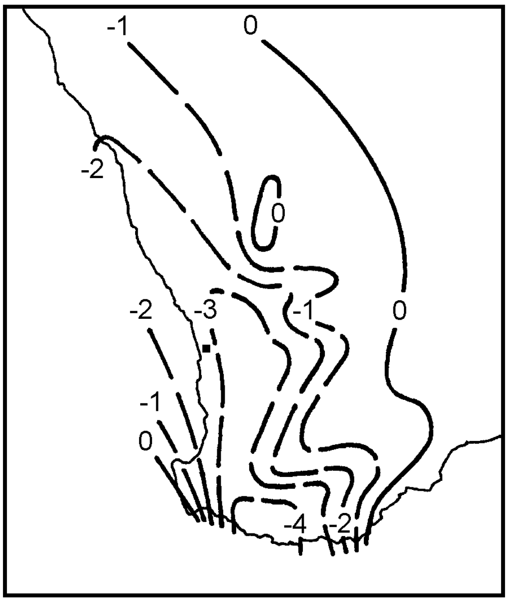


Figure 1: Trend in annual rainfall over the south-west of Western Australia, 1910-1989 (percent per decade).

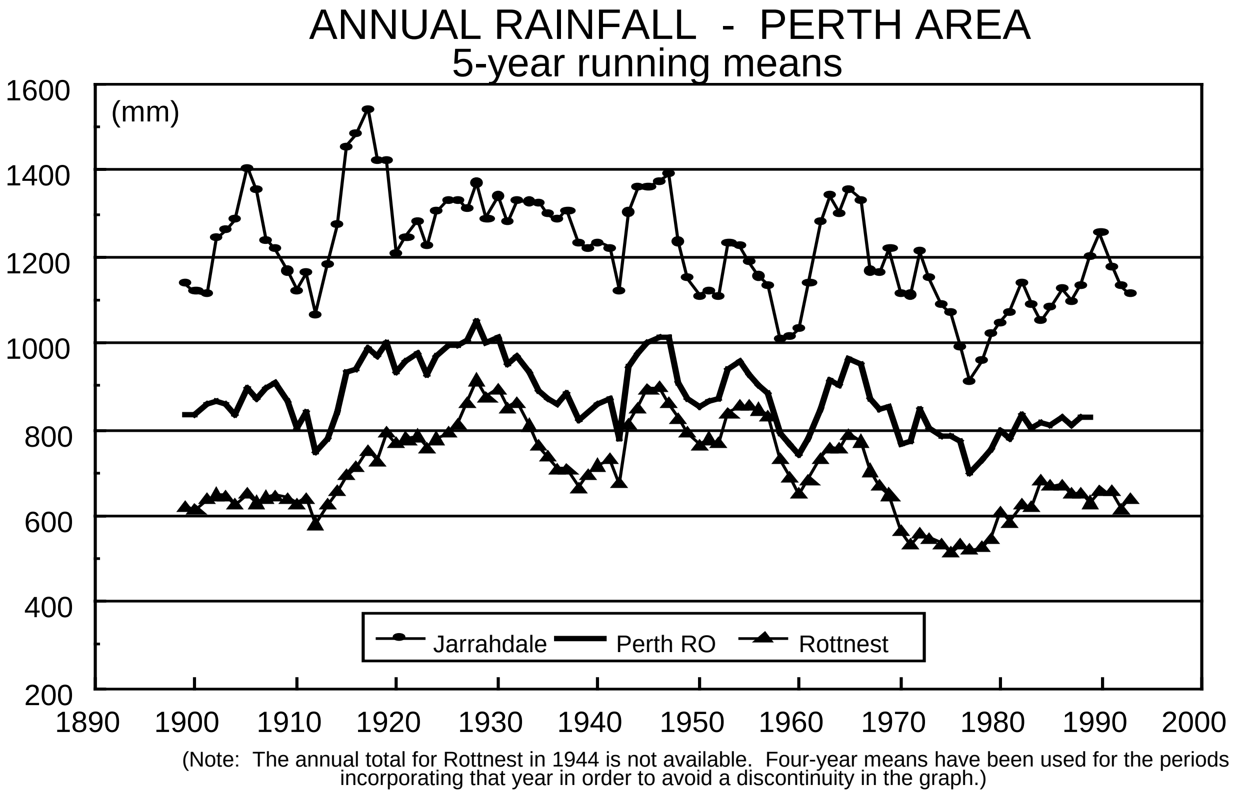


Figure 2: Variations in the annual rainfall in the Perth area since 1897.

2. Method of Analysis

2.1 Autocorrelation Function

The autocorrelation function is an important tool for detecting a lack o independence between observations in a data series. High autocorrelation values indicate a lack of independence which violates the assumptions of many statistical tests. The autocorrelation function at a lag of one was manually calculated using equation 3.1 (Chiew and McMahon, 1992) and was verified using the Sample Autocorrelation Function in the MHTS PC Package (McLeod and Hipel, 1995).

$$r_1 = \frac{\sum_{i=1}^{n-1}\left(X_i - \overline{X}\right)\left(X_{i+1} - \overline{X}\right)}{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2} \qquad (3.1)$$

where, X_i is the annual streamflow at time i, n is the sample size, and $\overline{X}$ is the mean annual flow.

A data series can be tested for short term dependence by checking whether the lag-one autocorrelation coefficient is significantly different from the expected value ($E(r_1)$). The lag-one autocorrelation coefficient is approximately normally distributed with the expected value, variance and test statistic (z-statistic) given by (Chiew and McMahon, 1992) :

$$E(r_1) = -1/n \qquad (3.2)$$

$$Var\ (r_1) = (n^3 - 2n^2 + 2)/\{n^2\ (n^2+1)] \qquad (3.3)$$

$$\text{z-statistic} = [r_1 - E(r_1)]/[Var(r_1)]^{0.5} \qquad (3.4)$$

Campbell (1998) states that the expected value and variance defined in equations 3.2 and 3.3 assumes that the series under study is not correlated in time, and the result for the expected value is well known. It is stated that in practice the expected value approximates 0 and the variance approximates n^{-1} at a lag of one. The results from equations 3.2 and 3.3 above will be approximately the same for moderate to large sample sizes (Campbell, 1998).

The null hypothesis, observations are independent (random), is accepted if -1.64 5< z < 1.645. A z-statistic value outside this range indicates the hypothesis that the sequence is not a random process is statistically significant, at a 10% level.

The MHTS PC Package (McLeod and Hipel, 1995) was used to verify these lag-one autocorrelation results and to examine the autocorrelation at higher lags. As a broad guide the sample autocorrelation should provide reasonable estimates to a lag of n/4 (n= number of data points in a series), which enables the presence of delayed effects to be detected, such as biennial patterns.

2.2 Statistical Trend Tests

A range of statistical trend tests were carried out on the annual streamflow data. These test include the distribution-free CUSUM Test and the Brillinger Trend Test. A number of other tests were applied to the data from the south-west gauging stations. These tests and their results are described in Appendix E.

2.2.1 Distribution -free CUSUM Test

The Distribution-free CUSUM Test is suitable for detecting long-term trends and step-jumps in a time series. The test does not require the data to be normally distributed and the CUSUM statistic is based on the sample median which leads to a test which is robust to outliers. The only disadvantage is the assumption of data independence, so the results from this test in the presence of high autocorrelation should be viewed with caution.

The distribution-free CUSUM test assigns a value of 1, 0, or -1 to each observation depending on whether it is greater than, equal to, or less than the median respectively. The maximum value of the sum of these values from the first observation is used to calculate a test statistic which has critical values defined in Grayson *et al*. (1996).

A more in depth description of the Distribution-free CUSUM trend test is provided in Grayson *et al*. (1996) and in Chiew and McMahon (1992).

2.2.2 Brillinger Trend Test

The Brillinger trend test is non-parametric and based on a Fourier analysis of the data series. The important advantage of this test is its validity in the presence of autocorrelation. The basic underlying model behind the Brillinger trend test can be written:

$$Y(t) = S(t) + E(t) \qquad (3.5)$$

where S(t) is assumed to be a smooth trend, estimated by a centred moving average of the data ,Y(t), and E(t) is a stationary autocorrelated error series. Under the null hypothesis it is assumed that S(t) is a constant, while the alternative hypothesis to be tested assumes that S(t) is a function of time.

The MHTS PC Package (McLeod and Hipel, 1995) was used to test the above hypotheses for the annual flow data from the south-west gauging stations. The MHTS PC Package (McLeod and Hipel, 1995) solves a number of equations based on the above model to determine a test statistic. A large departure of this test statistic from zero indicates the possibility of a trend in the series. The direction of the possible trend is increasing if the test statistic is positive and a negative test statistic implies a decreasing possible trend.

3. Trends in Annual Streamflow

3.1 Gauged Data

3.1.1 Annual Streamflow

The annual streamflow data for the south west of Western Australia, which includes AWRC Basins 601 to 617, during the last two decades has typically been below the long term mean annual flow (Figures 3.1 and 3.2). This decrease in annual streamflow is most evident in the high rainfall areas (mean annual rainfall >1,100mm/year) portions of Basins 606 to 608, 612 to 614 and 616 (Figure 3.1). This reduction appears as a gradual decrease in the annual flows for gauging stations where recording commenced in the early 1960's as shown in the Weld River plot in Figure 3.1. Alternatively, at stations where a longer period of record is available the change appears to have been more of a step decrease during the mid 1970's (North Dandalup River in Figure 3.1).

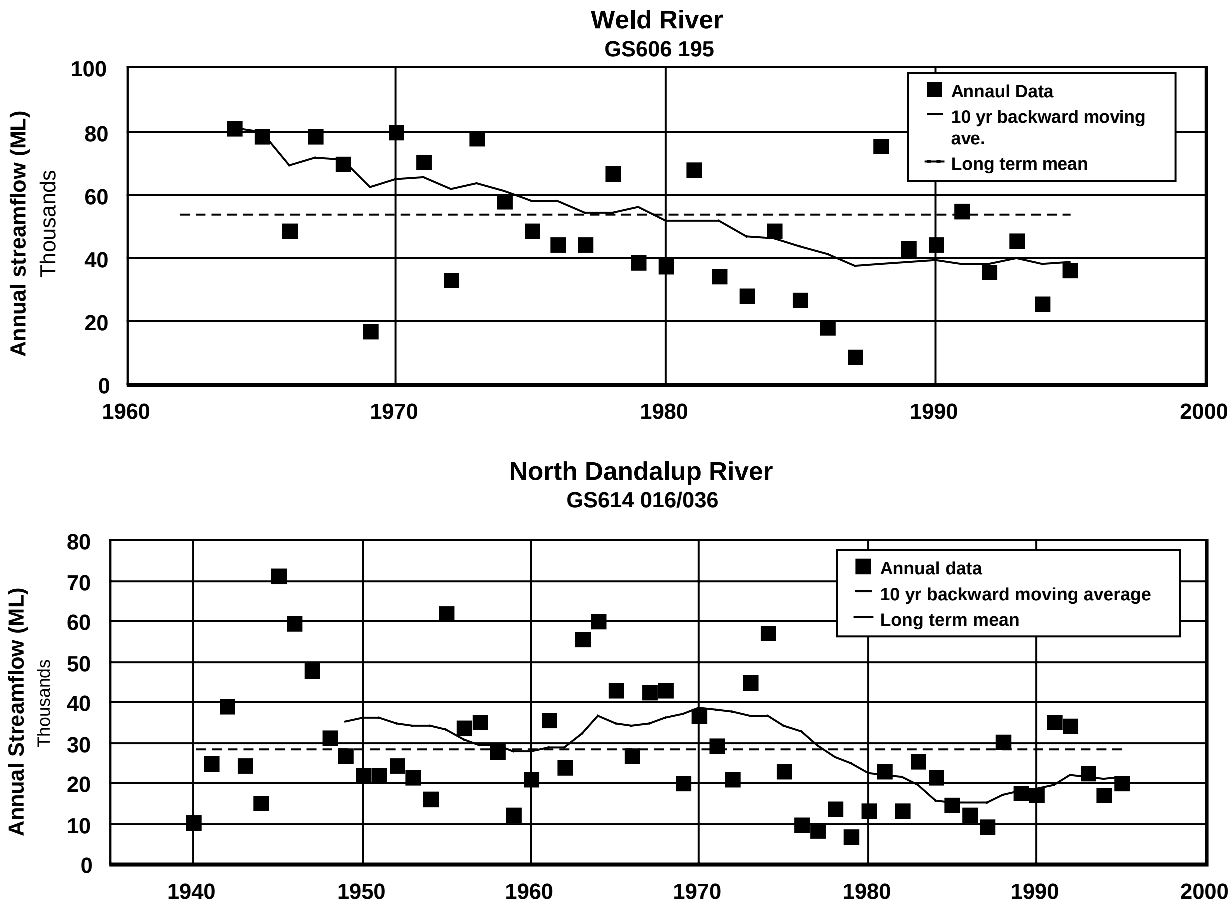


Figure 3.1. Variation in annual streamflow for the high rainfall areas of south-west Western Australia.

In many cases the reduction in recorded streamflow, during the last two decades, in the streams of the lower rainfall areas is less evident, however, the majority of these streams do exhibit an extended period of below average annual flows during this time (Figure 3.2). Although the flows in the south-west during the last two decades have been relatively low, compared to the long term mean, there appears to have been an increasing trend back towards the mean during the 1990's. This may well suggest that the period of low flows did not represent a change in the long term mean, that it was just a relatively long period of below average flows. The data for the streams in Figures 3.1 and 3.2 illustrates this trend back toward the long term mean in the last few years, although flows have still tended to be below the long term recorded mean.

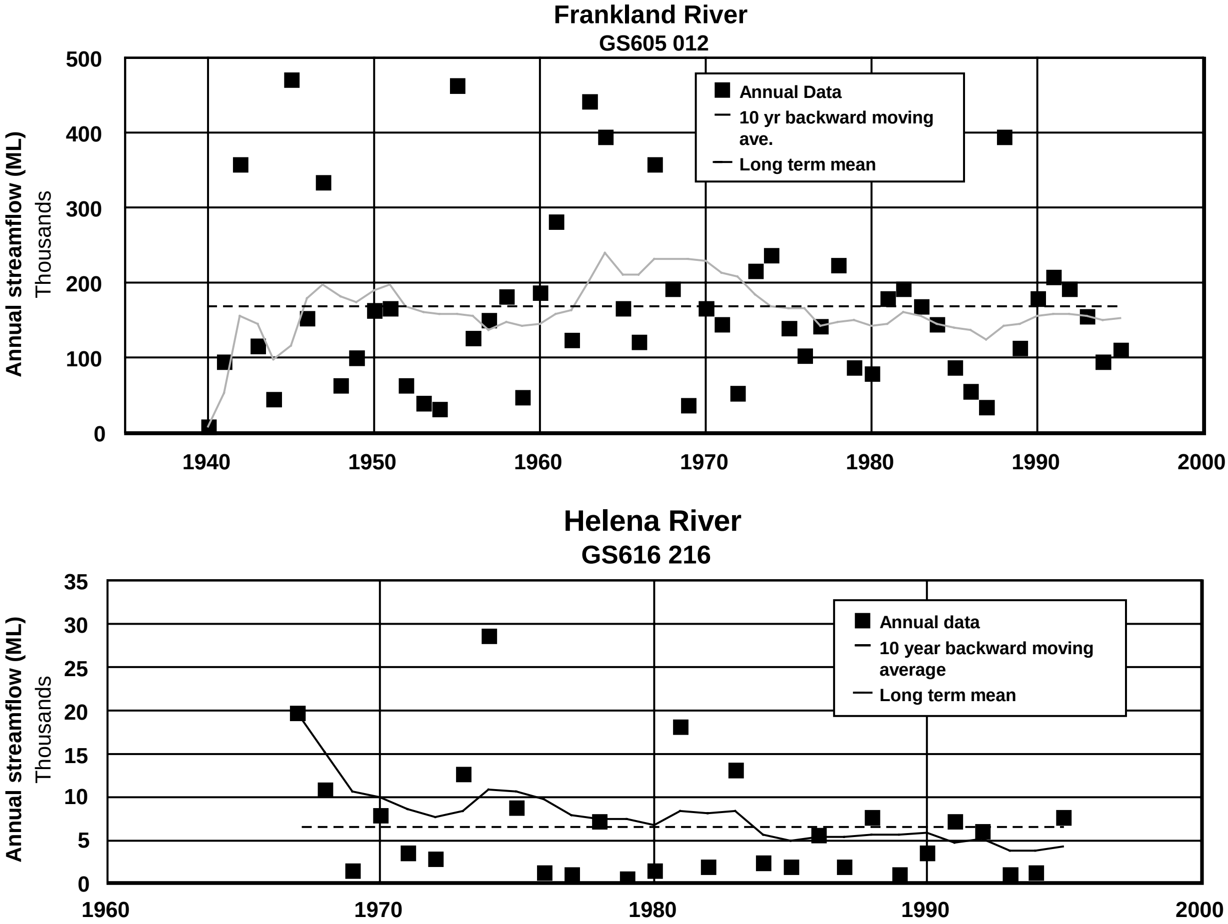


Figure 3.2. Variation in annual streamflow in the lower rainfall areas of south-west Western Australia

This possible increasing trend in mean annual flow since the late eighties, following a typically below average streamflow period between the mid seventies and eighties, is indicated by the negative values in the 1977-86 mean annual flow column in Table 3.1. The data in Table 3.1 also indicates the presence of a high flow period (strongly positive percentage change) between 1957 and 1966 across much of the south-west. This is most evident in the high rainfall catchments (>1,000 mm/year) where the increase in mean annual flow for 1957-66 from that in 1987 to 1996 is in excess of 40 % and is almost twice the observed 1987-96 (200% increase) mean annual flow at the Davies Brook gauging station in Basin 614. The mean annual streamflow during the 1967-76 period is also significantly larger (>25%) than the average flow for 1987-1996 in the higher rainfall catchments of the south west (>1,000 mm/year) (Table 3.1), with the exception of the Donnelly and Harris Rivers and Bancell Brook catchments. These exceptions may be caused by the relatively high degree of clearing within the Donnelly River and Bancell Brook catchments, approximately 22% and 20 % cleared respectively, as the difference in mean annual flow appears to be less marked in the highly cleared catchments. The Harris River catchment may not indicate the observed differences in mean annual flow due to errors in flow estimation. The gauged data for the Harris River ceased in 1989, since which time the annual data has been estimated from relationships with adjacent catchments. The low quality of these estimates will have a significant effect on the Harris River data shown in Table 3.1 as each period is compared to the mean annual flow for the 1987-96 period which is composed of 7 years of low quality annual flow estimates for the Harris River. Additionally, the location of Basins 612, 613, 614 and 616 on the west coast, rather than the south coast (Basins 602-609), may lead to differing climatic and hydrologic conditions operating in the catchments within these Basins which may lead to the different decadal variation in mean annual flow observed in Harris River and Bancell Brook catchments.

The difference in the mean annual flow during the 1977-86 and 1987-96 periods is typically low (<5 %) in the high rainfall catchments (>1,000 mm/year) catchments. The Donnelly and Harris Rivers and Bancell Brook catchments are again exceptions, as is the Barlee Brook catchment in Basin 608 and the high rainfall (>1,000 mm/year) catchments in Basins 614. The absolute value of the percentage change in mean annual flow for each of the periods of record examined is significantly larger in the high rainfall (>1,000 mm/year) catchments of Basin 614 which may suggest that the hydrology and/or climatic conditions acting on the catchments may be different to the remainder of the south- west.

Table 3.1. Summary of the change in mean annual flow with period of record.

Station Number	Stream	Catch. R'fall (mm/yr)	MAF[1] 1987-96 (GL/yr)	Variation in mean annual flow with record period[2] 1940-46 (%)	1947-56 (%)	1957-66 (%)	1967-76 (%)	1977-86 (%)
602 031	Waychinicup Creek	760	9.4				-23.3	3.72
602 199	Goodga River	870	4.8				-25.0	-6.25
603 136	Denmark River	800	35.0	27.1 *(7)*	31.4	-11.4	-25.1	-10.6
603 190	Yate Flat Creek	780	5.6				-15.9	-3.4
604 053/010	Kent River	800	94.1	-4.7 *(7)*	-1.9	-3.3	-16.8	-16.7
605 012	Frankland River	600	181	-34.3 *(7)*	-13.9	16.3	-8.5	-24.5
606 185	Shannon River	1,230	62.2				34.2	-4.4
606 195	Weld River	1,275	43.1				30.2	-1.0
607 001/009/013	Lefroy Brook	1,170	33.6	79.6 *(7)*	46.9	70.4	41.6	2.8
607 144	Wilgarup River	950	30.7			50.5 *(6)*	4.6	-14
607 145/004	Perup River	750	17.5			77.1 *(6)*	4.0	-26.3
607 155	Dombakup River	1,430	33.6			61.0 *(6)*	25.0	3.0
607 220	Warren River	800	298	25.7 *(7)*	6.5	24.7	8.8	-16.9
608 002/047	Carey Brook	1,410	28.9			63.3 *(6)*	33.6	-1.7
608 148/001	Barlee Brook	1,160	24.6			82.5 *(5)*	27.2	-14.6
608 151	Donnelly River	1,110	113	39.5 *(7)*	36.0	41.2	13.4	-10.4
608 171	Fly Brook	1,420	19.2			53.6 *(5)*	25.0	-4.2
609 025/007	Blackwood River	550	563	-8.9 *(7)*	-13.2	48.1	10.5	-20.4
610 128/001	Margaret River	1,055	73.5	20.4 *(7)*	13.6	41.6	52.2	-4.5
611 111	Thomson Brook	960	12.8			23.4	-4.7	-22.7
612 001	Collie River East	710	46.6				11.2	-19.3
612 014/037	Bingham River	750	7.9			116.5	-10.1	-35.4
612 017/036	Harris River	1,000	35.0			29.7	10.0	-38.9
612 034	Collie River South	780	40.5		-36.8 *(5)*	0.5	22.2	-37.5
613 007/013	Bancell Brook	1,225	4.84	25.9 *(7)*	21.7	13.0	-3.5	-11.6
614 006	Murray River	650	279				9.3	-24.9
614 016	Nth. Dandalup River	1,300	22.8	53.9 *(7)*	36.0	50.4	44.3	-32.4
614 044	Yarragil Brook	1,090	1.96			183 *(8)*	117.9	-19.4
614 047	Davies Brook	1,215	4.41			135.8	98.6	-26.3
614 196	Williams River	600	75.5				14.4	-26.6
616 165	Lennard Brook	730	6.99				-16.7	-15.7
616 216	Helena River	680	5.93				64.4	-9.1
617 058	Gingin Brook	715	13.0 *(7)*			10.8	13.8	-3.1

1. Mean annual flow for the entire gauged record.
2. Percentage change in the mean annual flow from the mean annual flow between 1987 and 1996 for the decades with greater than 5 years of data. Brackets indicate the number of years of data available. Negative values indicate a percentage decrease of the given amount from the 1987-96 mean annual flow.

The mean annual flow between 1977 and 1986 for the lower mean annual rainfall catchments, in Basins 604-612 and Basin 614, averages between 15 - 25 % less than the 1987 to 1996 flows, while the average flow between 1967 and 1976 is typically 10 % larger. The catchments in 602 to 605 exhibit a increasingly larger decrease in the percentage difference in mean annual during 1977-86 and 1987-96 in a westerly direction. The catchments in Basins 604 and 605 do not show this approximate 10 % larger flows during 1967 to 1976, instead they exhibit a percentage decrease in flows during this period which is increasingly smaller in a westerly direction from the 25 % decrease in flows observed catchments of Basins 602 and 603.

The flow throughout the south-west between 1940 and 1956 appears to have been significantly larger (>15 %), than those since 1987, in catchments which receive greater than 1,000 mm of rainfall annually (Table 3.1). The data for the Warren River indicates a similar pattern of large flows between 1940 and 956 relative to those since 1987. This may be due to an average annual rainfall of greater than 1,000 mm occurring over about half of the Warren River catchment. The other sites with data back to 1940 with annual catchment rainfall of less than 1,000 mm per year are the Denmark, Kent , Frankland and Blackwood Rivers. The difference in streamflow on the Denmark, Kent and Frankland Rivers between 1940 and 1956 relative to the flows since 1987 decreases in a westerly direction from about 30 % larger on the Denmark to about a 30 % smaller on the Frankland. The flows on the blackwood River were around 10 % smaller between 1940 and 1956 compared to those since 1987.

The streamflow in the catchments in the extreme north of the study area, situated on the coastal plain away from the influence of the Darling Escarpment, is characterised by a large baseflow component which may mask any similarities, or differences, in the decadal variation in mean annual flow. This different catchment hydrology leads to dissimilar results for the Lennard and Gingin Brook catchments to the remainder of the south west catchments examined.

The variation in decadal mean streamflow, for the longer term gauged rivers (1940-96) is illustrated graphically in Appendix B.2.

3.1.2 Sample Autocorrelation

The sample autocorrelation function over a range a lags was examined using the MHTS PC Package (McLeod and Hipel, 1995). A lack of independence in a data series may be indicated by the presence of statistically significant correlation. The MHTS PC Package (McLeod and Hipel, 1995) was used to examine the independence of the annual flow volume data to a significance level of 5%. The autocorrelation function can also used to detect long range dependence, which is illustrated by the persistence of high autocorrelation over many lags

There is a number of zones within the south-west in which the autocorrelation results follow similar patterns. This may suggest similarities in the hydrological behaviour of catchments within these zones. The sample autocorrelation results are summarised in Appendix C.

The analysis of the data for the two streams from Basin 602 both had high correlations at lags of 1, 5 and 6, however, the lag one autocorrelation coefficient at the Goodga River gauging station (GS 602 199) was the only statistically significant result (Figure 3.3). The autocorrelation coefficients for the data from the examined streams in Basins 603 to 605 were low indicating that the data may be considered independent (Figure 3.4).

The gauging stations examined in Basins 606 and 607 can be split into two groups depending on the autocorrelation results of their recorded mean annual flows. Statistically significant autocorrelation at lag 3 and high, but non-significant, autocorrelation at lags of 7 and 8 were observed for the high rainfall (>1,100 mm/year) catchments.

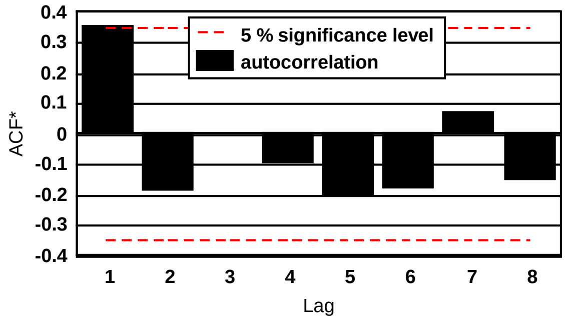


Figure 3.3. Sample autocorrelation for the Goodga River (GS602 199).

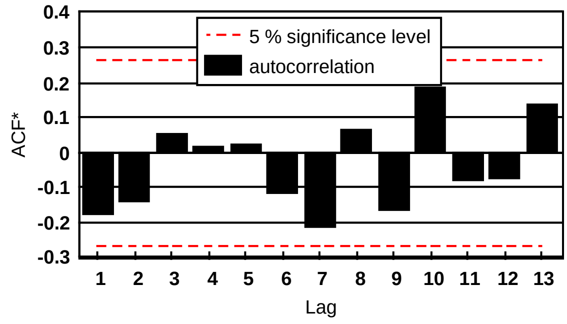


Figure 3.4. Sample autocorrelation for the Kent River (GS604 053/010).

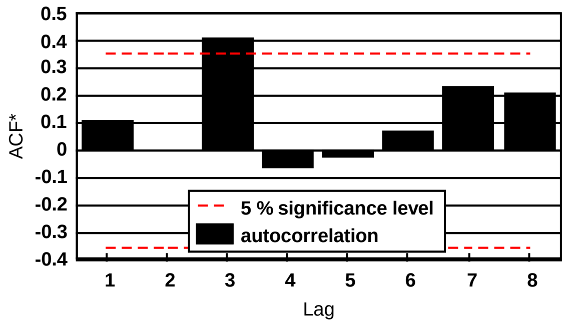


Figure 3.5. Sample autocorrelation for the Shannon River (GS606 185).

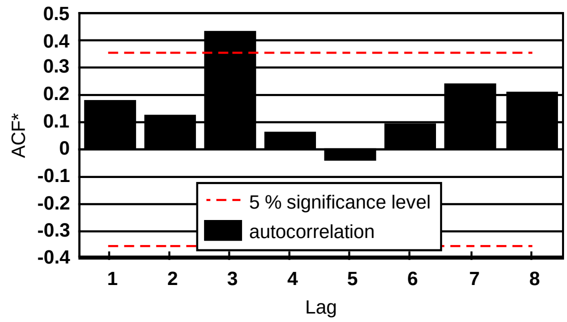


Figure 3.6. Sample autocorrelation for the Dombakup River (GS607 155).

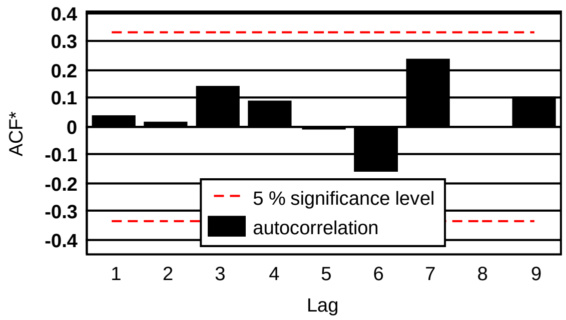


Figure 3.7. Sample autocorrelation for the Wilgarup River (GS607 144)

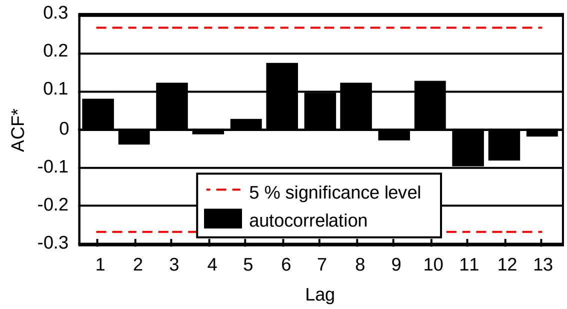


Figure 3.8. Sample autocorrelation for the Margaret River (GS610 128/001).

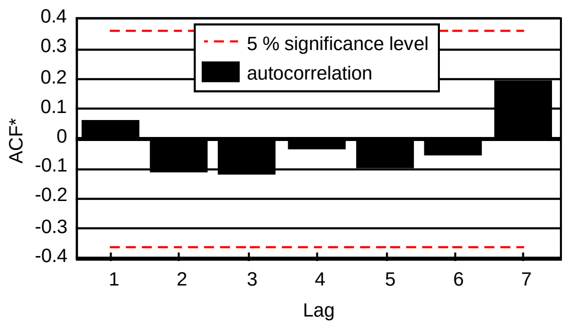


Figure 3.9. Sample autocorrelation for the Williams River (GS614 196).

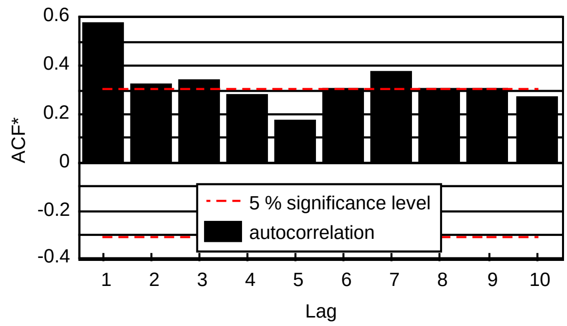


Figure 3.10. Sample autocorrelation for Davies Brook (GS614 044).

An exception is the data for Lefroy Brook, which has a mean annual rainfall of around 1,200 mm/year, has high, non-significant, autocorrelation over a number of lags, and is not statistically significant at lag 3. The lower rainfall (<1,100 mm/year) catchments in Basins 606 and 607 did not exhibit statistically or high, non-significant autocorrelation.

The autocorrelation of the data for gauging stations in the Donnelly River Basin (608) varies slightly throughout the Basin. The Fly Brook data has a high, non-significant, autocorrelation at lags of 3 and 8 which is similar to the pattern exhibited in the high rainfall catchments of Basins 606 and 607. This autocorrelation pattern is also observed to a certain extent in the Barlee Brook annual streamflow data. However, a statistically significant autocorrelation at a lag of 1 and a high, non-significant, autocorrelation at a lag of 10 are more pronounced. The Donnelly River data has a statistically significant autocorrelation at a lag of 10 and once again a non-significant autocorrelation at a lag of 8.

High, non-significant, autocorrelation at lags of 1, 8, and 10 is also observed in the Blackwood River annual streamflow data. The remainder of the gauged streamflow data examined from Basin 609 and Basins 610 and 611 the autocorrelation is low over the entire range of lags. The data for a number of the stations in Basin 612 exhibits a high, non-significant, autocorrelation at lag one. This high lag one autocorrelation is statistically significant for the Bancell Brook data from Basin 613. The data for the lower rainfall catchments in the east of Basin 614 do not exhibit high autocorrelation while at a number of the stations in the Darling Range, where rainfall is higher, statistically significant correlation at lag one is observed and also at a number of higher lags at individual stations. The Davies and Yarragil Brook data has high autocorrelation at the majority of lags between 1 and 10.

The data for stations in Basin 616 do not tend to exhibit high autocorrelation, although stations in the extreme north of the Basin may have high lag one correlations. The data for Lennard Brook has a statistically significant lag one correlation, while Gingin Brook in Basin 617 just to the north of Lennard Brook has high, non-significant lag one correlation.

A complete collection of the autocorrelation output from the MHTS PC package (McLeod and Hipel, 1995) is contained in Appendix C. Autocorrelation coefficients beyond the inner dashed lines indicates the presence of significant autocorrelation at a 5 % significance level.

The persistence of high autocorrelation coefficients is often indicative of a trend in the data series. With this in mind, there is some evidence for the presence of a trend in the annual flow data at a number of the gauging stations studied.

3.1.3 Loess and Alternative Smoothers

The MHTS PC package applies the Cleveland (1979) robust Loess regression smooth to fit a curve to the annual flow data for each station of interest. A limitation of the Loess smoother is that it sometimes tends to overstate any upward or downward trends in the data near either end of the series (McLeod and Hipel, 1995). There are many similar smooths readily available in statistical analysis packages. One such example is the distance weighted least square regression in STATISTICA. The results of the distance weighted least square regressions on the data for each of the south-west gauging stations is shown in Appendix D and for selected sites in Figure 3.11.

The Loess regression results indicate that there was a period of increasing flows between 1940 and the mid-late 1960’s. The slope of this increase is only slight, at most a 10 % change over the period. This increasing period of flow is followed by a period of decreasing flow volumes between the late sixties to the early eighties. The slope of this decrease is variable with quite steep slopes observed for the high rainfall (>1,100 mm/year) catchments subject to very little clearing while the slope is quite gentle for other catchments which have lower mean annual rainfall, and/or subject to a higher degree of clearing. Since the early 1980’s the Loess regression has shown a slight increase which in the low rainfall and the largely cleared, catchments has taken the regression curve to a very similar level as the initial, in many cases slightly higher (Kent and Warren Rivers in Figure 3.11). The limitation, discussed above, regarding the overstating of any trends at the end of a series may mask any notable downward trends in these lower rainfall catchments. The slope of the regression curve for the high rainfall catchments, since the early 1980's, was not sufficient to approach the level of the curve during the years prior to the decrease in the late 1960's (North Dandalup River in Figure 3.11). This may indicate the presence of a significant trend or change in mean in annual streamflow volume in these high rainfall catchments.

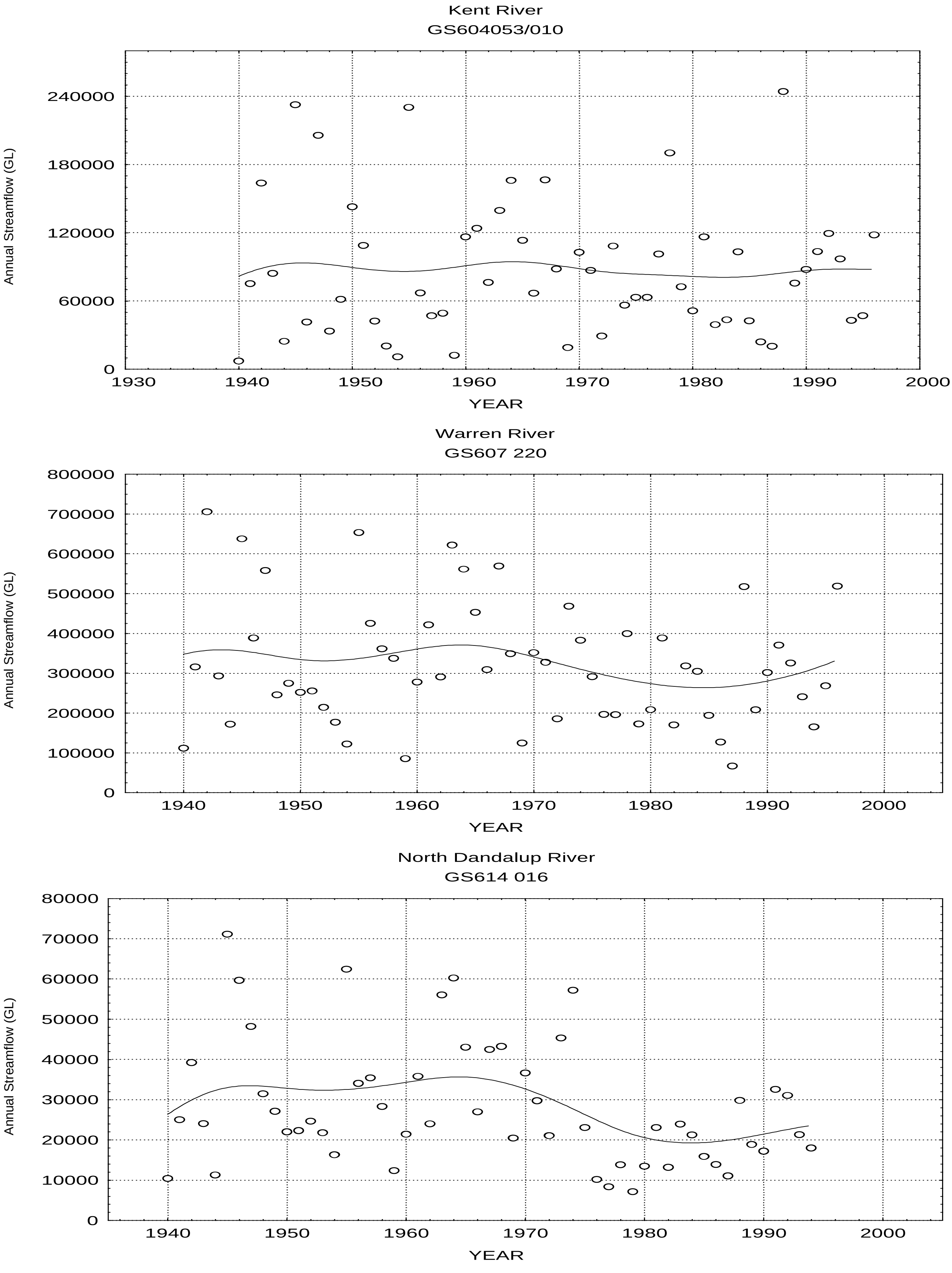


Figure 3.11. Typical distance weighted least square regression results for south west streamflow gauging stations

3.1.4 Trend Tests

The results from the Distribution-free CUSUM Test and the Brillinger Trend Test are summarised in Table 3.2. Critical values for two-sided probability were used in the tests to determine whether either an increasing or decreasing trend, or a change in the mean, is present. The null hypothesis is rejected only if a change or trend is detected above the 90 per cent significance level. The direction of any trend, not necessarily statistically significant is indicated in the results of the Brillinger Trend Test, while the timing of the change is indicated in the Distribution-free CUSUM test.

Table 3.1. Summary of the trend test results for the long term gauged data in the south-west.

Station Number	Stream	Possible Trend Detected [1]		Change compared to the 1962 to present data (%)	
		Distribution-free CUSUM Test[2]	Brillinger Trend Test[3]	77-86	87-96
602 031	Waychinicup Creek	No	No (+)	7.5	9.8
602 199	Goodga River	No[4]	Yes (+)	4.7	11.6
606 185	Shannon River	Yes (1975)	Yes (-)	-8.0	-14.4
606 195	Weld River	Yes (1975)	Yes (-)	-12.2	-12.2
612 001	Collie River East	No	No (-)	-17.0	2.9
614 006	Murray River	No	No (+)	-23.7	4.0
614 196	Williams River	No	No (+)	-23.5	4.2
616 165	Lennard Brook	Yes (1980) [4]	Yes (+)	-5.2	12.6
616 216	Helena River	No	No (-)	-23.2	-15.5
607 144	Wilgarup River	No	Yes (-)	-9.6	5.1
607 145/004	Perup River	Yes (1968)	Yes (-)	-20.4	8.0
607 155	Dombakup River	Yes (1975)	Yes (-)	-4.7	-7.4
608 002/047	Carey Brook	Yes	Yes (-)	-17.7	-16.2
608 148/001	Barlee Brook	Yes (1974) [4]	Yes (-)	-18.2	-4.1
608 171	Fly Brook	Yes (1975)	Yes (-)	-9.2	-5.3
612 014/037	Bingham River	No	No (-)	-23.8	18.1
611 111	Thomson Brook	No	No (+)	-14.7	10.3
612 017/036	Harris River	Yes (1974)	Yes (-)	-29.1	1.7
612 034	Collie River South	No	No (+)	-34.1	5.5
614 044	Yarragil Brook	Yes (1974)	Yes (-)	-39.2	-24.6
614 047	Davies Brook	Yes (1975) [4]	Yes (-)	-40.6	-19.4
617 058	Gingin Brook	No	No (+)	-10.6	-7.8
603 136	Denmark River	No	No (-)	1.6	13.6
604 053/010	Kent River	No	No (+)	-4.9	14.2
605 012	Frankland River	No	No (+)	-12.2	6.5
607 001/009/013	Lefroy Brook	Yes (1974)	Yes (-)	-10.4	-12.9
607 220	Warren River	No	No (+)	-12.2	5.6
608 151	Donnelly River	Yes (1974)	Yes (-)	-9.6	0.9
609 025/007	Blackwood River	Yes (1954)	Yes (+)	-17.7	3.4
610 128/001	Margaret River	No	No (+)	-17.6	-13.8
613 007/013	Bancell Brook	No[4]	Yes (-)	-6.1	6.1
614 016	Nth. Dandalup River	Yes (1974) [4]	Yes (-)	-20.8	5.5

1. Possible trend detected at a significance level of greater than 90 %.
2. Brackets indicate the year associated with the trend
3. Brackets indicate the direction of the trend, a positive sign implies an increasing trend and a negative sign a decreasing trend.
4. Indicates statistically significant lag-1 autocorelation (at 95% confidence).

The length of gauged record on a stream may have biased the trend test results. Gauging stations which commence operation between 1960 and 1962 may over emphasise the possibility of a trend in the data due to the commencement of recording at the onset of a period of typically high flows, between 1960 and 1968, indicated in the longer term gauging station data. This may provide an understanding of why some of the south-west streams with lower catchment rainfall, like the Perup and Wilgarup Rivers in Basin 607, which have period of records starting in 1961, show the presence of a trend or change in mean (Table 3.2). However, if the Perup and Wilgarup Rivers annual flow data for 1965 to 1996 (excluding four years of data) is used during the analysis then there is no evidence of a significant trend or change in mean in the results for either of the trend tests.

The timing of the trend in the annual streamflow data tends to be centred on the years of 1974 and 1975. The change takes place the year following this maxima in the Distribution-free CUSUM test statistic (1975 and 1976). This was established by identifying the year during which the test statistic for the Distribution-free CUSUM test is maximised. Interestingly, two of the three exceptions are the Blackwood River and Lennard Brook, which were the only stations in the Brillinger trend test to exhibit an increasing trend. The presence of a trend in the data for the Perup River was unexpected, according to the catchment rainfall, and was the other exception in trend timing. A number of the gauging stations where there was no significant trend in annual streamflow also had Distribution-free CUSUM test statistics which were a maximum in 1974 or 1975.

Another interesting feature is the direction of the change indicated by the Brillinger Trend Test. Trends of decreasing annual flow volumes were observed in all but three of the stations at which a statistically significant trend was identified. These exceptions represent the eastern and northern extremities of the study area and the Blackwood River, which is by far the largest catchment within the study. These three catchments are also the only catchments for which a possible statistically significant trend was observed with clearings greater than 50%. This relationship between the direction of the trend in annual streamflow and catchment clearing is also observed in those streams where no statistically significant trend was observed. Of the 15 stations where there is no significant trend, 10 have positive Brillinger test statistics indicating an increasing trend, although not significant. These ten streams all have catchment clearings greater than 30 %. The remaining five streams for which a decreasing trend, although not significant, is observed the catchment clearing is less than 30 %.

Table 3.2 also shows the changes in streamflow for two periods of ten years, 1977-86 and 1987-96, relative to the longer term mean annual flows at each of the gauging sites. For the 1977 to 1986 period there was widespread reductions compared to the longer term values. The extreme south-east catchments in AWRC Basins 602 and 603 are the only sites at which an increase in the annual streamflow for the 1977 to 1986 period relative to the longer term mean is observed.

The picture is not as clear for the more recent ten year period, 1987-96, where a reduction in the mean annual streamflow relative to the 1962 to 1996 mean is only observed at less than half of the gauging sites. These sites include the high rainfall (>1,000 mm/year) catchments in the AWRC Basins 606 to 608 that have low percentages of cleared natural vegetation. The one exception is the Donnelly River catchment that has a similar mean annual streamflow for both the 1987 to 1996 and 1962 to 1996 periods (less than 1 % increase). There is also a decrease in 1987 to 1996 mean annual streamflow at a few of the high rainfall (>1,000 mm/year) gauged sites in AWRC Basins 614 and 616 relative to the longer term (1962 to 1996) mean flows.

3.2 Modelled Data

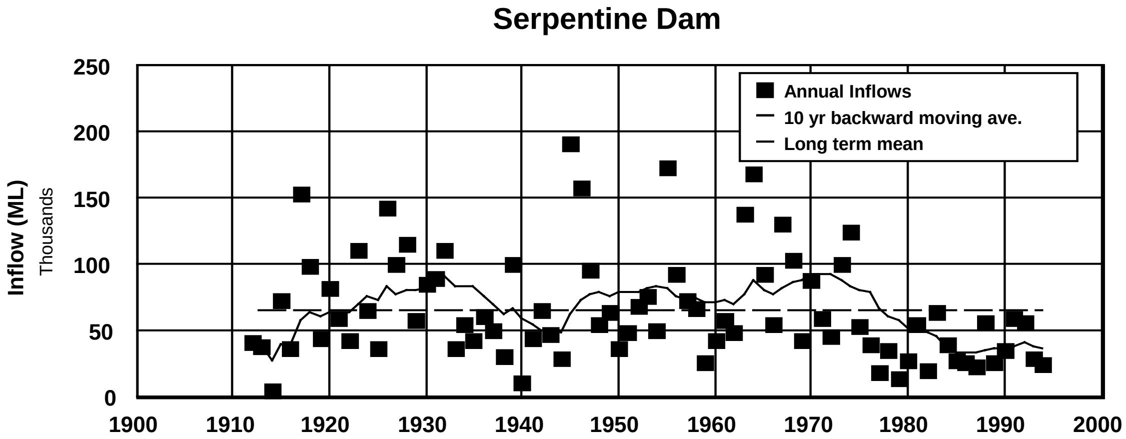
To obtain long term streamflow records for the water supply dams for the Perth metropolitan area a Sacramento model incorporating rainfall, evaporation, soil type parameters was used. The modelled monthly inflows were converted to annual values which were then used to test for a trend or a change in mean.

3.2.1 Annual Variation

The change in the mean annual flow for various periods is shown in Table 3.2. The total mean annual inflows to the metropolitan sources since 1974 is just under 200 GL while the mean for the period of 1950 - 1994 was in excess of 280 GL, a 30 % reduction in the mean annual inflows. The combined mean annual inflow for the entire period from 1912 to 1994 is greater than 315 GL. The mean combined annual inflow between 1974 and 1994 is in excess of 37 % less than the long term mean (1912-1994). The annual variation in the modelled inflow data is graphically summarised in Figure 3.12. Figure 3.12 illustrates that there has been an extended period of below average annual inflows to the metropolitan reservoirs about since 1974.

3.2.2 Sample Autocorrelation

The autocorrelation of the modelled annual inflow data to the metropolitan reservoirs was examined to a lag of twenty using the Sample Autocorrelation Function in MHTS PC Package (McLeod and Hipel, 1995). High autocorrelation, though not necessarily statistically significant, were observed at lags of 1, 5, 9, 10, 12, 14 and 19 at a number of the reservoirs. A high lag 3 autocorrelation was also observed in the Bickley Brook and Victoria Reservoir inflow data (Figure 3.13). The sample autocorrelation results for each of the Reservoirs is illustrated graphically in Appendix 1.



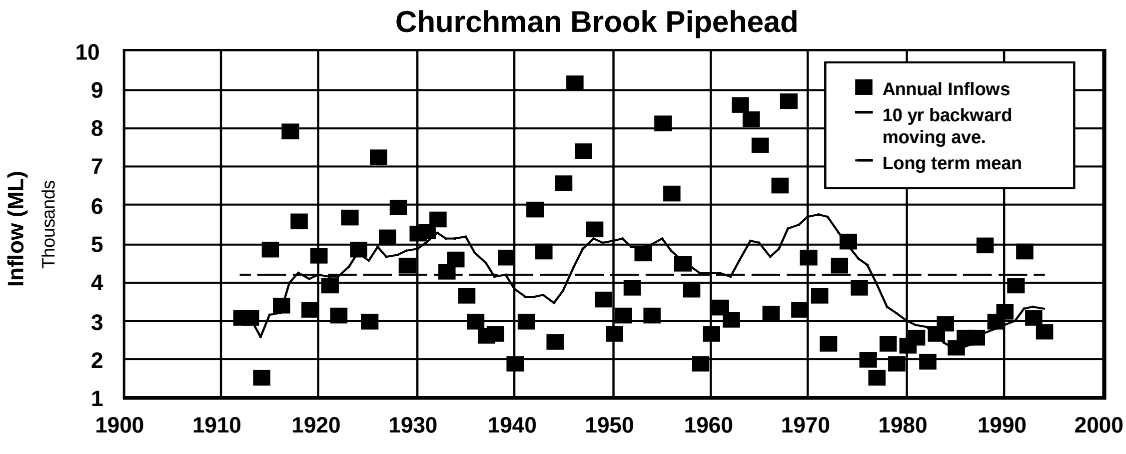


Figure 3.12. Annual variation in the modelled inflows to Serpentine Dam and Churchman Brook Pipehead Dam.

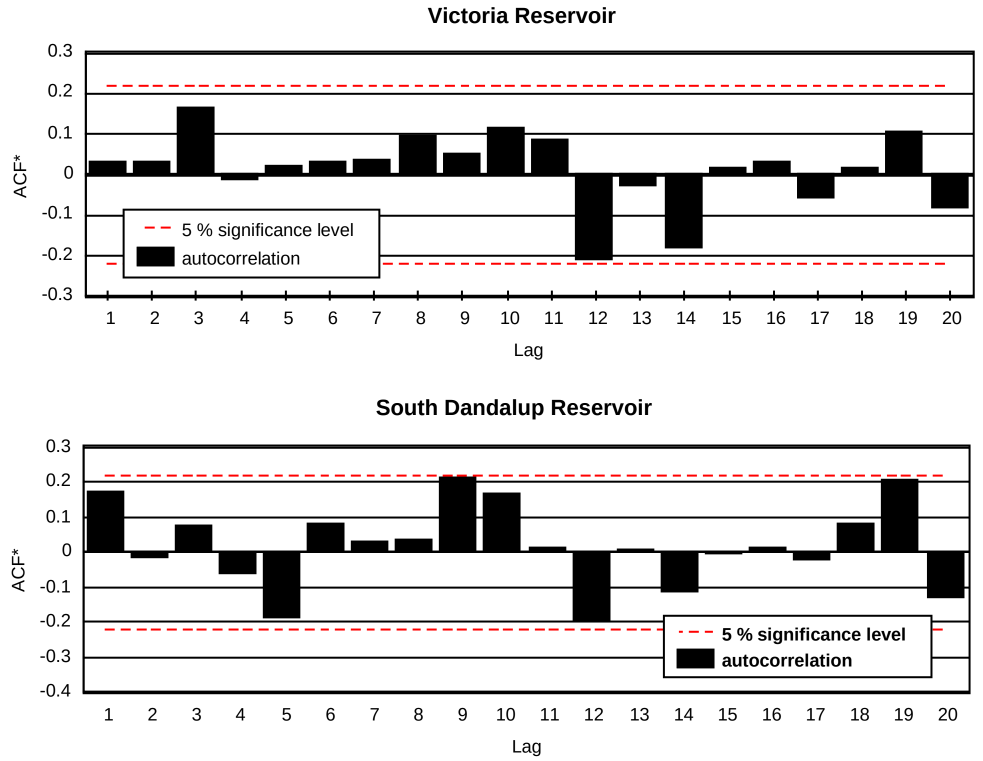


Figure 3.13. Typical sample autocorrelation for the modelled annual inflows to metropolitan reservoirs.

3.2.3 Loess and Alternative Smoothers

The analysis of the modelled inflow data utilised both a Loess smooth from the MHTS PC Package (McLeod and Hipel,1995) and the distance weighted least square regression in STATISTICA. Similar results were observed using both smoothing techniques and the complete results are shown in Appendix 2 and is summarised in Figure 3.14. There appears to have been a decrease in the annual inflow to all of the metropolitan reservoirs since the early 1970's following a relative constant annual inflow period between 1920 and 1970, after an initial increase in annual inflows to 1920 (Figure 3.14).

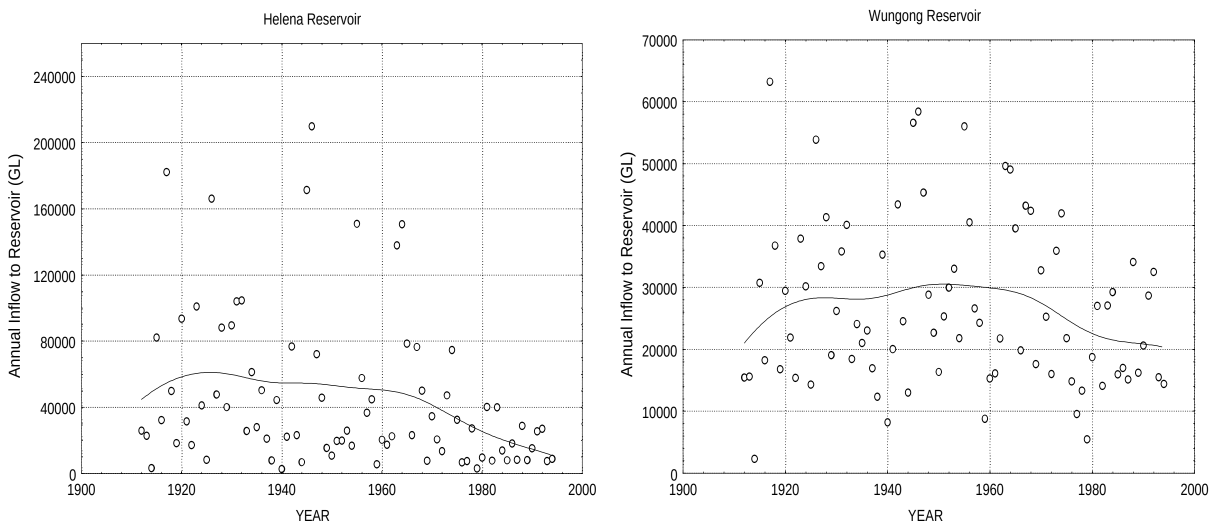


Figure 3.14. Typical distance weighted least square regression plots for the modelled annual inflow data to metropolitan reservoirs.

3.2.4 Trend Tests

The trend tests, which were applied to the gauged data for the longer term streamflow gauging stations in the south-west, were also applied to the modelled inflow data for the metropolitan sources in Table 3.2. The results, shown in Table 3.2, indicate the presence of a statistically significant decrease in mean at half the metropolitan sources examined. The presence of a significant trend in the annual inflows to North Dandalup reservoir was not observed using the Brillinger Trend test, although the test statistic was very close to the significant value, while the Distribution-free CUSUM test did identify a significant trend in the North Dandalup inflows. This was the only site for which the results from the two tests did not concur.

A decreasing trend in the long term modelled annual flow for each of the sources was identified, although not necessarily significant. All of the metropolitan source catchments are free of significant amounts of clearing which may provide further evidence for the decreasing trend in annual streamflow observed in relatively uncleared catchments identified in the gauged data trend test results.

Table 3.2. Summary of trend test results for modelled reservoir inflow data.

Inflow Site	Stream	Possible trend detected at 90 % significance level [1]	
		Distribution-free CUSUM	Brillinger Trend Test
Mundaring Reservoir	Helena River	Yes	Yes (-)
Canning Reservoir	Canning River	No	No (-)
Wungong Reservoir	Wungong Brook	No	No (-)
Serpentine Reservoir	Serpentine River	Yes	Yes (-)
South Dandalup Reservoir	South Dandalup River	No	No (-)
North Dandalup Reservoir	North Dandalup River	Yes	No (-)
Victoria Reservoir	Mundays Brook	Yes	Yes (-)
Lower Helena Pipehead	Helena River	No	No (-)
Serpentine Pipehead	Serpentine River	Yes	Yes (-)
Churchman Brook P/head	Churchman Brook	Yes	Yes (-)
Bickley Pipehead	Mundays Brook	Yes	Yes (-)
Conjurunup Pipehead	Conjurunup Creek	No	No (-)

1. Brackets indicate the direction of the trend in the annual streamflow data. A negative sign indicates a decreasing trend and a positive sign indicates an increasing trend.

The mean annual inflow to the metropoltan surface water sources for the 1975 to 1994 period is 30 % less than the mean annual flow for the longer 1950 to 1994 period (Table 3.3). The reduction at the individual sources ranges from 15 % to 41 %. The variation in the annual streamflow to the surface water metropolitan sources generally decreased for the shorter 1975 –1994 period. The variation in annual streamflow into North Dandalup Reservoir and Conjunurup Pipehead was greater over the shorter period of record compared to the 1950 to 1994 period. The remainder of the metropolitan surface water sources exhibited a decrease in the annual streamflow variation over the last twenty years.

Table 3.3. Trends in modelled annual inflows to metropolitan surface water sources.

Inflow site	River	Mean annual flow (GL)				Coefficient of Variation		
		1912-94	1950-94	1975-94	% reduction[1]	1912-1994	1950-94	1975-94
Mundaring Reservoir	Helena River	45.1	33.5	19.9	41	1.01	1.06	0.83
Canning Reservoir	Canning River	55.9	48.8	30.4	38	0.76	0.79	0.69
Wungong Reservoir	Wungong Brook	26.6	25.3	20.6	19	0.49	0.46	0.43
Serpentine Reservoir	Serpentine River	66.4	61.4	41.2	33	0.60	0.62	0.58
South Dandalup Reservoir	South Dandalup River	31.2	29.2	21.4	27	0.66	0.59	0.56
North Dandalup Reservoir	North Dandalup River	29.4	27.1	20.2	26	0.52	0.51	0.54
Victoria Reservoir	Mundays Brook	4.1	3.8	3.1	18	0.42	0.41	0.41
	SUB – TOTAL	258.8	229.2	156.9	31			
Lower Helena Pipehead	Helena River	18.3	17.2	13.7	20	0.51	0.47	0.38
Serpentine Pipehead	Serpentine River	6.4	5.9	3.9	33	0.60	0.62	0.58
Churchman Brook Pipehead	Churchman Brook	4.2	3.9	3.0	23	0.44	0.48	0.33
Bickley Pipehead	Mundays Brook	2.8	2.5	2.0	20	0.42	0.41	0.38
Conjurunup Pipehead	Conjurunup Creek	10.1	9.6	8.1	15	0.43	0.42	0.45
Araluen Pumpback	Canning River	3.5	3.4	2.3	32	0.49	0.51	0.47
Lower South Dandalup	South Dandalup River	12.4	11.9	9.1	24	0.43	0.42	0.30
	SUB-TOTAL	57.7	54.4	42.1	23			
	TOTAL	316.5	283.6	199.0	30			

(1) % reduction is based on the difference between the inflows for the 1950 - 94 and 1975 - 94 periods.

4. Trends in Flow Duration

4.1 Flow Duration

In order to examine the presence of any trends in flow duration for the streams of the south-west, the flow duration curves over two periods were utilised. These periods, prior to 1976 and since 1976, corresponds to the onset of the apparent trend in annual streamflow, as discussed in section 3.1.3. These periods are also loosely related to a change in the sea surface temperature in the Indian Ocean, which adds physical evidence to the selected periods.

The reduction in streamflow observed at the gauging stations since 1976 in the high rainfall areas (mean annual rainfall >1,100 mm) has resulted in a significant change in the flow duration of the streams. The flow duration, in the streams of the high rainfall areas flow, at various flow rates has typically decreased by between 10 and 25 %. This is most evident by the 25 % reduction in the period of time during which the Yarragil Brook streamflow gauging station has recorded flow since 1975 compared to prior to 1975 (Figure 4.1).

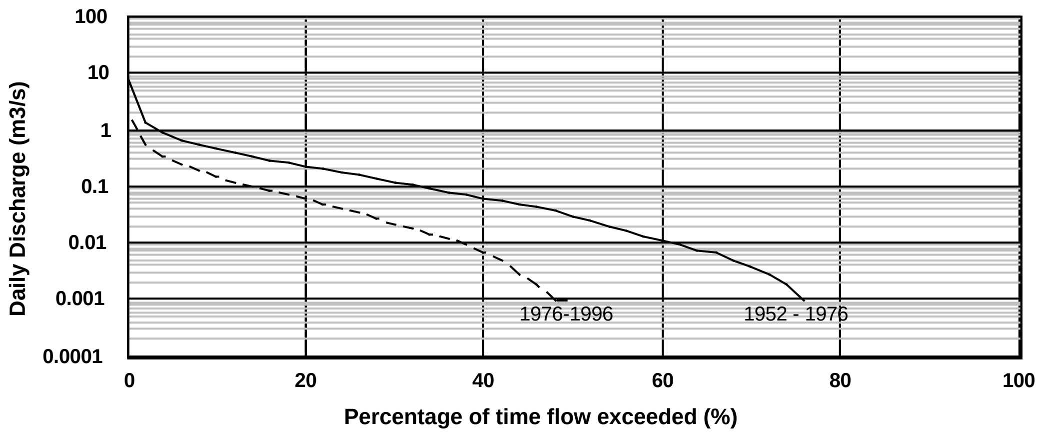


Figure 4.1. Flow duration curves for the Yarragil Brook gauging station (614 044).

The gauged streams draining catchments with lower mean annual rainfalls do not exhibit a similar response in flow duration since 1976 as observed in the higher rainfall areas. Flow duration at various flow rates has changed only slightly since 1975 at high and medium flows, while the duration of the very low flows (<1 m^3/s) has typically increased. This is evident at the Thomson Brook gauging station (Figure 4.2) where an approximate 10% increase in flow duration is observed at these very low flow rates. The relatively high degree of clearing which is commonplace in the lower mean annual rainfall catchments, including Thomson Brook, may be altering the hydrologic characteristics of the catchments. The high degree of clearing may also indirectly alter the flow in streams due to the construction of small farm dams and embankments, to irrigate crops and provide a drinking supply for stock. A number of the larger catchments in these lower rainfall, largely cleared catchments exhibit very little change in the flow duration between the period prior to 1976 and since this date. The catchments which receive the least rainfall of those studied, Williams and Murray Rivers in Basin 614, both show that a decrease in the flow duration has taken place since 1976. This may imply that the increase in runoff resulting from a high degree of catchment clearing may be more than negated by the impact on runoff resulting from a decrease in annual rainfall.

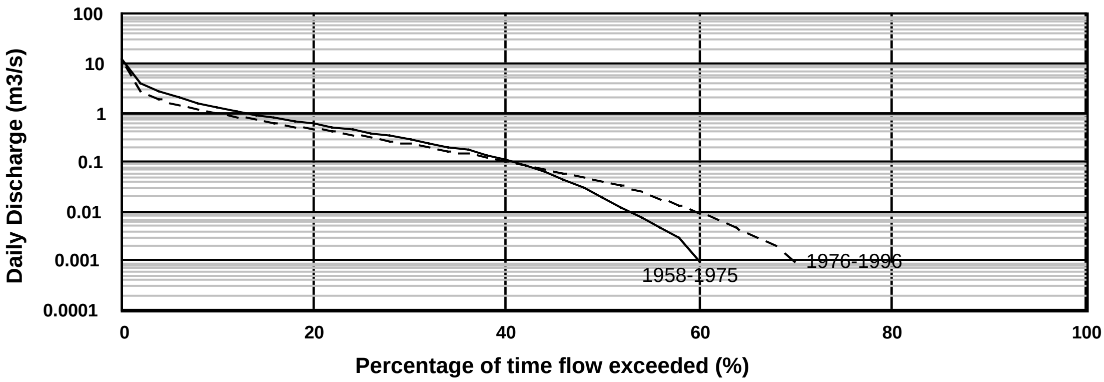


Figure 4.2. Flow duration curves for the Thomson Brook gauging station (611 111).

4.2 Monthly Streamflow

As discussed in Section 3.1.3 the timing of the observed trend or change in mean in the annual streamflow in the south west of Western Australia was focussed between the years of 1974 and 1976. In order to investigate the change in monthly flows, since this trend or change in mean was observed in annual flows , the average monthly flows prior to, and including, 1975 and the average since 1975 were examined.

The mean monthly streamflow since 1975 is less than the mean prior to 1975 for all long term (>50 years of data) gauged streams (Figure 4.3). The difference between the mean monthly streamflow prior and post 1976 tends to increase as the mean annual catchment rainfall increases from Basin 602 to 614. The decrease is only evident in the largest streamflow months of July and August in Basins 602 to 605, but is increasingly more evident during the entire high flow season of May to October, in the remaining Basins 606 to 614.

The results from gauging stations in Basins 602 and 603 with period of records of less than fifty years indicate that the mean monthly streamflow has tended to increase since 1975 (Appendix A). This would not appear to agree with the results for the long term Mt Lindesay gauging station on the Denmark River for which a slight decrease in mean monthly streamflow was observed, most notably during the peak flow month of August. The increase in the mean monthly streamflow since 1976 is also observed at the Mt Lindesay gauging station if a shorter period of record is selected (Figure 4.4). This may indicate that there was a period of relative low flows during the 1960's and early 1970's in Basins 602 and 603 and that the monthly streamflow since 1976 has tended to be equivalent to the various averages.

There is no similar dependence on the period of record for the gauging stations in Basins 606 to 614. The decrease observed in mean monthly streamflow during the high flow period at the long term gauging stations is also illustrated in the results of a similar analysis at the gauging stations with shorter periods of record (<50 years of data) (Appendix A). This may imply that the monthly streamflow since 1976 has been below average in the streams of these Basins.

A similar result is observed in the Helena River data in higher rainfall, hills area of Basin 616. The streamflow in Lennard and Gingin Brooks to the north of Perth, in coastal plain portions of Basins 616 and 617, is characterised by a high baseflow component. This baseflow may mask any change in the mean monthly streamflow, generated from surface runoff. The change in mean monthly streamflow since 1976 has been only slight in both of the streams with Lennard Brooks' streamflow marginally greater since 1976 (Appendix A).

The modelled inflow data for the metropolitan water source reservoirs, in Basins 614 and 616, all show a similar result as the gauged data for Basins 606 to 614 and the hills region of Basin 616. The monthly flows since 1976 have averaged significantly less than the average of the monthly flows during the 65 years of data prior to 1976 (Figure 4.5).

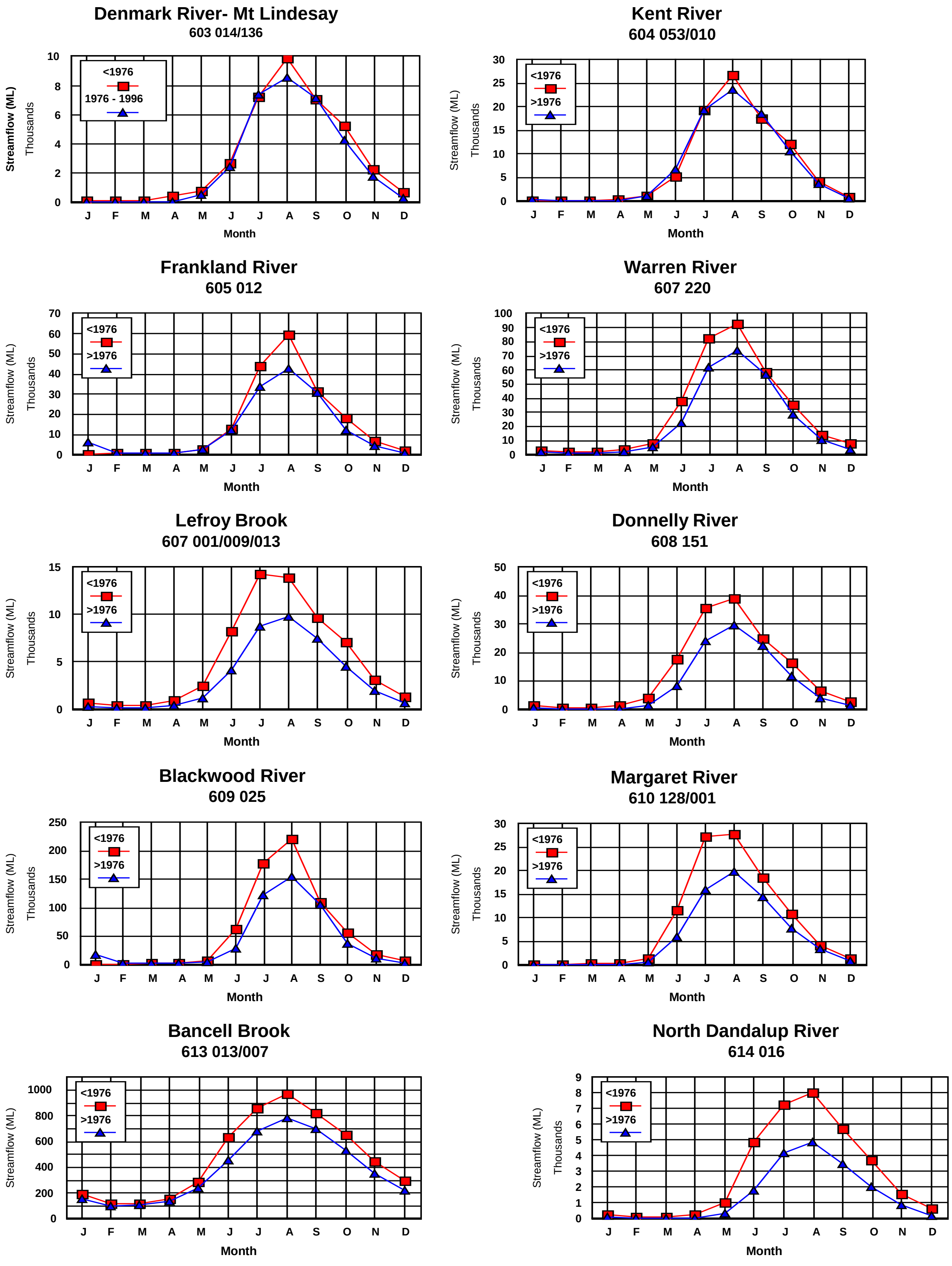


Figure 4.3. Variation in monthly streamflow at the long term gauging sites in the south-west.

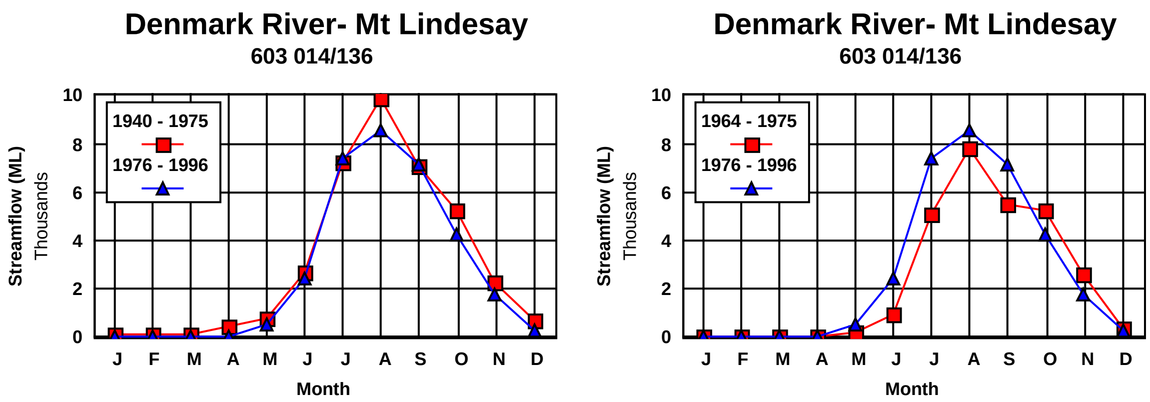


Figure 4.4. Effect of period of record on mean monthly streamflow at the Mt. Lindesay gauging station on the Denmark River.

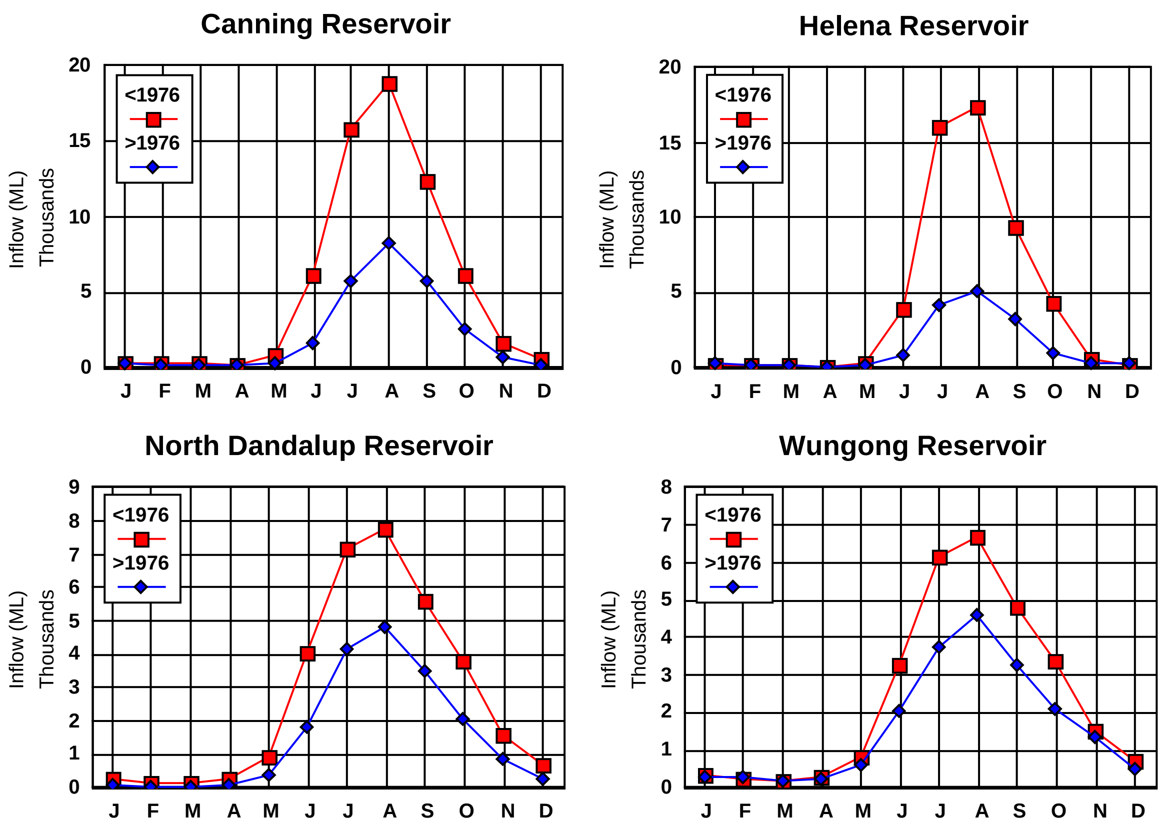


Figure 4.5. Variation in monthly inflows to the metropolitan water source reservoirs.

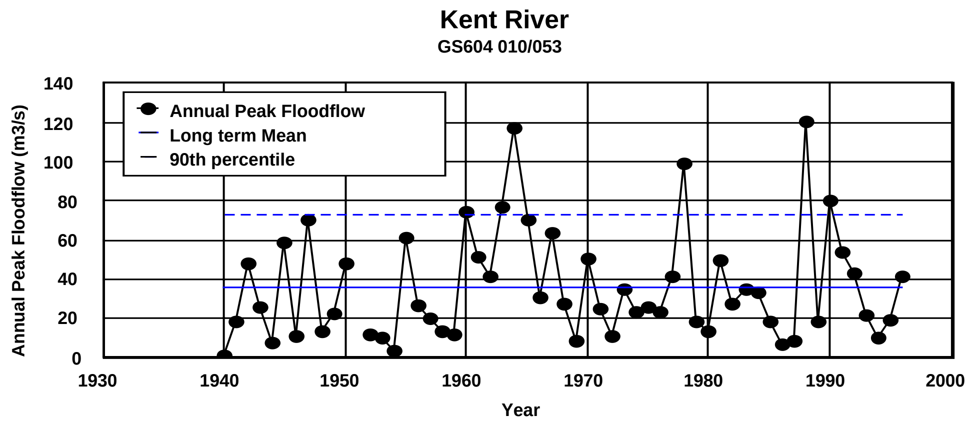
5. Trends in Floodflows

5.1 Gauged Data

5.1.1 Annual floodflow

The annual floodflows for a number of gauging stations in the south-west is illustrated in Figures 5.1 and 5.2. The streams in the south west with mean annual catchment rainfalls of less than 1000 mm show no evidence of any trend in peak annual floodflows (Figure 5.1). The peak annual floodflows in the southern higher rainfall (>1000mm/year) catchments, covering portions of Basins 606 to 609 and 613 and 614, appear to illustrate a slight trend toward lower floodflows since 1975 (Figure 5.2). However, the presence of a downward trend in annual peak floodflows does not appear to be as evident in the data for the Donnelly River and Bancell Brook gauging station, shown in Figure 5.2. This lack of evidence toward a trend in peak floodflows at the longer term gauging stations in Figure 5.2 may indicate that the apparent trend, at the shorter term gauging sites in the south-west, may result from the coincident timing of the beginning of floodflow records and a period of large floodflows in the late 1950's and early 1960's.

Although no obvious trend in peak annual floodflow data exists in Figures 5.1 and 5.2 there would appear to be a reduction in the number of extreme flooding events (greater than, or approaching, the 90th percentile) in the higher rainfall areas of the south-west, independent of the period of record, since 1975 (Figure 5.2). This reduction in major floodflows is not observed in the lower mean annual catchment rainfall areas (Figure 5.1).



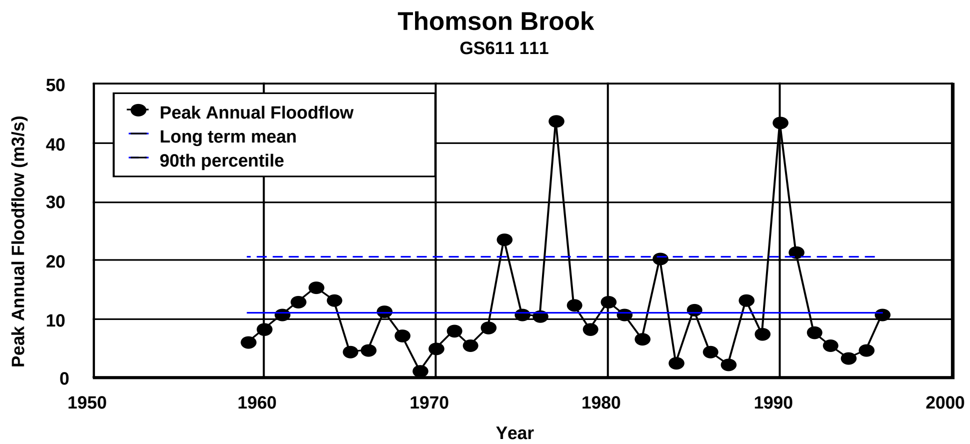


Figure 5.1. Annual Floodflow data for the lower rainfall (<1000mm/year) catchments in south-western WA.

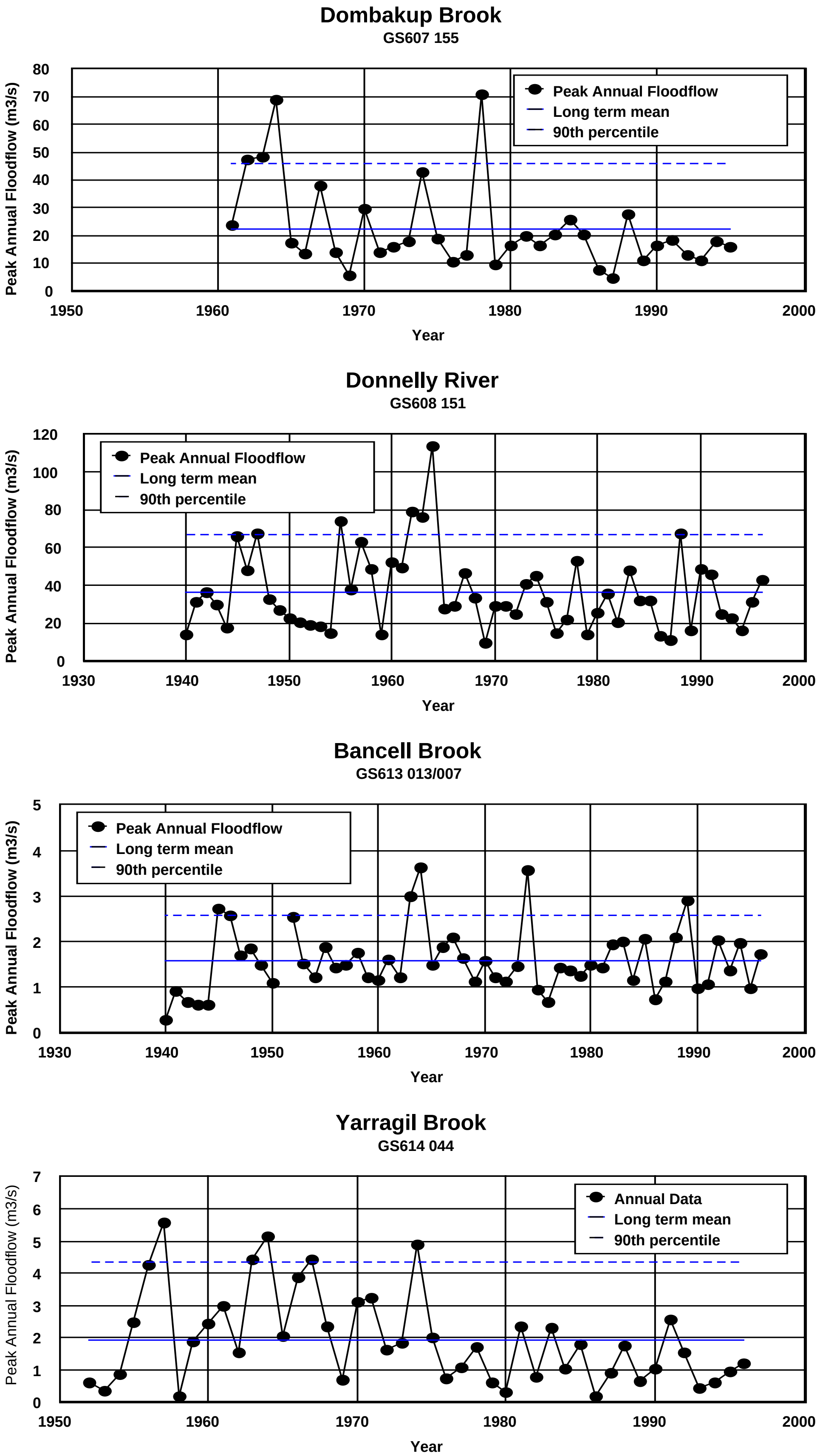


Figure 5.2. Annual Floodflows for the high rainfall (>1000mm/year) catchments in the south-west of WA.

5.1.2 Loess Regression

The Loess regression curves on the peak annual floodflows, for the gauging sites with data beginning in 1940, are similar throughout the south-west. The curves illustrate that the peak floodflow typically increased between the mid 1950's into the early 1960's, since which time it has typically decreased to a similar level to that prior to the increase. The floodflow data at shorter term gauging sites appear to show a decreasing trend, but, are most likely to be illustrating this decrease in annual peak floodflows from the relatively high period during the mid-1950's and early 1960's observed in the longer period gauged data sets. Figure 5.3 shows the typical shape of distance weighted least squares regression curves using the Statistica Package, which are similar to the Loess curves in MHTS (McLeod and Hipel, 1995).

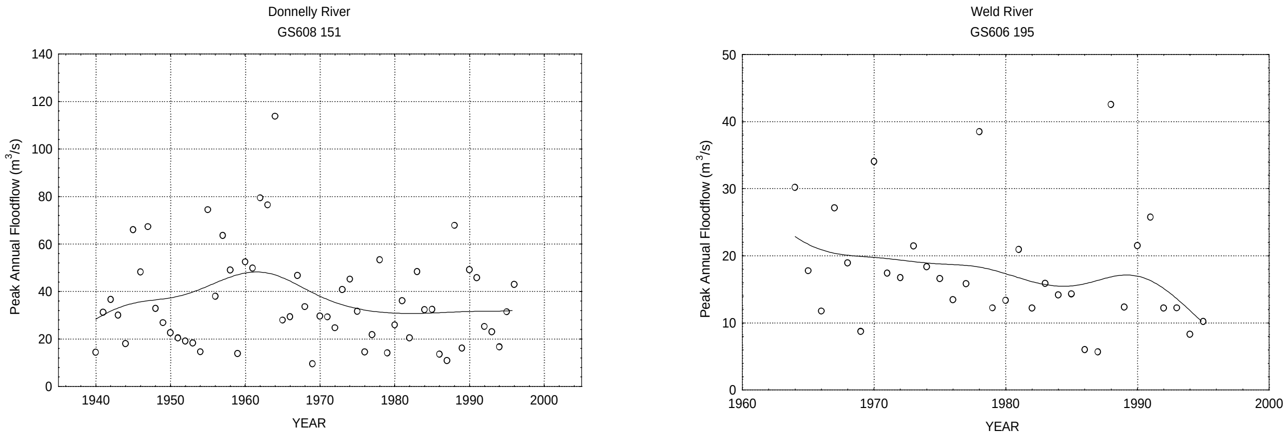


Figure 5.3. Least squared regression curves for the Donnelly and Weld Rivers

5.1.3 Design Floodflows

The design floodflows for period starting in 1976 was compared to the design floodflows for the entire period of record at the gauging stations with long term annual floodflow data (> 36 years). The comparison was based on the results from the AFAP flood frequency analysis program.

The effect on the design flood estimates of the reduced number of extreme flood events in the high mean annual rainfall catchments since 1976 is illustrated in the flood frequency curves for the North Dandalup gauging station (Figure 5.4). The flood frequency curve for the North Dandalup gauging station shows that the design flood estimates are substantially lower for the period since 1976 than for the entire period of record, in this case 1940 to 1994 (Figure 5.4). This decrease observed in the 100 year design floodflow estimate at the long term gauging stations in the AWRC Basins 607, 608, 610, 613 and 614 ranges from 50% to around 5%, with a mean and median of about 75%. It is likely that a similar result would be observed in Basins 606 and the high rainfall catchments of Basin 609 if longer term floodflow data sets were available.

A similar result is not observed in the flood frequency curves for the Frankland River gauging station (Figure 5.5). The Frankland River flood frequency data is representative of the results from gauging stations in the lower mean annual catchment rainfall areas of the south-west. The design floodflows are typically slightly higher for the period since 1976, than for the entire period of record (Figure 5.5). This result was observed for stations in AWRC Basins 603 to 605, 611 and 612.

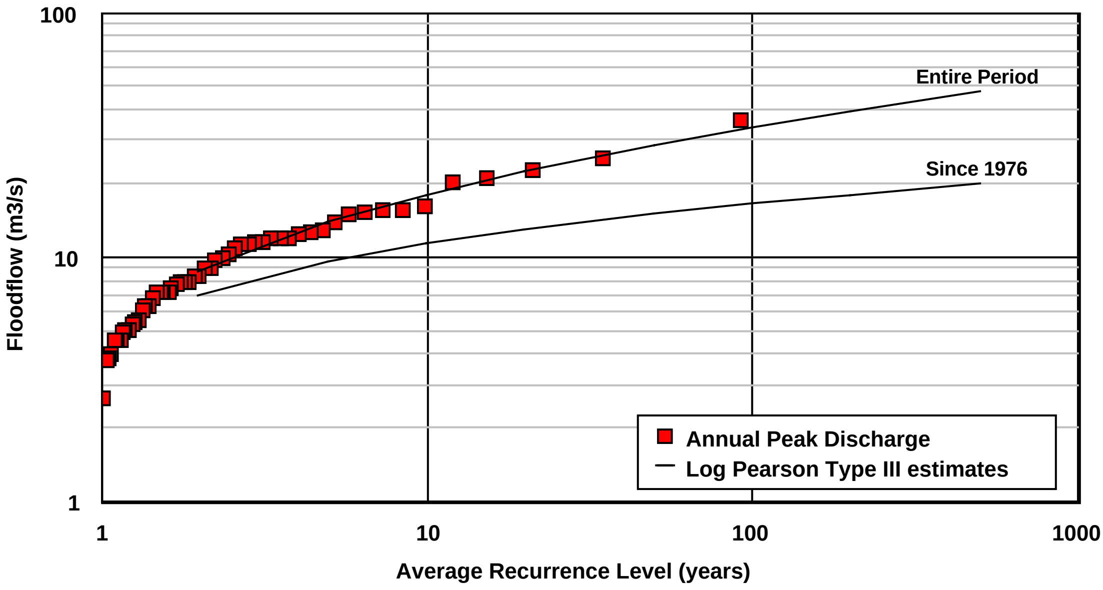


Figure 5.4. Flood frequency curve for the North Dandalup River at the Scarp Road gauging station.

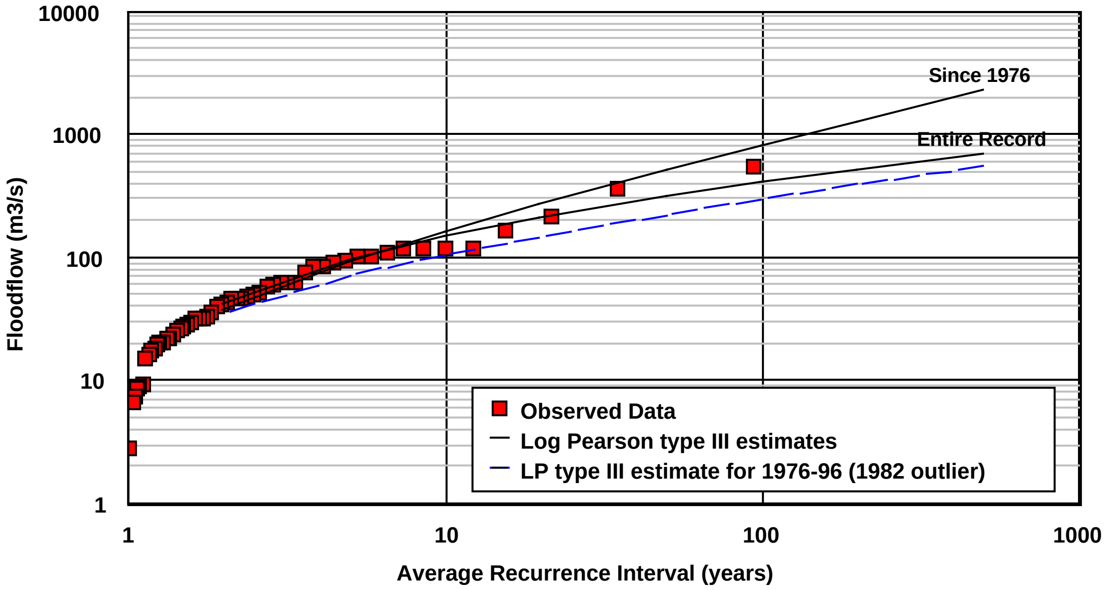


Figure 5.5. Flood frequency curve for the Frankland River at the Mt Frankland streamflow gauging station.

5.1.4 Trend Analysis

The trend tests described in section 2.2 were applied to the peak annual gauged floodflow data for the streamflow sites described in able 2.1. The Brillinger trend test was not appropriate for the floodflow trend analysis because it is based on a centred moving mean which is not robust enough to cope with outliers. The Distribution-free CUSUM test, which is based on comparing annual floodflows to a median value is sufficiently robust to analyse the floodflow data. However, the annual floodflow data still has high autocorrelation which may influence the results in the Distribution-free CUSUM test.

The results of the trend analysis on gauged floodflows does not provide evidence of a statistically significant trend, or change in mean, in the majority of cases. The Weld River, in Basin 606, and Davies and Yarragil Brooks, in Basin 614, are the only streams for which there is a significant trend in floodflows indicated by the results of the Distribution-free CUSUM test. The trend in annual floodflow occurs between 1975 and 1976 at each of these three stations. The three catchments all receive greater than 1000mm of rainfall annually and are free from any significant clearing. This result may provide further evidence that any trend in peak floodflows decreases with increasing clearing.

5.2 Modelled Data

5.2.1 Annual Floodflows

The annual floodflows for the Avon River at the Walyunga streamflow gauging station since 1907 are shown in Figure 5.6. The floodflows since 1970, when the Walyunga gauging station commenced operation, are gauged flows. Prior to this date the annual floodflows have been estimated by multiplying a scaling factor by the peak daily discharge in each year from a Sacramento model developed for the Avon River (Lawrence and Harvey, 1978). Figure 5.6 shows that, although there has been a few large observed floodflows, the gauged floodflows were typically less than the long term mean and median for the period between 1970 and 1990. This is most evident during the six year period between 1984 and 1989, inclusive. Since 1990 the observed floodflows on the Avon River have tended to be more scattered about the long term median, but, floodflows are still relatively small, with a maximum only slightly greater than the long term mean.

An indicative data set of instantaneous peak floodflows since 1907 for the Blackwood River Darradup gauging station has also been developed. The gauged data at the station extends from the present back to 1955 and the floodflows prior to 1955 have been estimated using a Sacramento model for the Blackwood River catchment (PWD, 1984). A comparison of Figures 5.6 and 5.7 show that the periods of large and low floodflows are similar for both the Avon and the Blackwood Rivers.

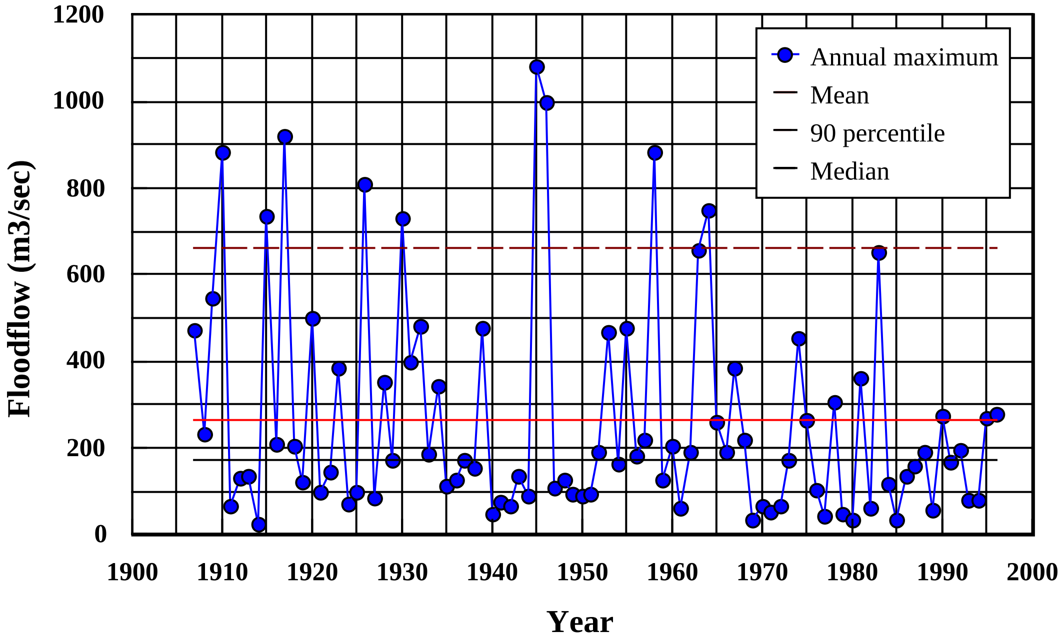


Figure 5.6. Estimated and gauged annual floodflow for the Avon River (GS 616 011).
(note: Floodflows since 1970 are gauged while those prior to 1970 are modelled)

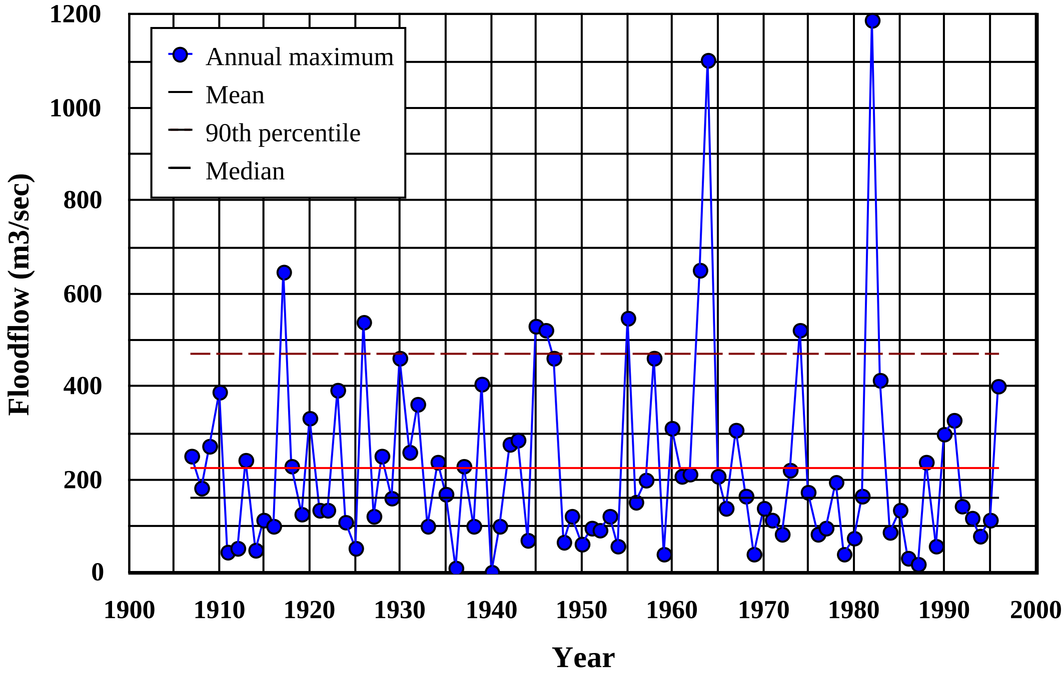


Figure 5.7. Estimated and gauged annual floodflow for the Blackwood River (GS 609 025).
(note: Floodflows since 1955 are gauged while those prior to 1955 are modelled)

5.2.2 Loess and Alternative Smoothers

The Loess and distance weighted least square regression curves, using the MHTS PC and Statistica packages respectively, for the extended Avon River floodflow data set indicates there has been a slight decreasing trend in annual floodflows over the entire period of the data. A similar analysis of the extended Blackwood River floodflows does not indicate any trend in the floodflow data (Figure 5.8).

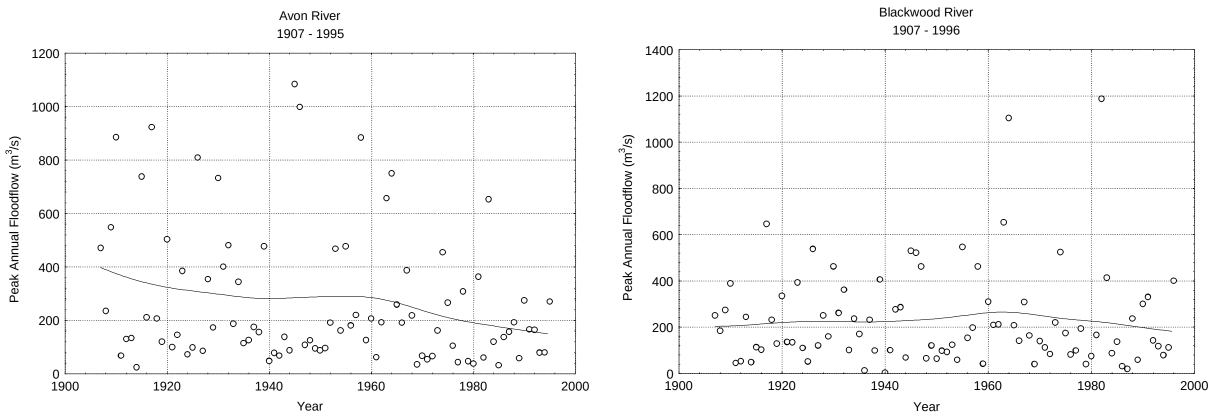


Figure 5.8. Distance weighted least square regression curves for the modelled floodflows on the Avon and Blackwood Rivers.

5.2.3 Design Floodflows

The effect of the period of record used during a flood frequency analysis was examined for both the Blackwood and Avon Rivers floodflow extended data sets. Interestingly, the effect differs markedly between the two stations. The design 1 % Annual Exceedance Probability (AEP) floodflow for the Blackwood River Darradup gauging station and a period of record beginning in 1980 is approximately twice that obtained using the entire period of record. This is due to the extreme events which took place in July 1964 and January 1982, which are almost twice the magnitude of any other event during the 1907 to 1996 period, biases the smaller periods of record results. The 1% AEP design flow increases by approximately only 10% for periods of record starting between 1940 and 1907. The 1 % AEP design flow then increases by about 60% for a period of record back to 1950 and then decreases by about 15% for a period of record of 1970 to present, only to increase by 25 % for a period of record beginning in 1980. The increase in the 1 % AEP design flow is consistent with the results from the gauged floodflow data in relatively low mean annual rainfall catchments.

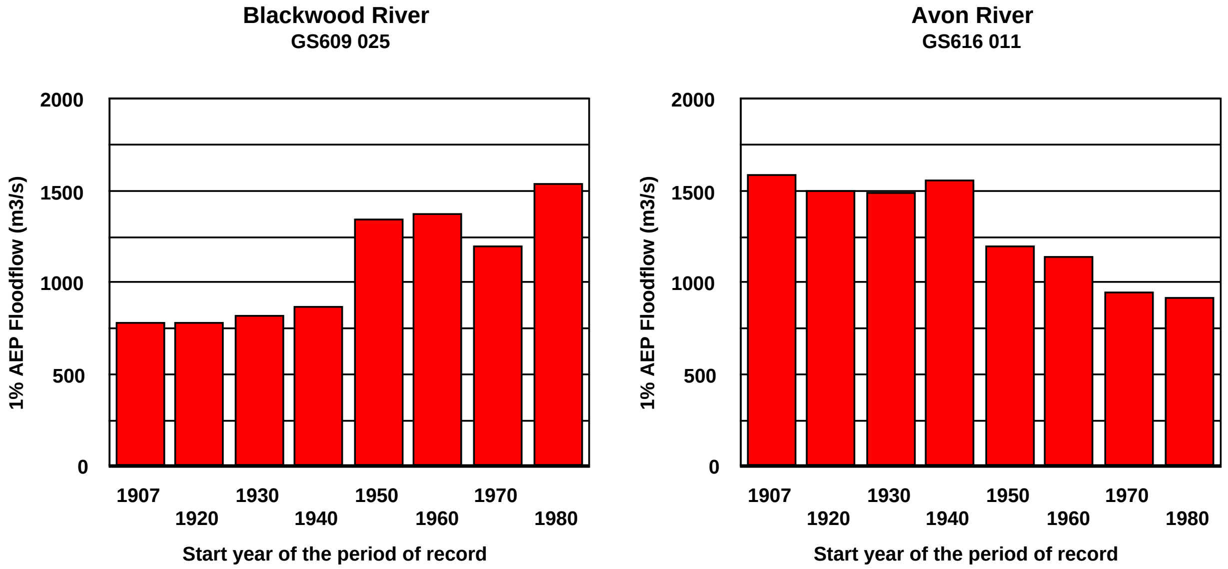


Figure 5.9. Effect of the period of record on the design 1 % AEP floodflow.

The 1 % AEP floodflow for the Avon River Walyunga gauging station is also fairly constant at periods of record starting earlier than 1940. However, for a period of record starting in 1950 the design 1 % AEP floodflow falls by around 20 % and then continues to fall with periods of record beginning in 1960, 70 and 80. The percentage decrease from the 1 % AEP floodflow using the entire period of record (1907-1996) to that for a period of record of 1980 - 1996 is approximately 42 %. This may indicate that there has been a decreasing trend in peak annual floodflows since 1940 which is not consistent with the gauged floodflow data for relatively low mean annual rainfall catchments. However, the gauged data results is based on flows in the Collie and Preston River Basins and catchments along the South Coast rather than in the wheatbelt.

The 1 % AEP floodflow for the gauged data for the Blackwood and Avon Rivers begins in 1955 and 1970, respectively. These starting years represent an increase of around 70 percent in the Blackwood River, and a 40 percent decrease in the Avon River design 1 % AEP floodflow estimates compared to the estimate for the entire record.

5.2.4 Trend Analysis

The Distribution-free CUSUM test was applied to the extended peak annual floodflow data sets for the Blackwood and Avon Rivers. The results of the trend analysis for both the Blackwood and Avon Rivers floodflows does not indicate that there has been a statistically significant trend , or change in mean.

6. Relationship of Streamflow with Climate

6.1 Streamflow and Rainfall in the south-west

The annual runoff in the south west of Western Australia is related annual catchment centroidal rainfall and a number of physical catchment characteristics such as clearing (Muirden, pers. comm). Ruprecht *et al*. (1996) discusses the results of an analysis of long term rainfall records by Roger Tapp from the Bureau of Meteorology. The results of this analysis is summarised in Figure 1.1. The areas of large decreases in decadal rainfall coincide with the areas which indicate the possible existence of a trend or change in mean of annual streamflow (Section 3). Ruprecht *et al*. (1996) state that the trend in decreasing rainfalls indicated by Roger Tapp's analysis is strongest for the period May to October and weaker and more varied between November and April. Allowing for a lag of one month between relative peaks in rainfall and streamflow this corresponds with the results observed in the monthly analysis (Section 5.3).

6.2 Streamflow and the Southern Oscillation Index (SOI)

The flow in the streams of south west Western Australia has been shown to be strongly linked to rainfall during the May to October period. The rainfall during this six month period contributes on average over 85% of the total annual rainfall and appears to be linked to the SOI averaged over the same period (Sadler, 1997). Not surprisingly, the May to October streamflow in the south west of Western Australia also appears to relate to the average SOI for the May to October period.

The six month period between May and October typically accounts for greater than 90% of the annual streamflow. During an El Nino period (SOI<-5) the streamflow during the May to October period is typically less than the long term mean and it is unlikely that a high flows will be observed in the south west streams (Figure 6.1). Conversely, during a La Nina period (SOI>5) south west streamflow is typically large with flows greater than the long term mean common. During a normal year (-5<SOI<5) there is no identifiable relationship with streamflow in the south west. However, the larger frequencies of the extreme high and low flows during La Nina and El Nino periods may indicate that these extremes are less likely to occur during a normal year (Figure 6.1).

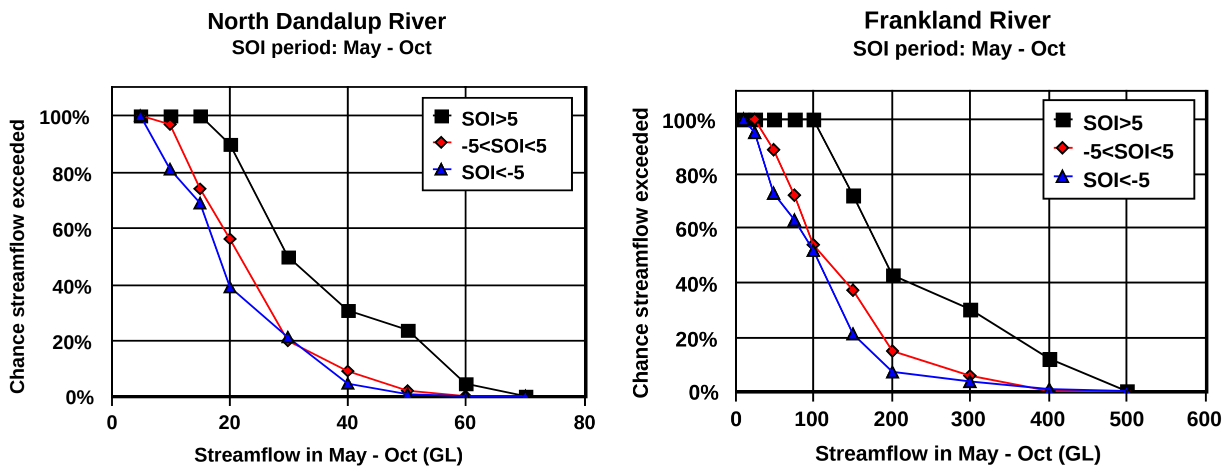


Figure 6.1. Effect of mean May - October SOI on the streamflow during the same period.

This relationship between the SOI and the streamflow in the south west helps to explain the reason for the reduction in streamflow volumes observed in the streams of the south west since 1976. During the last two decades there has been a total of eight El Nino and only four La Nina (including 1996) May to October periods. In contrast, between 1940 and 1975 there was eight El Nino and twelve La Nina, May to October, periods.

The effect of using a different mean SOI period on the May to October streamflow has a significant impact on the observed relationship (Figure 6.2). The March to May mean SOI reduces the number of observed La Nina periods since 1940 from 16 to 10, while the number of El Nino periods has remained constant at 16. Since 1976 the number of March to May El Nino periods has increased slightly from eight to nine and there has been only two La Nina March to May periods.

The relationship between El Nino periods and low streamflow volumes in south-west streams and the La Nina periods with high flows is not as evident when using an average SOI prior to the winter period(Figure 6.2).

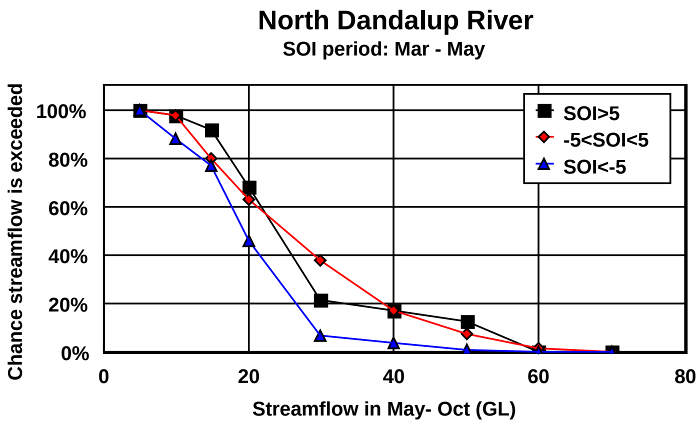


Figure 6.2. Effect of mean March to May SOI on streamflow between May and October in the south west of Western Australia.

7. Concluding Discussion

7.1 Climate Variability

Decadal to multi-decadal variability in climate has been well documented.

Recent modelling suggests that interdecadal (~15-35 years) period and century-scale (~(50-150 years period) climate variability may be intrinsic to the climate system (Mann et al, 1995).

Ware (1995) has identified four dominant time series:

- 2-3 year (quasi-biennial oscillation)
- 5-7 year (El Nino - SO)
- 20-25 year (bidecadal oscillation)
- 50-75 year (poorly resolved, low frequency oscillation)

Studies in North America of instrumental climate data and isolated long-term proxy records suggest that interdecadal climate variability is closely related to a pressure anomaly pattern called the “Pacific Pan American”. Connections have also been found with low-frequency changes such as ENSO.

7.2 Implications for Water Resource Management

The relatively recent climate history is considered to be part of the natural climate variability.

Allocations for water abstraction should take into account the lower streamflow observed in the last two decades, particularly for the Perth water supply. However the long term sustainable yield should be based on long periods of data which incorporate the extended dry periods observed in the last 25 years. Additional performance criteria need to be developed to incorporate the impact of sustained periods of time when streamflow is below average and consequently the water supply system is under some sort of restriction. The most useful terms are resiliency and vulnerability. Where resiliency is the ability of a system to recover from a failure and vulnerability is a measure of the likely severity of a failure. In the case of the Perth water supply system the resiliency of the system to recover from a failure is considered low given the period of restrictions observed in the last 30 years.

The impact of the interdecadal period of low streamflow on the ecology of our rivers needs to be understood. Many rivers, particularly in the Northern Jarrah Forest have had reduced streamflow are now reducing to no flow much earlier than in the period prior to 1975. The ecological impact of this change is uncertain and needs to be understood.

7.3 Implications for Flood Management

The lack of major floods in the areas from the Murray to Avon Rivers in the south west of Western Australia has significant environmental and social impacts. The environmental impacts are that there is substantial quantities of river sediment which in a major flood could be mobilised and impact on river pools along the Avon River and into a the Swan estuary. The social impacts are that the communities along the rivers, particularly the Swan, Avon, and Murray Rivers have not experienced flooding for many years, at least since 1964. The decline in the level of preparation of a community for flooding with duration after flooding is substantial. The percentage of a community prepared for flooding deteriorates to less than 10% 30 years after the last flood (Lustig and Maher, 1997).

7.4 SOI Relationship

The relationship between SOI and streamflow identified in section 6 has provided some potential to predict streamflow, particularly when the SOI is above 5. For example on the North Dandalup River there is change from only 40% to 90%

chance the mean annual flow of 20 GL will be exceeded if the SOI for winter and spring is below 5 compared to above 5.

7.5 Further Investigations

If greater understanding of the climate variability is to be achieved investigations with the following major objectives should be undertaken:

1) to better our understanding of mechanisms that lead to multi-year persistence of climate anomalies in the south west of WA;
2) to supplement the modern climate record by using carefully selected proxy records, such as tree rings; and
3) to improve estimates of the return periods of significant dry and wet regimes over the south west of WA by incorporating paleoclimate data.

Questions to be addressed about decadal scale variations include:

1) what are the spatial scales of multi-year fluctuations, and how do they compare with those of shorter period fluctuations?,
2) is the variability of precipitation independent from that of temperature on these multi-year time scales?, and
3) is there greater persistence in factors that drive winter wet/dry precipitation or in factors that drive summer warm/cool temperatures?

Extension of the hydroclimatological indices may provide insight into several questions:

a) are climatological shifts such as those witnessed in the mid-1970's seen in the pre-instrumental period?
b) in the long term, how prominent is decadal variability? and
c) how stable are the long-term statistics of droughts and wet periods in south west WA?

A basin-specific tree-ring reconstruction of streamflow in the south west would be useful to link our findings on large-scale patterns of hydroclimatic variability to the history of persistent flow anomalies in the critical water supply region.

Questions still unanswered include, are the climate anomaly patterns evident during the past couple of decades in the south west of WA unique? Are the observed recent large-scale patterns of hydroclimatic variability unusual in relation to past ENSO and hemispheric circulation patterns.

One major issue to be tested is whether there are tree ring indices applicable to south west Western Australia.

8. References

Brillinger, D.R., 1994, Trend Analyses: Time Series and Point Process Problems, Environmetrics Vol 5. pp 1-19

Brillinger, D.R., 1989, *Consistent detection of a monotonic trend superposed on a stationary time series*, Biometrika No. 76 pp22-30

Burroughs, W.J. 1992, *Weather cycles: real or imaginary?*, Cambridge University Press

Campbell, E.P., 1998, *A Review of Statistical Techniques For Assessing the Effect of Climate Variability on Streamflow*, CSIRO Mathematical and Information Sciences, Report No. CMIS98/32.

Chiew, F.H.S. and McMahon, T.A., 1993. *Detection of a trend or change in annual flow of Australian rivers*. International Journal of Climatology, 13, 643-653.

Cleveland, W.S. 1979, Robust locally weighted regression and smoothing scatterplots, Journal of American Statistics Association 74, p829-36

Grayson, R.B., McMahon, T.A., Nathan, R.J., Argent, R.M., Mein, R.G., 1996. *Hydrologic Recipes: Estimation Techniques in Australian Hydrology*, Cooperative Research Centre for Catchment Hydrology.

Helsel, D.R. and Hirsch, R.M., 1992, Statistical Methods in Water Resources, Studies in Environmental Science 49, Elsevier, Amsterdam, The Netherlands

Hipel. K.W. & McLeod, A.I., 1994, *Time Series Modelling of Water Resources and Environmental Systems*, Developments in Water Science Series No.45, Elsevier, Amsterdam, The Netherlands

Lawrence, G. and Harvey, R.A., 1978, Swan Avon Rivers Food Study, Water Resources Technical Report No.77, Planning Design and Investigation Branch, Public Works Department, Western Australia.

Luke G.J. Burke, K.L. and O'Brien, T.M., 1988, Evaporation Data for Western Australia, Western Australian Department of Agriculture, Technical Report No. 65.

McLeod, A.I. & Hipel, K.W. 1995, *The MHTS PC Package Reference Manual*

Meko, D., Stockton, C.W., and Boggess, W.R., 1995, The Tree-ring Record of Severe Sustained Drought, Water Resources Bulletin Vol. 31 No.5, pp 789-801

Ott, L. 1984, *An introduction to statistical methods and data analysis 3rd edition*, PWS-Kent Publishing Company, Boston

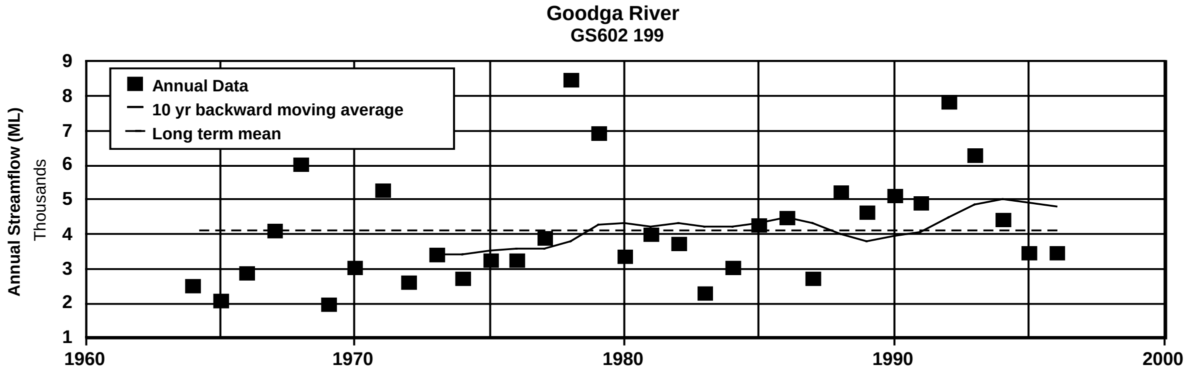
Ovington J.D. and Pryor, L.D. 1983. Temperate broad-leaved evergreen forests of Australia, In: J.D. Ovington (ed) Ecosystems of the world , Vol 10. Temperate broad-leaved Evergreen Forests. Elsevier, Amsterdam, pp 73-101.

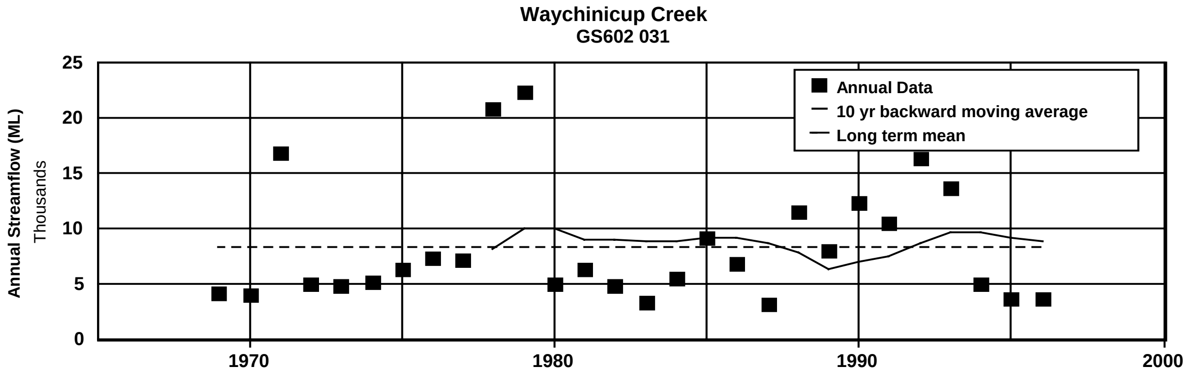
PWD, 1984, Blackwood River Flood Study, prepared for the Public Works Department, Western Australia.

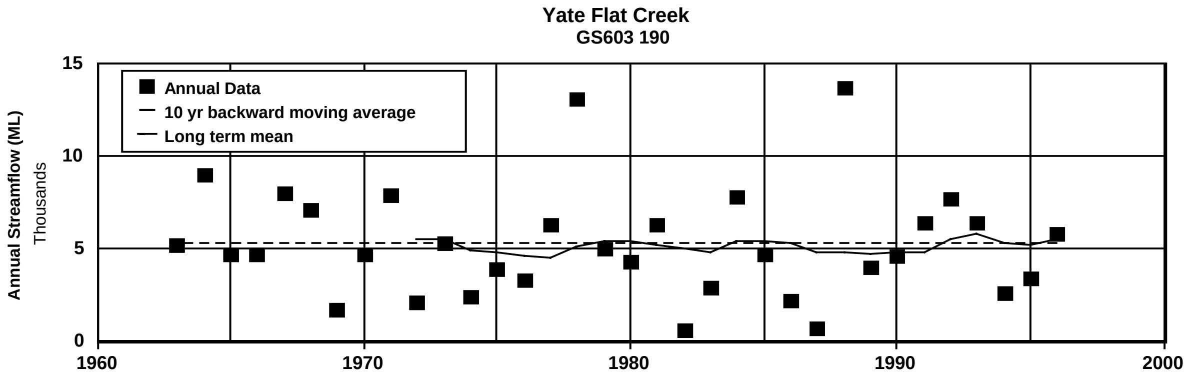
Ruprecht, J.K., Bates, B.C. & Stokes, R.A., eds. 1996, *Climate Variability and Water Resources Workshop*, Water and Rivers Commission, Water Resources Technical Report Series No WRT 5.

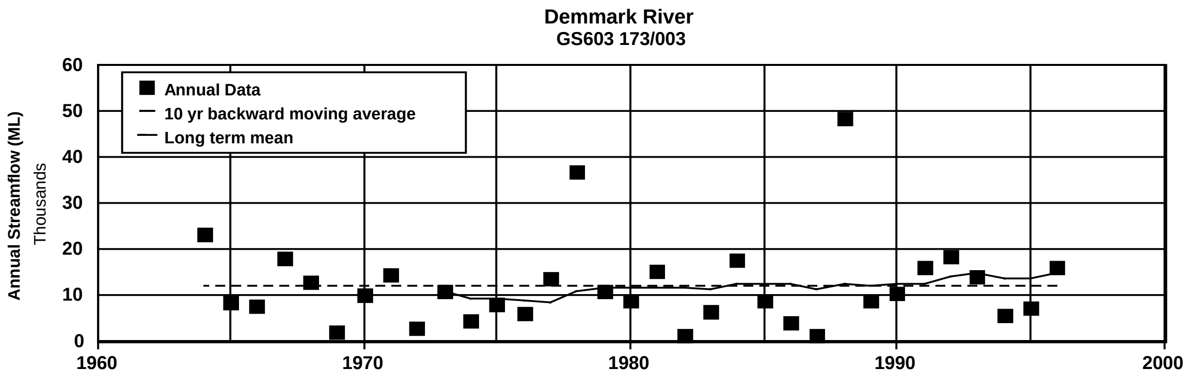
Appendix A: Annual and Seasonal Variation in Streamflow

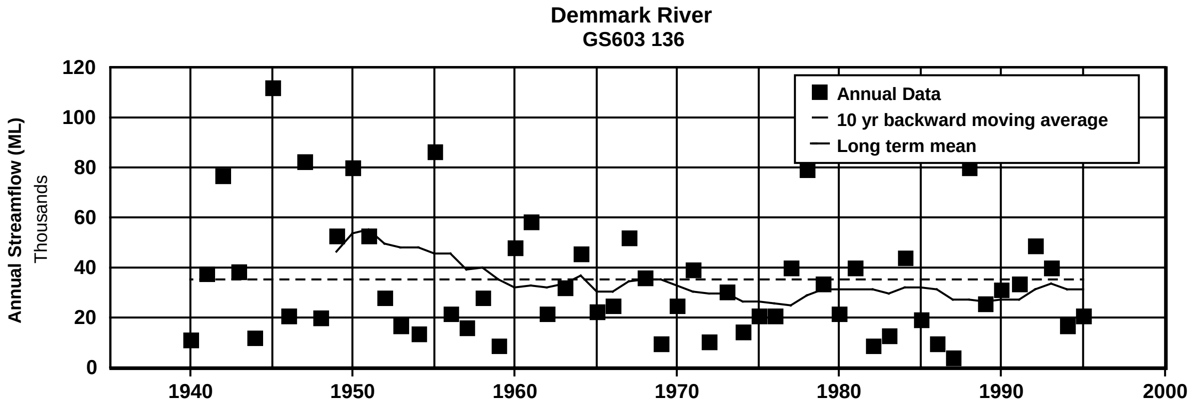
ANNUAL:

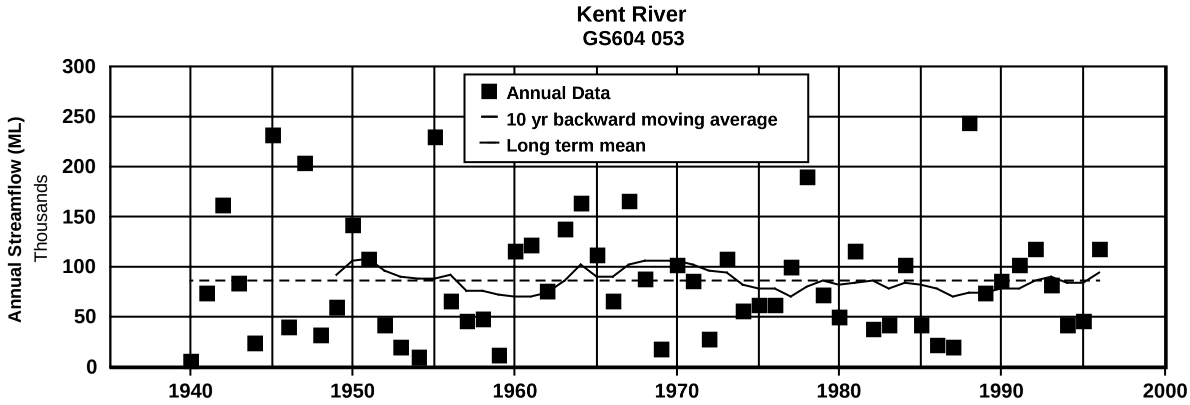


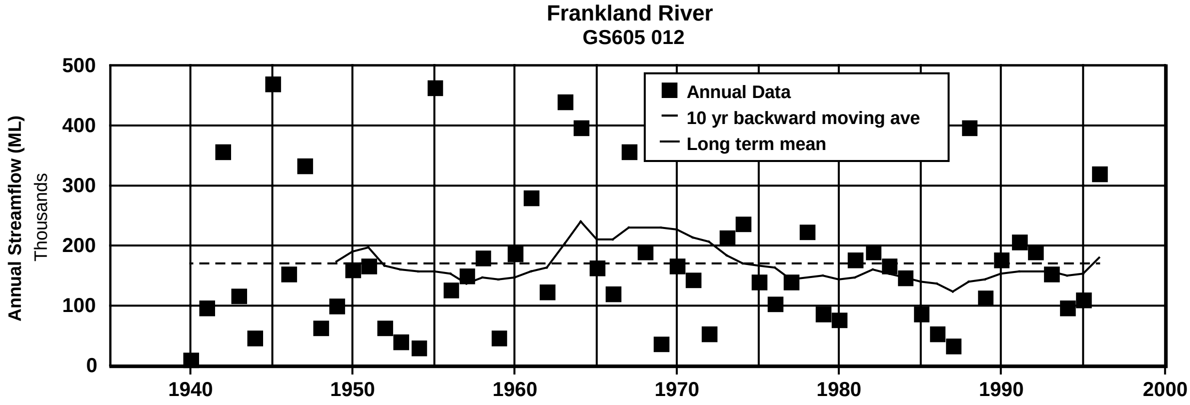


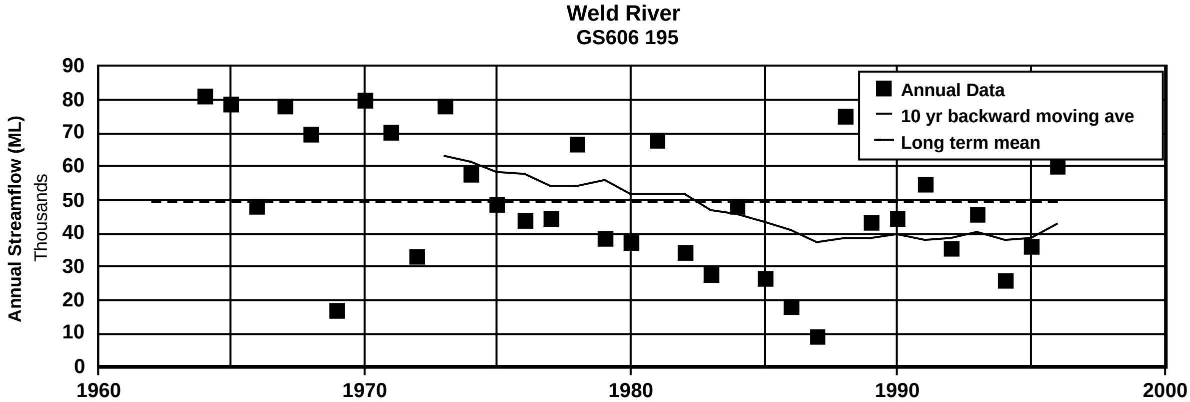




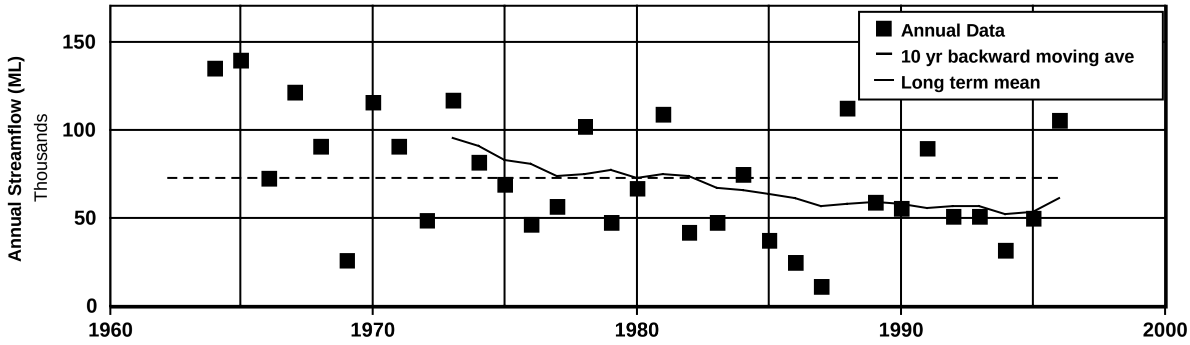

Demmark River
GS603 136
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving average
Long term mean
120
100
80
60
40
20
0
1940
1950
1960
1970
1980
1990
2000


Kent River
GS604 053
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving average
Long term mean
300
250
200
150
100
50
0
1940
1950
1960
1970
1980
1990
2000

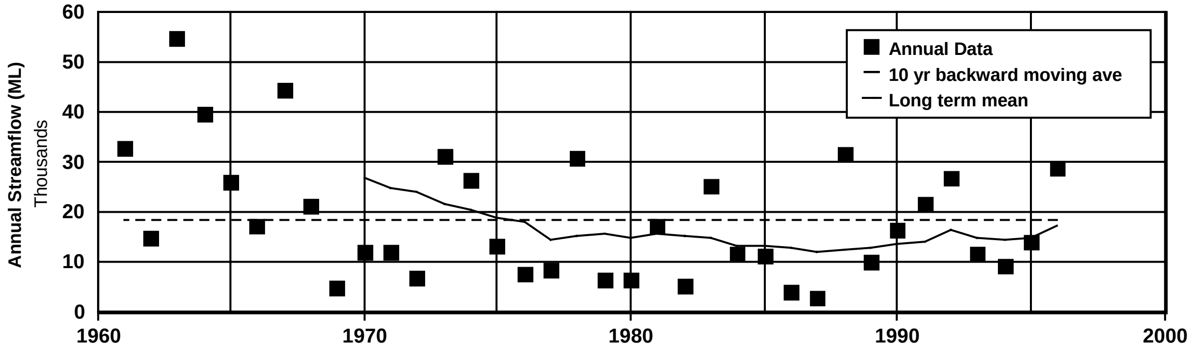

Frankland River
GS605 012
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving ave
Long term mean
500
400
300
200
100
0
1940
1950
1960
1970
1980
1990
2000


Weld River
GS606 195
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving ave
Long term mean
90
80
70
60
50
40
30
20
10
0
1960
1970
1980
1990
2000

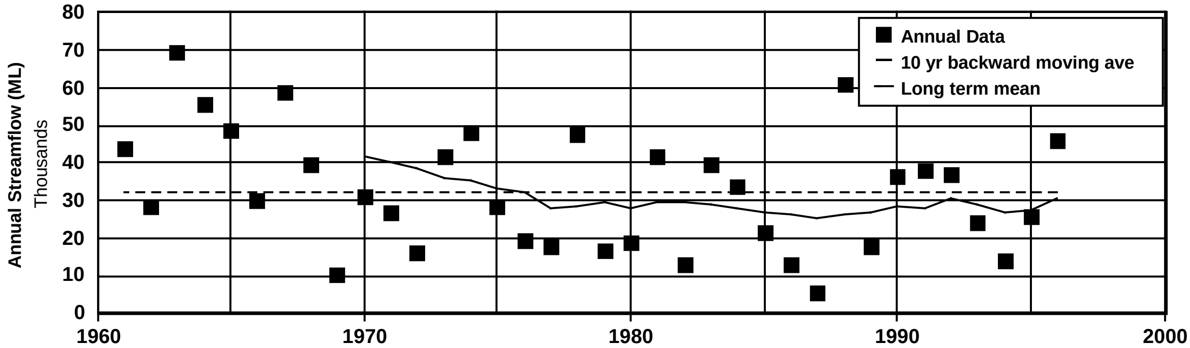
Shannon River
GS606 185



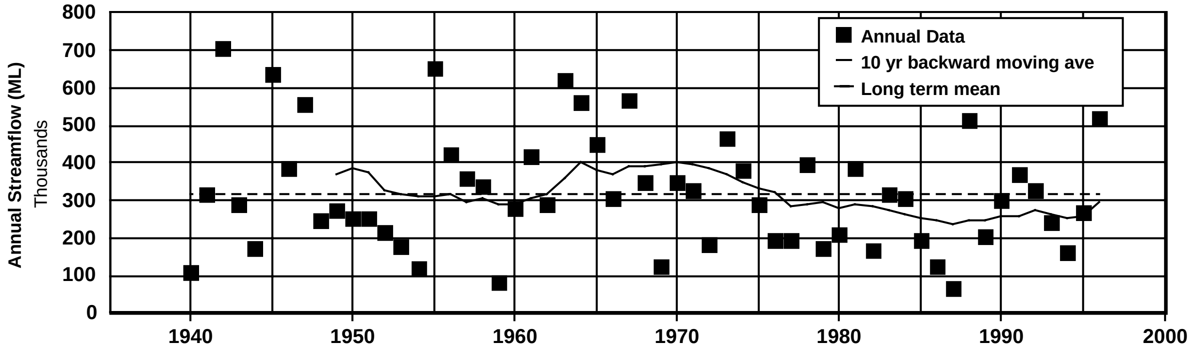
Perup River
GS607 004/145



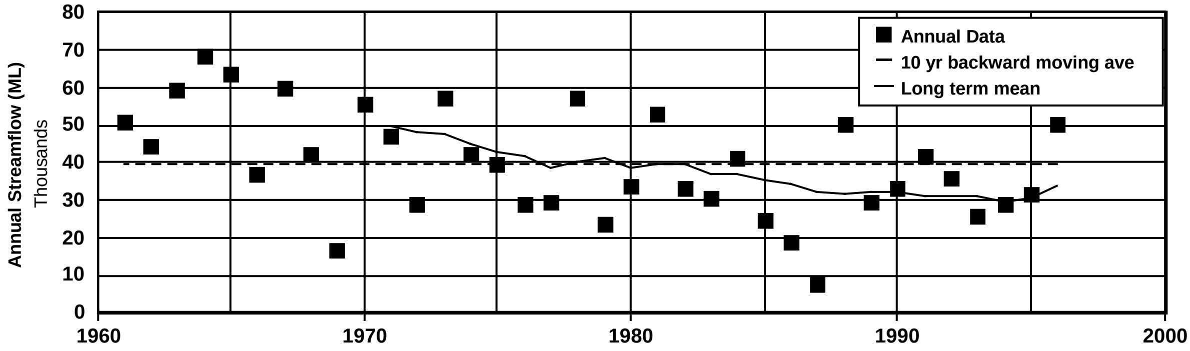
Wilgarup River
GS607 144



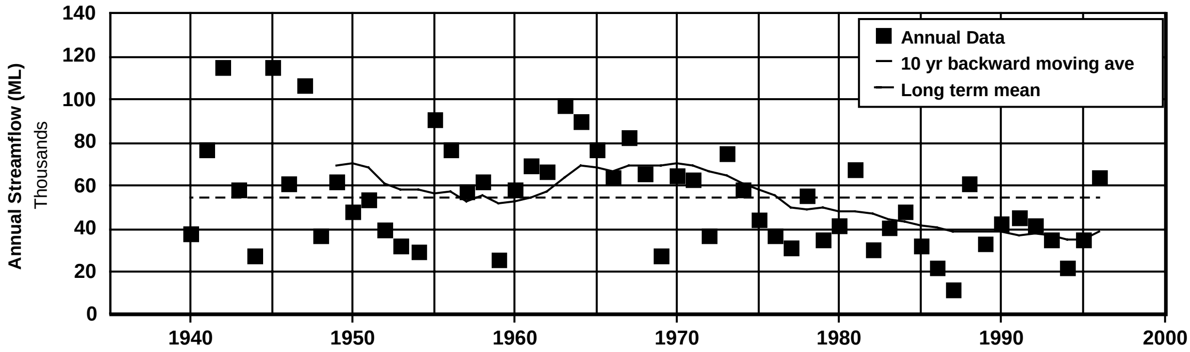
Warren River
GS607 220



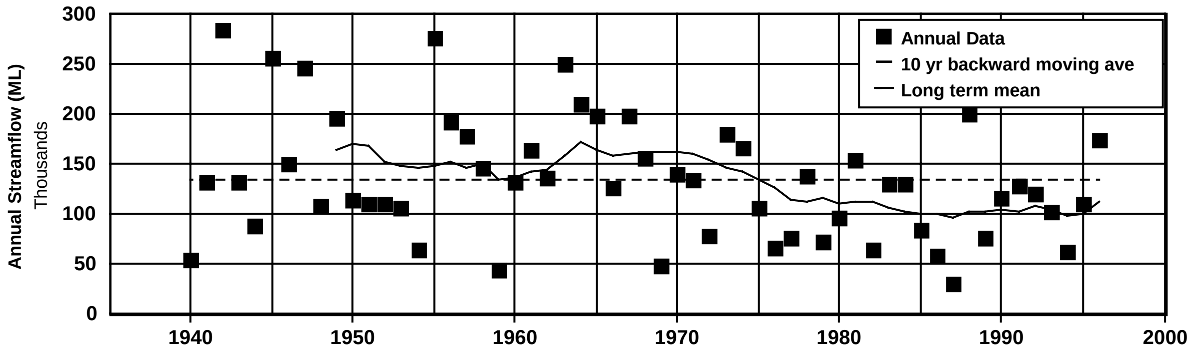
Dombakup Brook
GS607 155



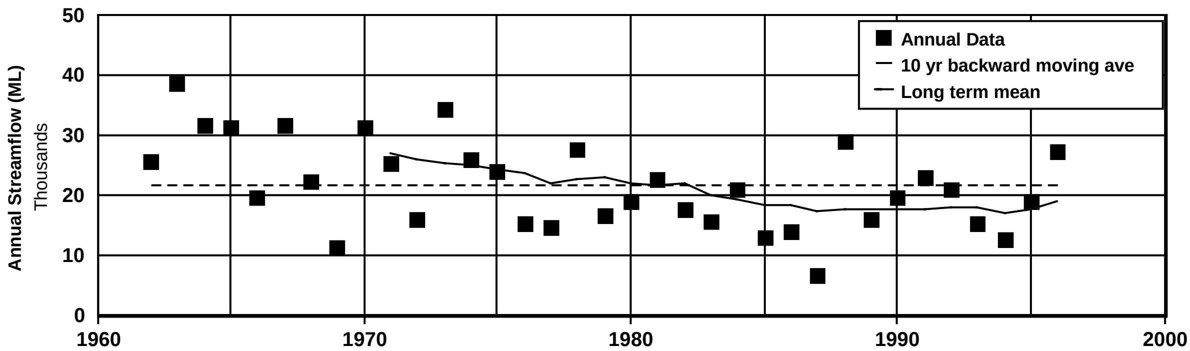
Lefroy Brook
GS607 009/013



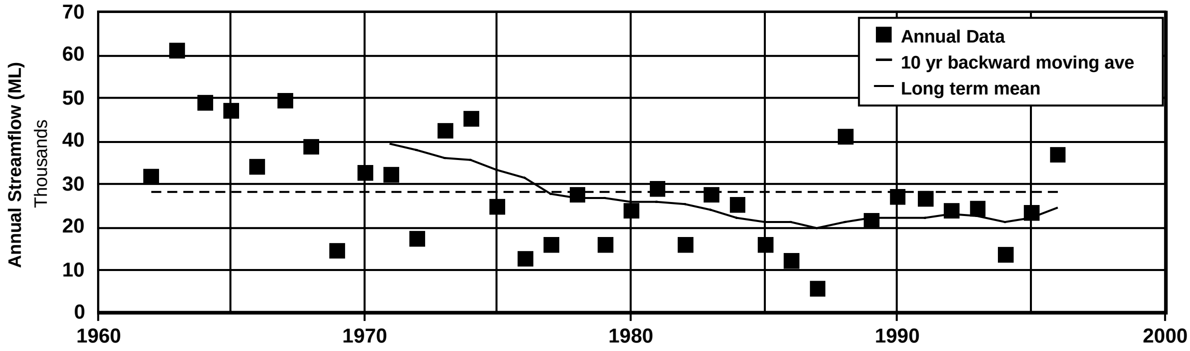
Donnelly River
GS608 151



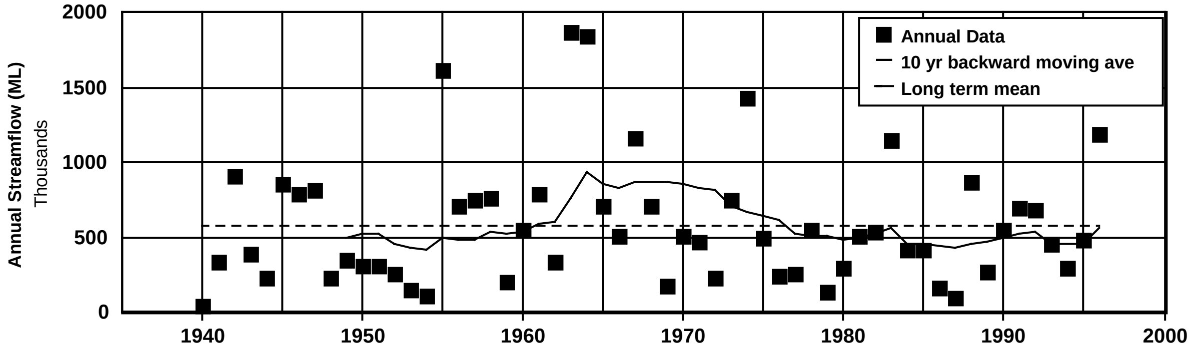
Fly Brook
GS607 171



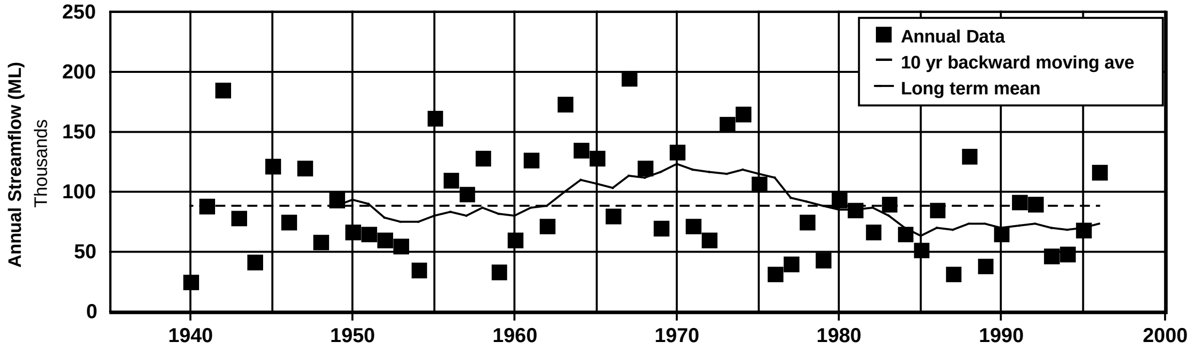
Barlee Brook
GS608 148/001



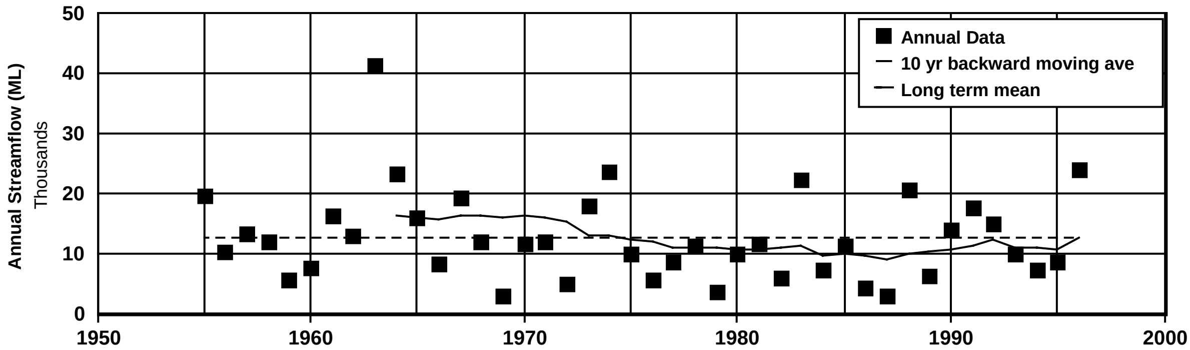
Blackwood River
GS609 025



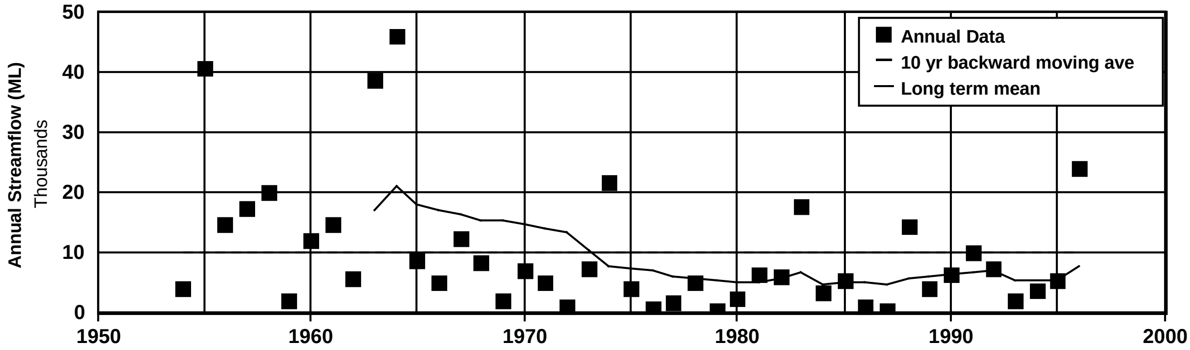
Margaret River
GS610 128/001



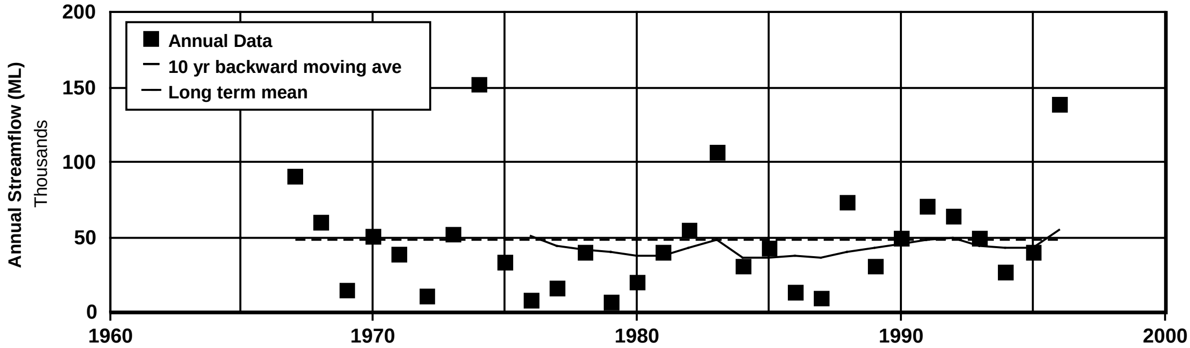
Thomson Brook
GS611 111



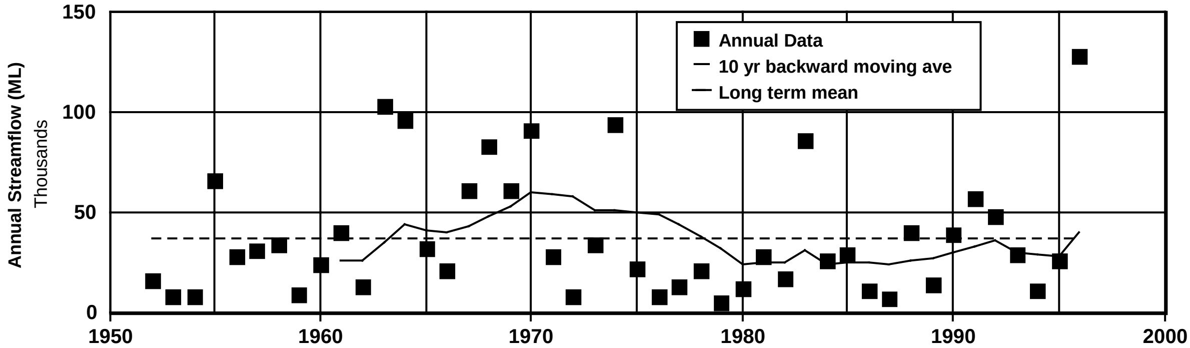
Bingham River
GS612 014/037



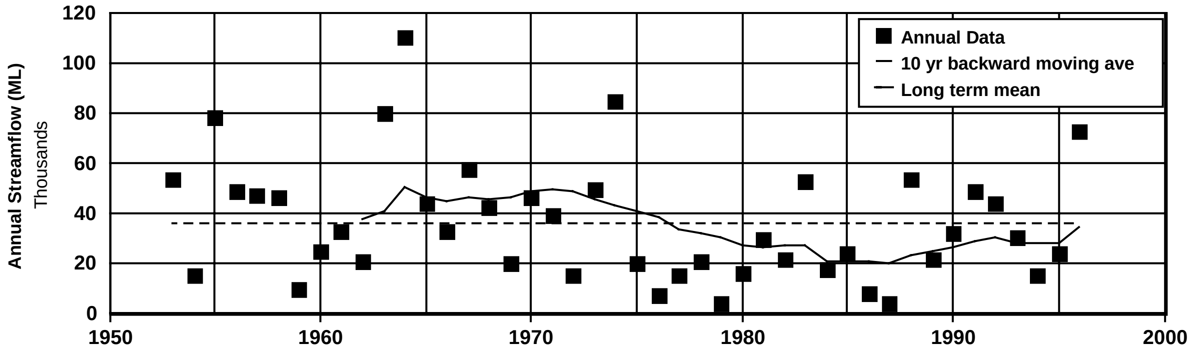
Collie River East
GS612 001

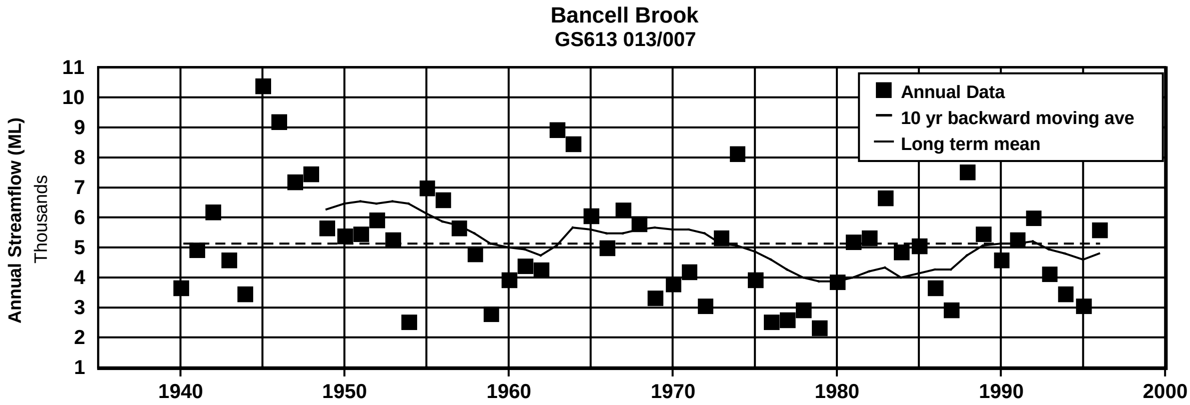


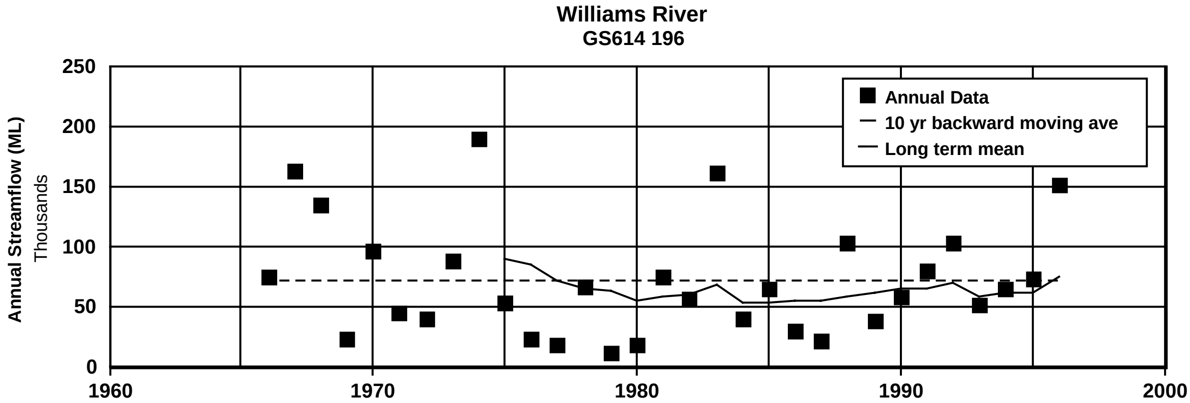
Collie River South
GS612 034

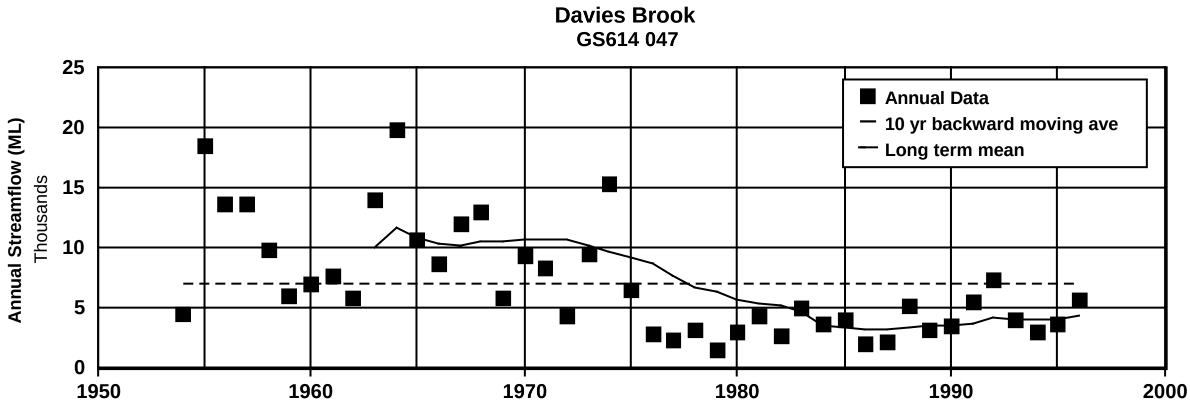


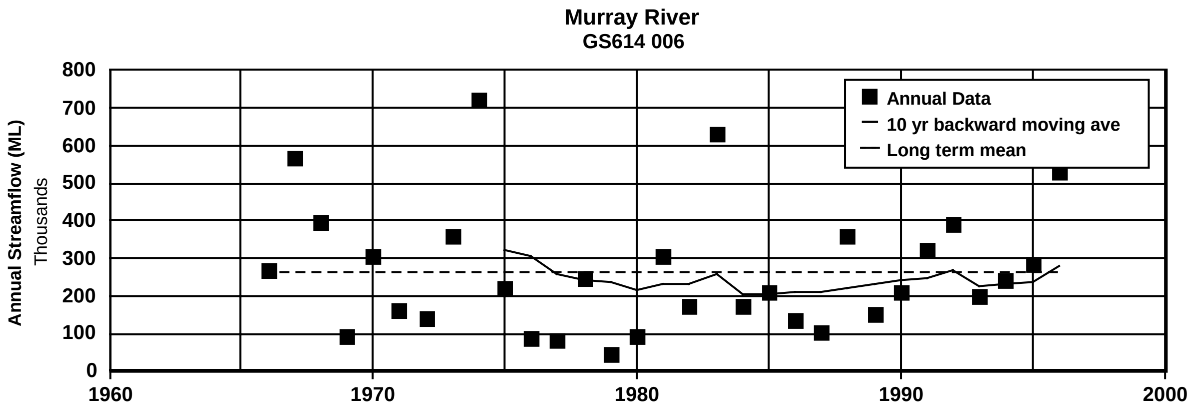
Harris River
GS612 017/036

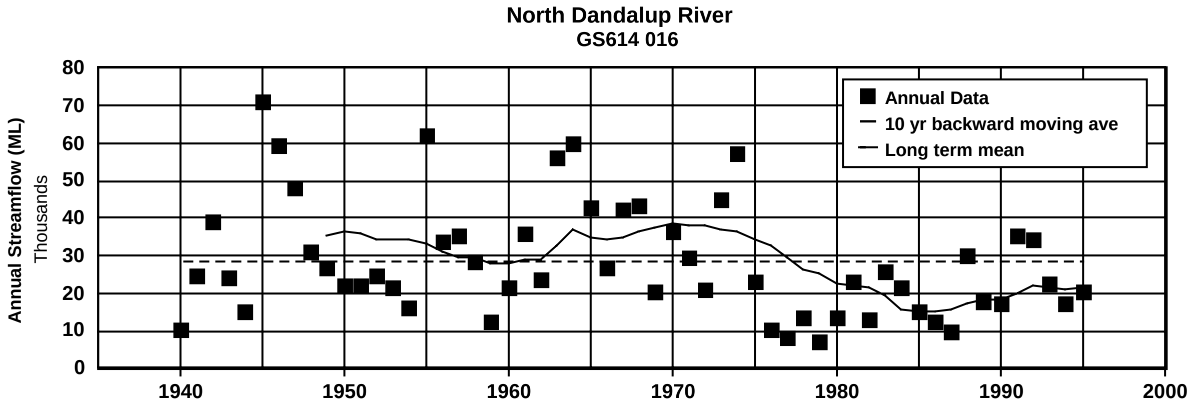


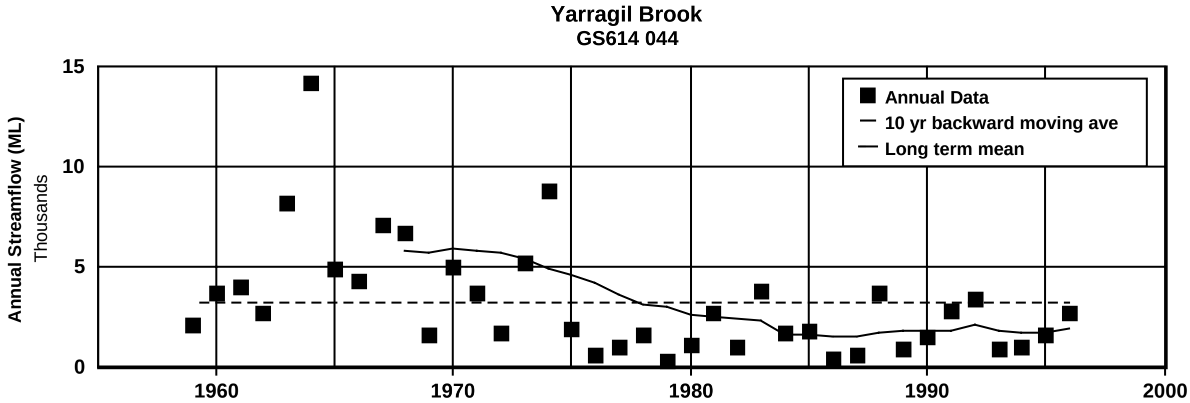

Bancell Brook
GS613 013/007
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving ave
Long term mean
1940 1950 1960 1970 1980 1990 2000

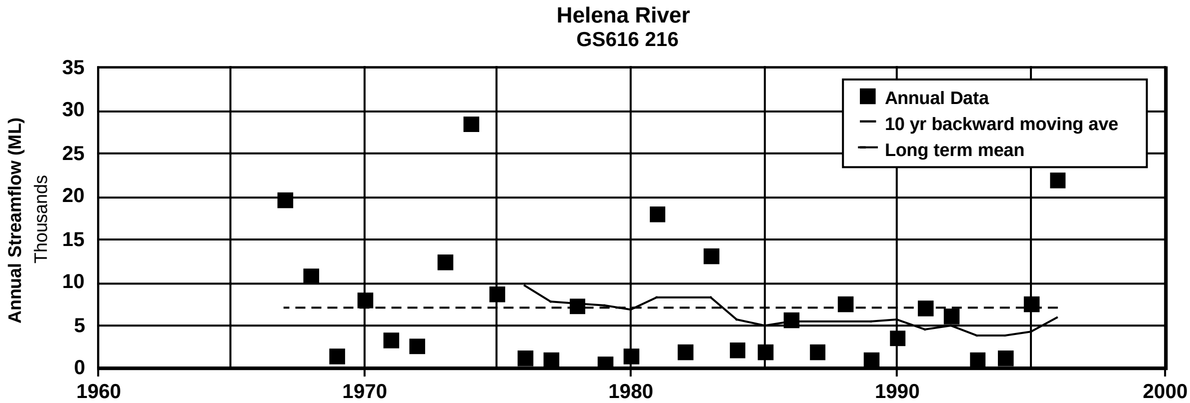

Williams River
GS614 196
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving ave
Long term mean
1960 1970 1980 1990 2000

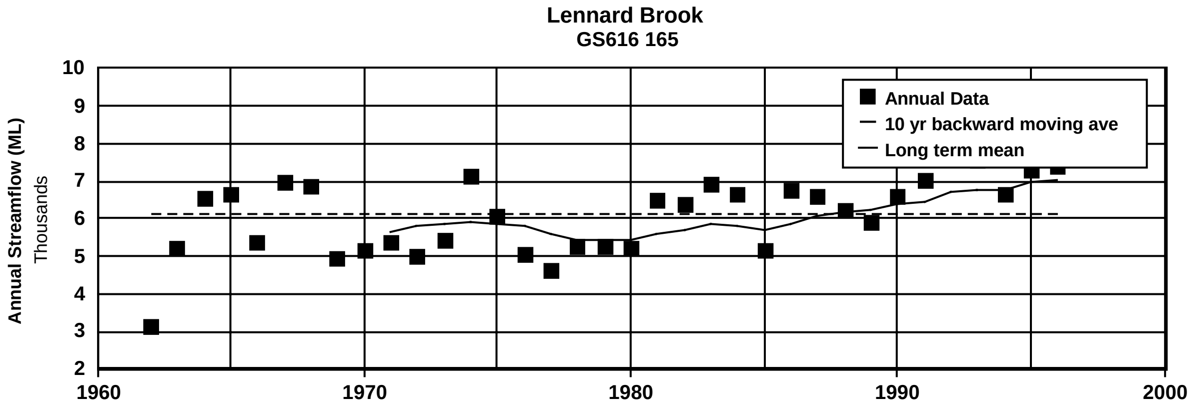

Davies Brook
GS614 047
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving ave
Long term mean
1950 1960 1970 1980 1990 2000

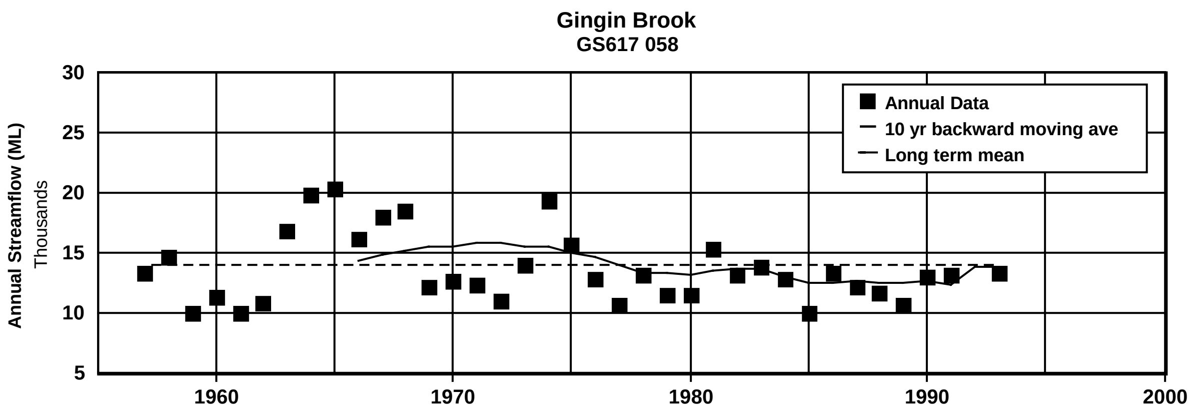

Murray River
GS614 006
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving ave
Long term mean
1960 1970 1980 1990 2000


North Dandalup River
GS614 016
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving ave
Long term mean
80
70
60
50
40
30
20
10
0
1940
1950
1960
1970
1980
1990
2000

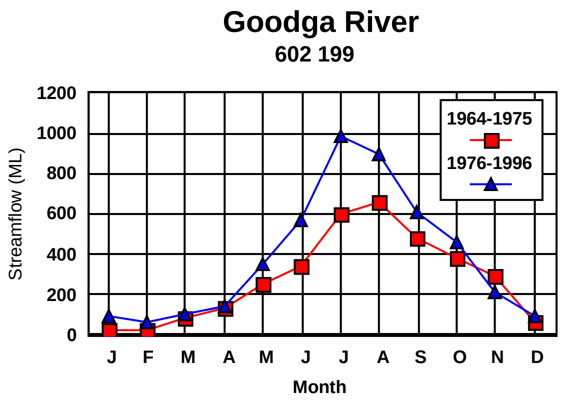

Yarragil Brook
GS614 044
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving ave
Long term mean
15
10
5
0
1960
1970
1980
1990
2000

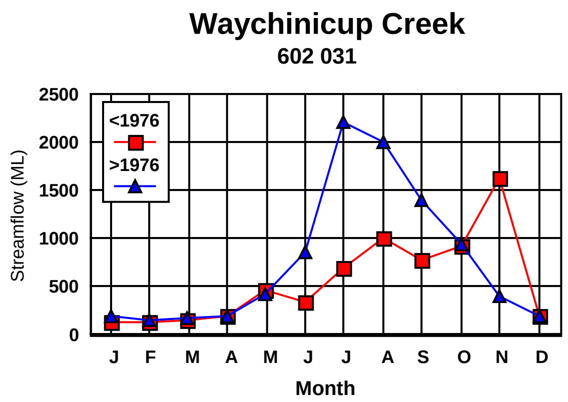

Helena River
GS616 216
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving ave
Long term mean
35
30
25
20
15
10
5
0
1960
1970
1980
1990
2000

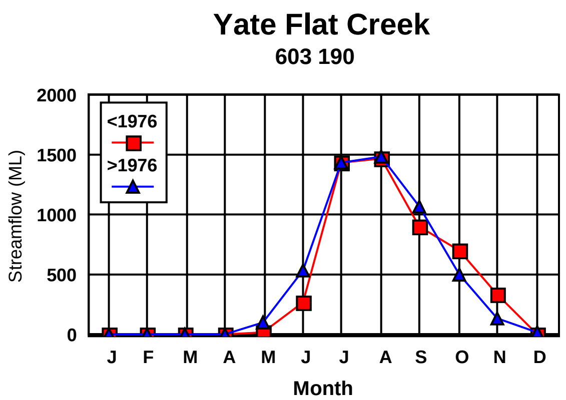

Lennard Brook
GS616 165
Annual Streamflow (ML)
Thousands
Annual Data
10 yr backward moving ave
Long term mean
10
9
8
7
6
5
4
3
2
1960
1970
1980
1990
2000

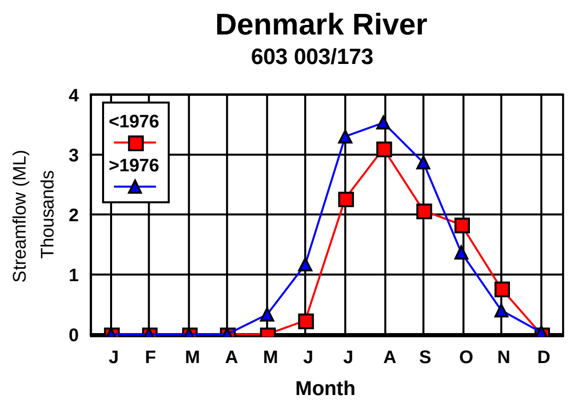


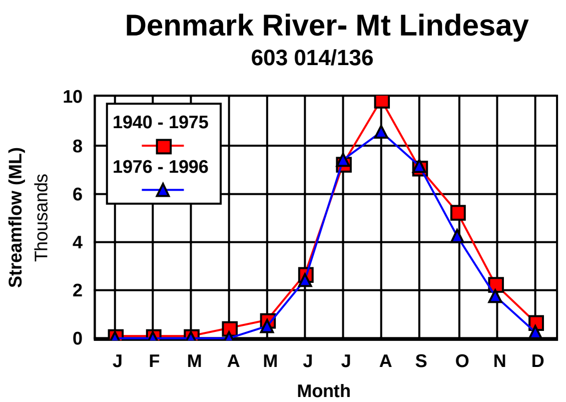
MONTHLY: Basin 602 - 604

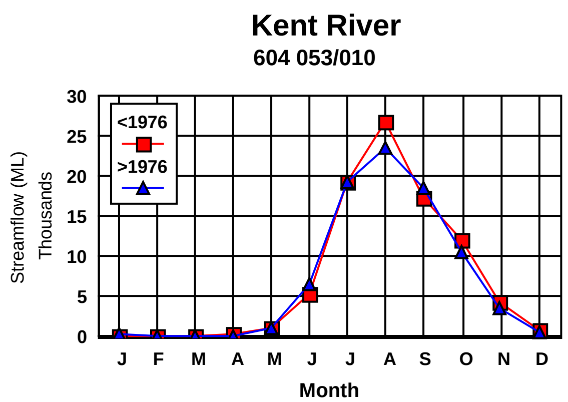






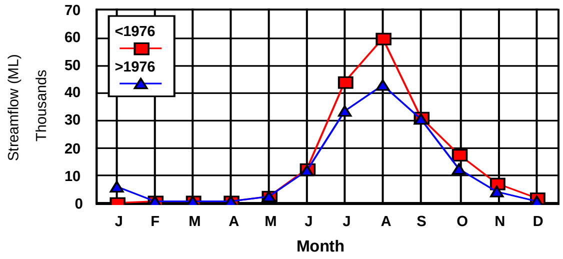




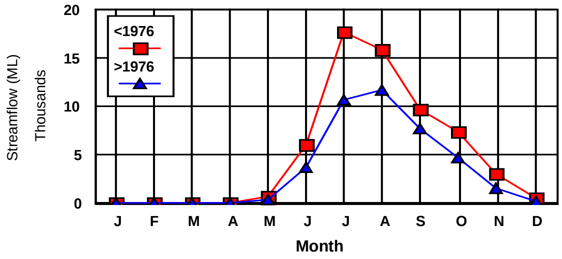


Basin 605 - 608

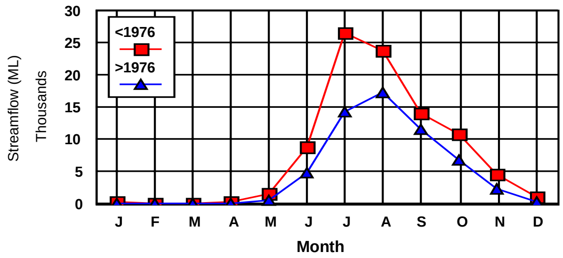
Frankland River
605 012



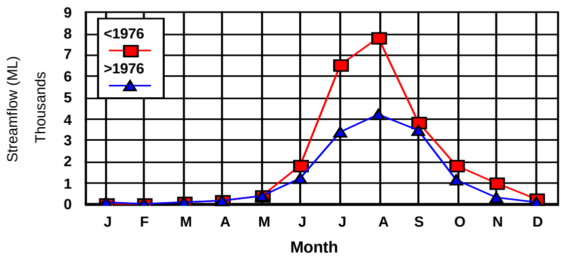
Weld River
606 195



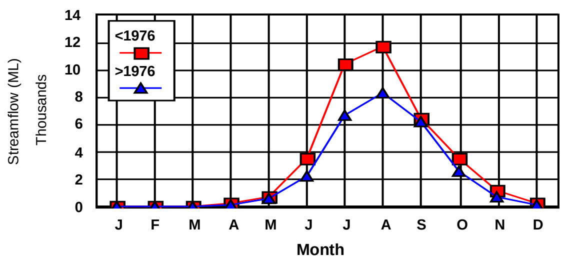
Shannon River
606 185



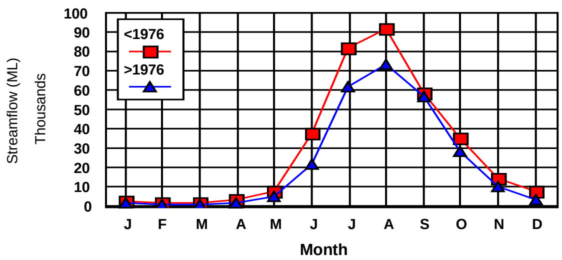
Perup River
607 145/004



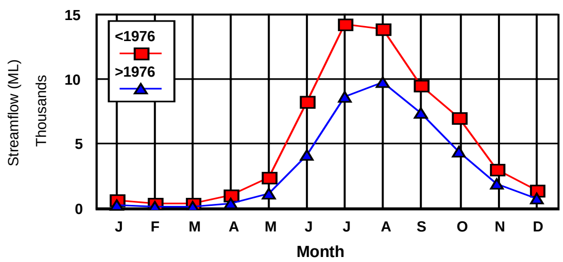
Wilgarup River
607 144



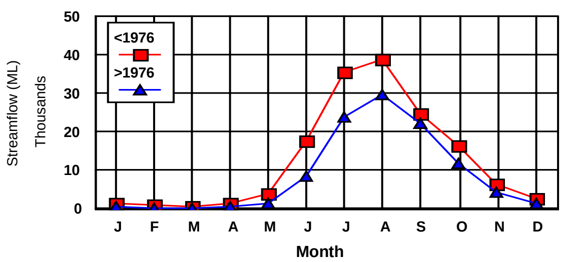
Warren River
607 220



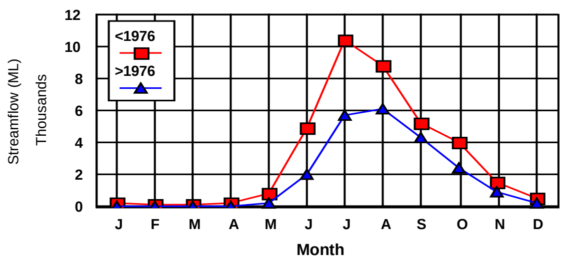
Lefroy Brook
607 001/009/013



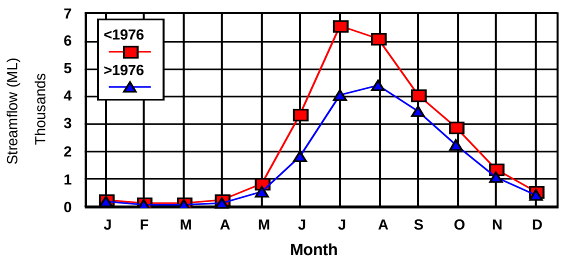
Donnelly River
608 151



Barlee Brook
608 148/001

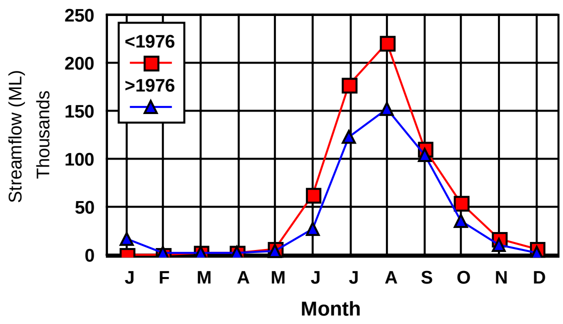


Fly Brook
608 171

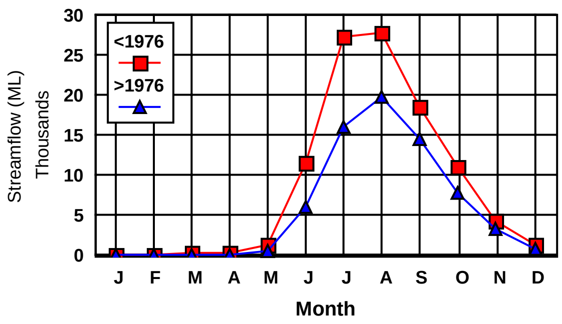


Basin 609 - 613

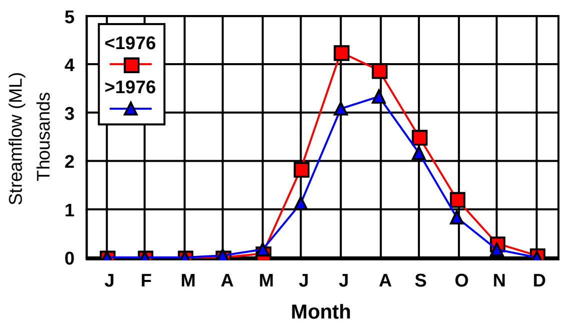
Blackwood River
609 025



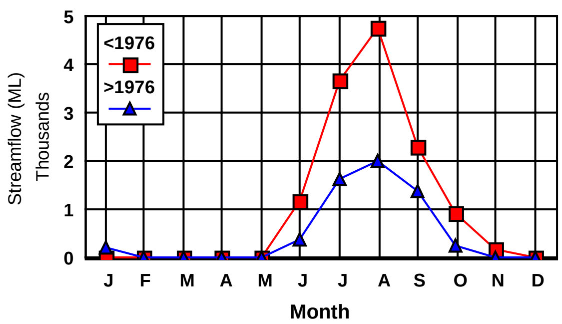
Margaret River
610 128/001



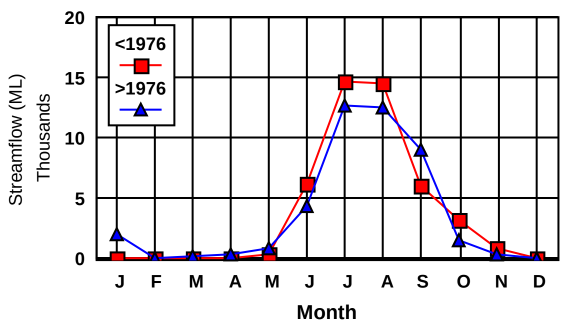
Thompson Brook
611 111



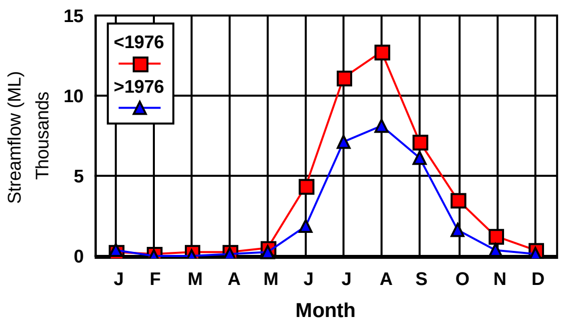
Bingham River
612 014/036



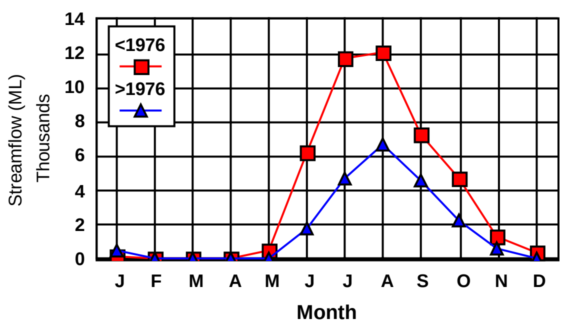
Collie River East
612 001



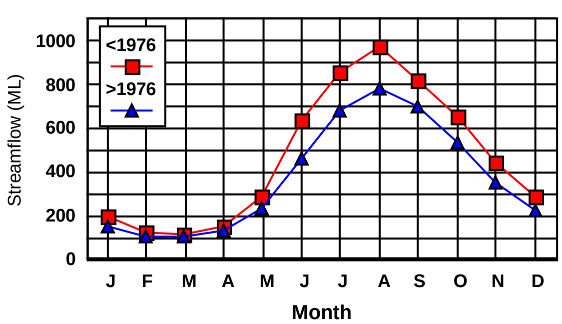
Collie River South Branch
612 034



Harris River
612 017/036

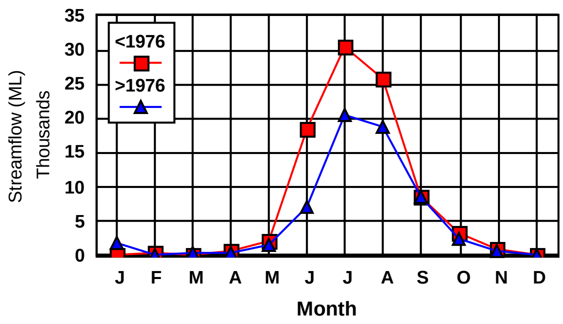


Bancell Brook
613 013/007

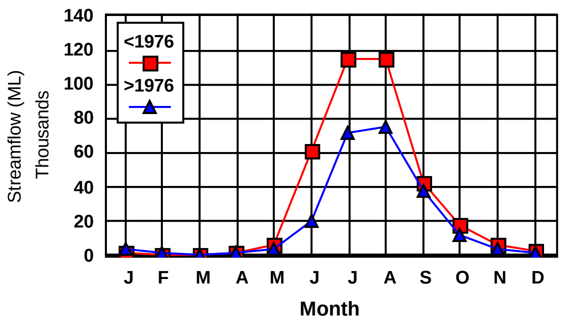


Basin 614 - 617

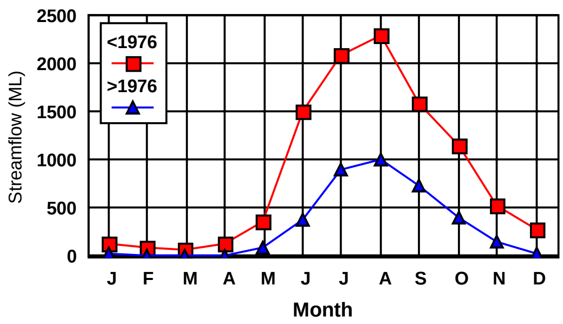
Williams River
614 196



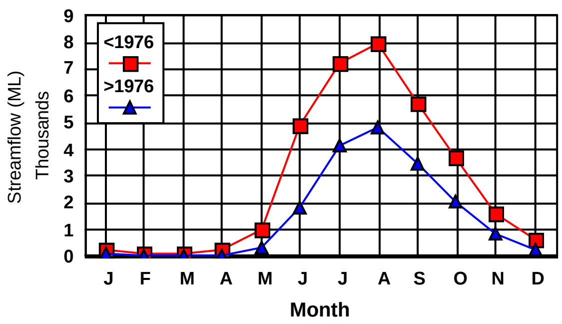
Murray River
614 006



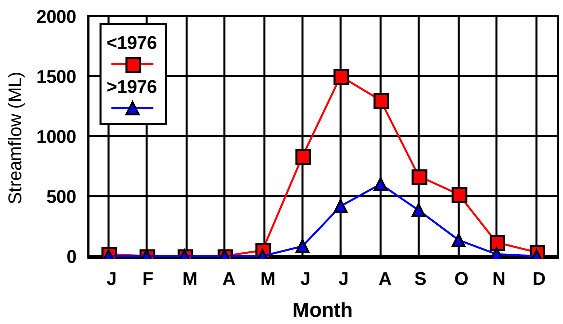
Davies Brook
614 047



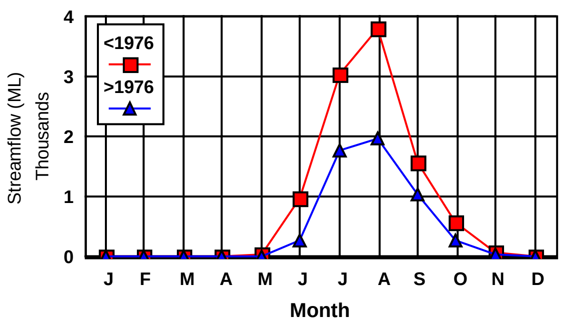
North Dandalup River
614 016



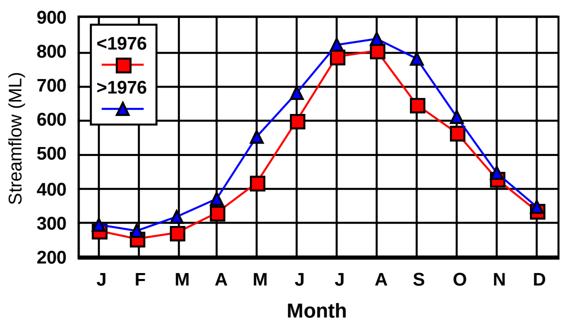
Yarragil Brook
614 044



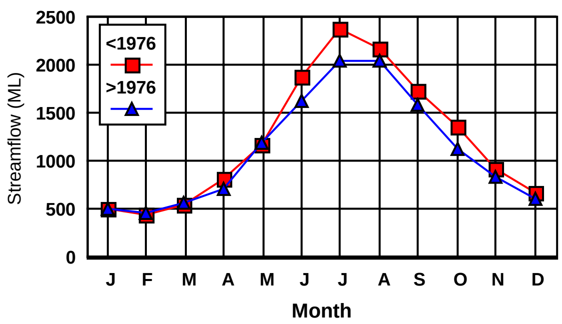
Helena River
616 216



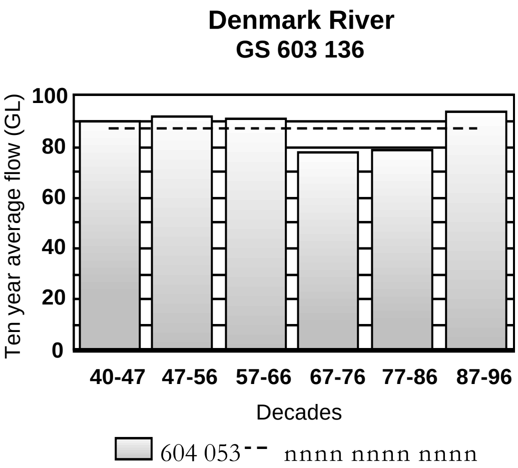
Lennard Brook
616 165

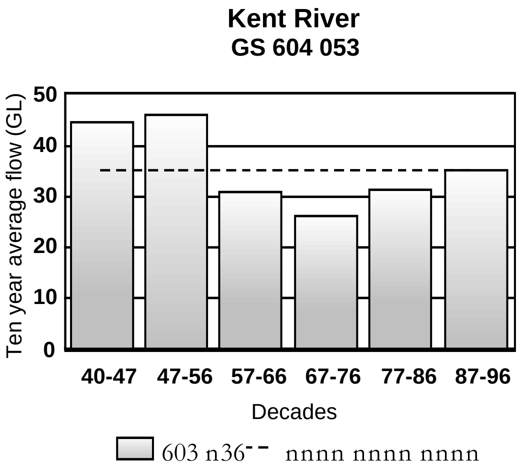


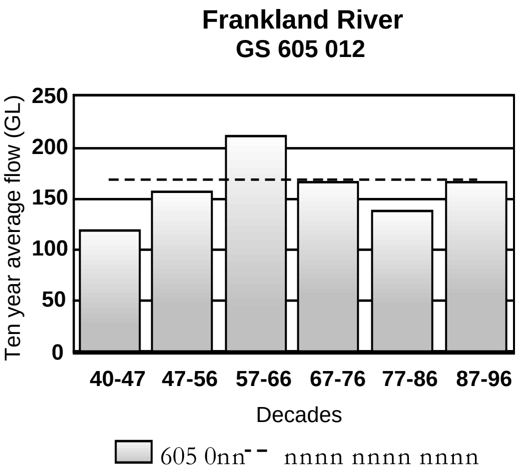
Gingin Brook
617 058

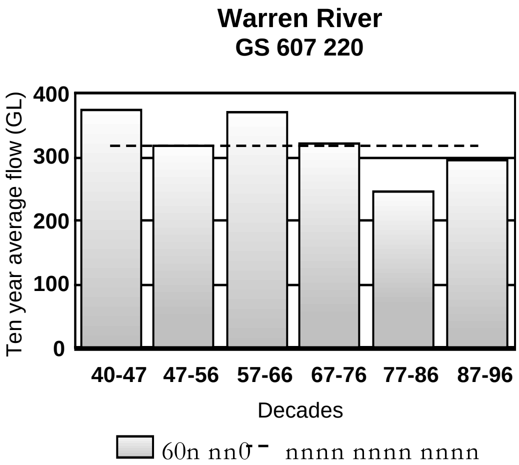


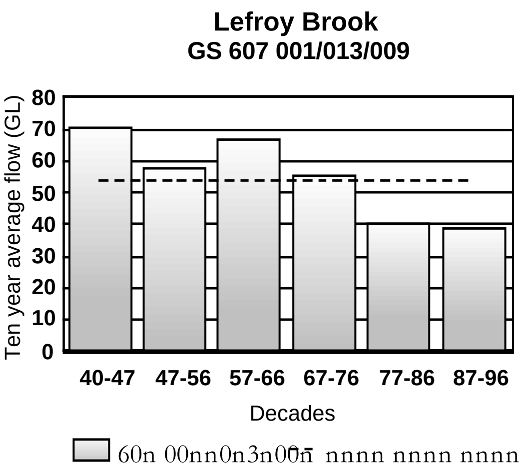
Appendix B: Decadal Variation in Streamflow

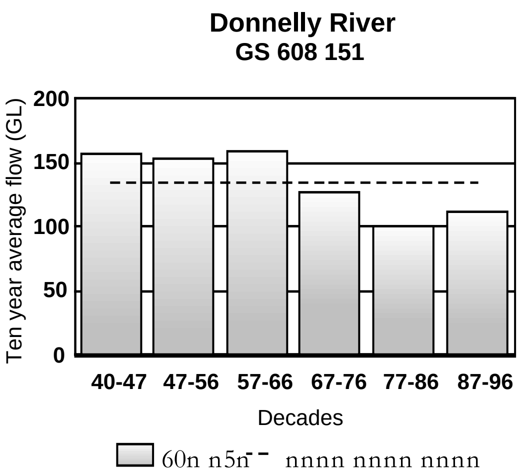


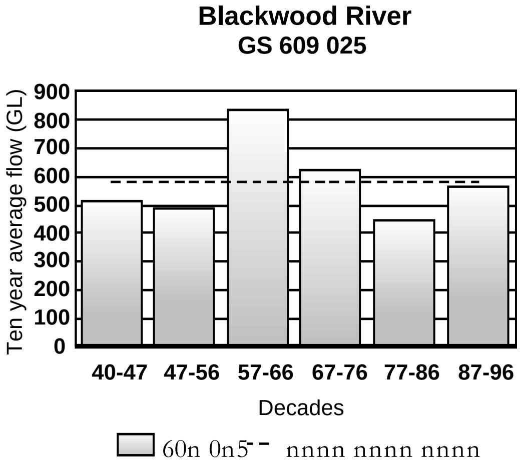


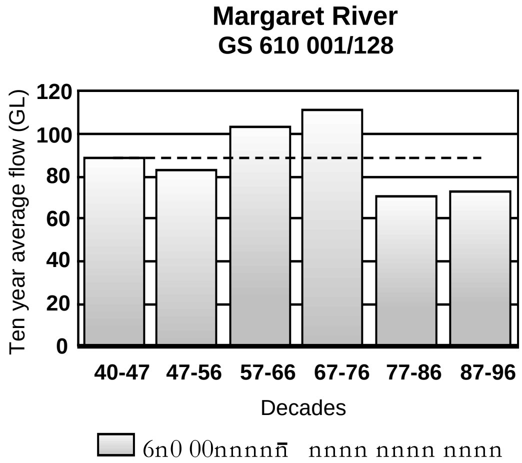


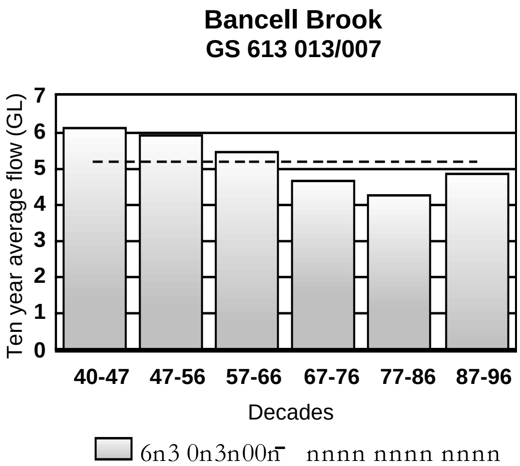


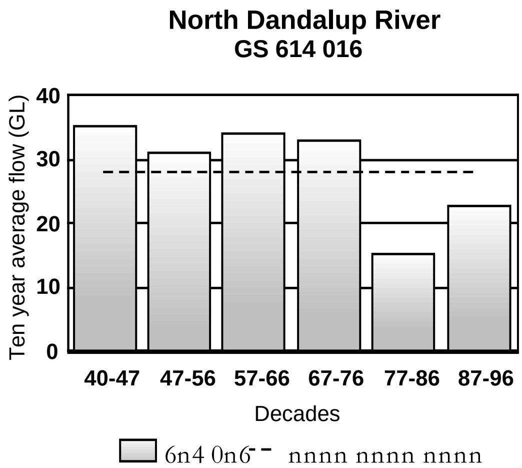





Blackwood River
GS 609 025
Ten year average flow (GL)
0
100
200
300
400
500
600
700
800
900
40-47
47-56
57-66
67-76
77-86
87-96
Decades


Margaret River
GS 610 001/128
Ten year average flow (GL)
0
20
40
60
80
100
120
40-47
47-56
57-66
67-76
77-86
87-96
Decades


Bancell Brook
GS 613 013/007
Ten year average flow (GL)
0
1
2
3
4
5
6
7
40-47
47-56
57-66
67-76
77-86
87-96
Decades

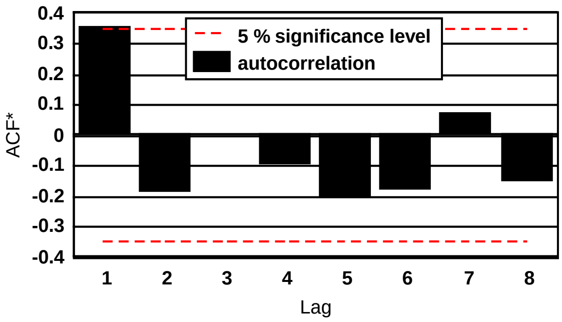

North Dandalup River
GS 614 016
Ten year average flow (GL)
0
10
20
30
40
40-47
47-56
57-66
67-76
77-86
87-96
Decades

Appendix C: Sample Autocorrelation

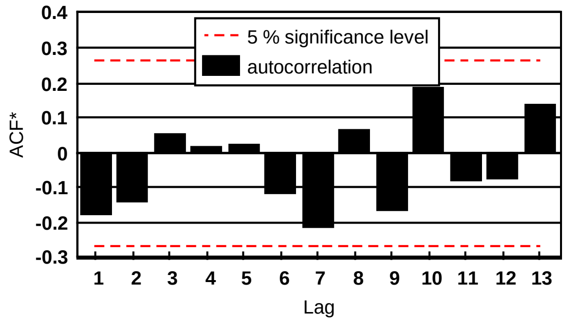
Summary of the sample autocorrelation results for the gauged streams in the south-west.

Station No.	Stream	Catchment R/fall (mm)	Catchment Clearing (%)	Statistically significant correlation at lags	High non-significant correlation at lags
602 199	Goodga River	870	10	1	5, 6
602 031	Waychinicup Creek	760	5	-	1, 5, 6
603 190	Yate Flat Creek	780	60	-	2, 6
603 003/173	Denmark River	760	32	-	-
603 136	Denmark River	800	20	-	-
604 010/053	Kent River	800	40	-	7
605 012	Frankland River	600	56	-	-
606 185	Shannon River	1,230	2.5	3	7, 8
606 195	Weld River	1,275	0	3	7
607 144	Wilgarup River	950	33	-	7
607 220	Warren River	800	40	-	10
607 009/013	Lefroy Brook	1,170	30	-	1-4, 8, 10
607 004/145	Perup River	750	18.5	-	-
607 155	Dombakup Brook	1,430	16	3	7, 8
608 151	Donnelly River	1,110	22	10	8
608 148/001	Barlee Brook	1,160	0	1	3, 7, 10
608 171	Fly Brook	1,420	25	-	3, 8
609 025	Blackwood River	550	85	-	1, 8, 10
610 128/001	Margaret River	1,055	16	-	-
611 111	Thomson Brook	960	30	-	-
612 014/037	Bingham River	750	10	-	1
612 034	Collie River South	780	27	-	1
612 001	Collie R. East Trib.	710	28	-	2
612 017/036	Harris River	1,000	5	-	1, 7
613 013/007	Bancell Brook	1,225	20	1	-
614 196	Williams River	600	80	-	-
614 006	Murray River	650	50	-	-
614 047	Davies Brook	1,215	5	1-3, 6-9	4 , 10
614 016	North Dandalup River	1,300	0	1, 10	9
614 044	Yarragil Brook	1,090	0	1, 3	4, 7
616 216	Helena River	680	10	-	-
616 165	Lennard Brook	730	60	1	-
617 058	Gingin Brook	715	75	-	1

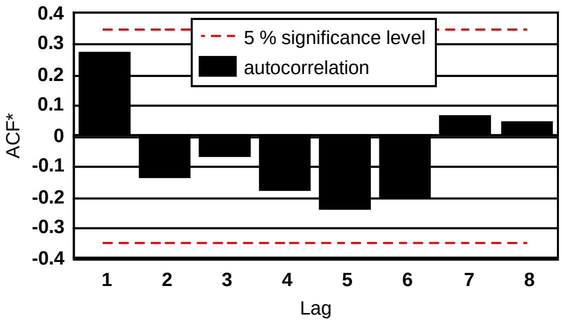
Basin 602 to 606



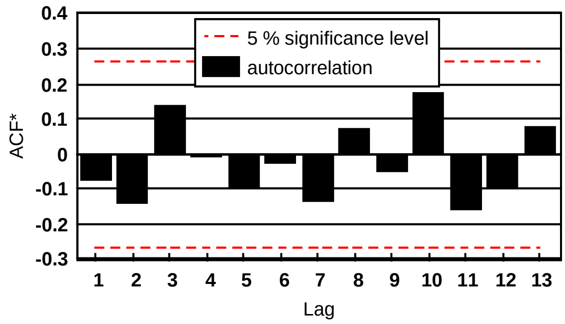
Goodga River (GS602 199)



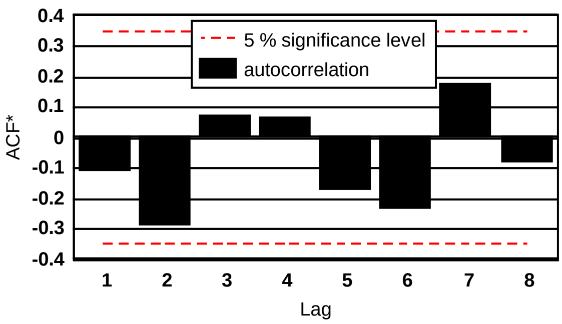
Kent River (GS604 053/010)



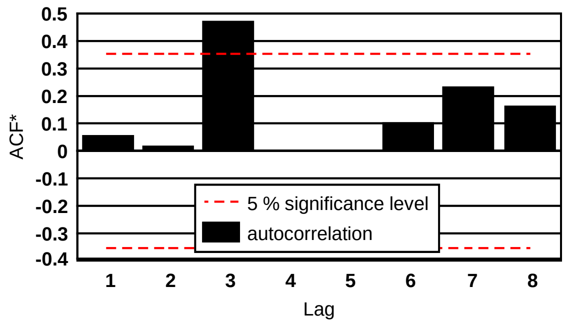
Waychinicup Creek (GS602 031)



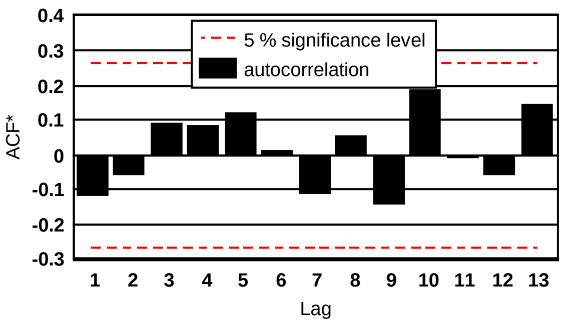
Frankland River (GS605 012)



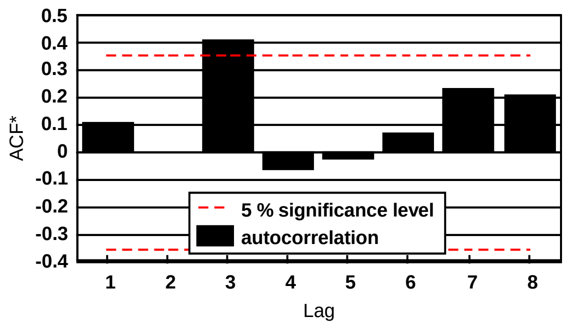
Yate Flat Creek (GS603 190)



Weld River (GS606 195)

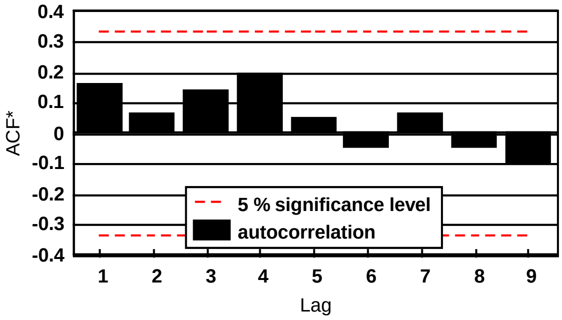


Denmark River (GS603 014/136)

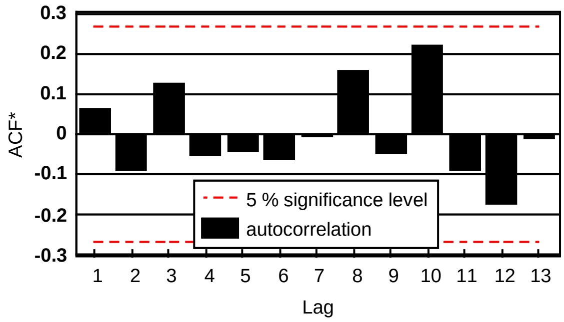


Shannon River (GS606 185)

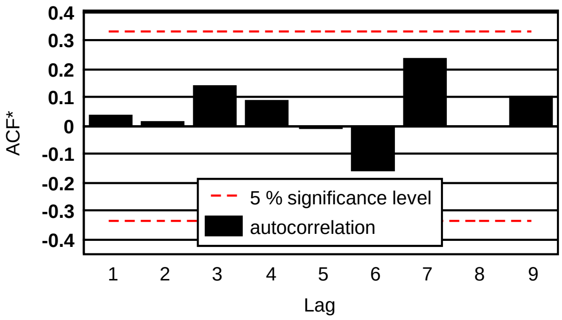
Basin 607 to 608



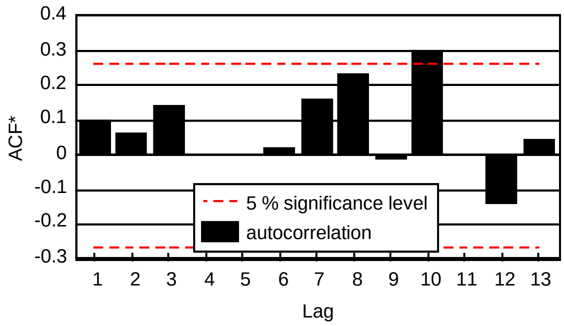
Perup River (GS607145/004)



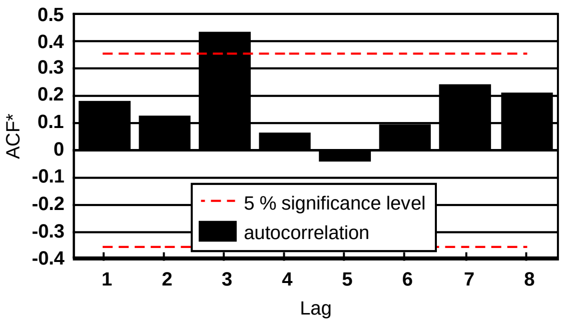
Warren River (GS607 220)



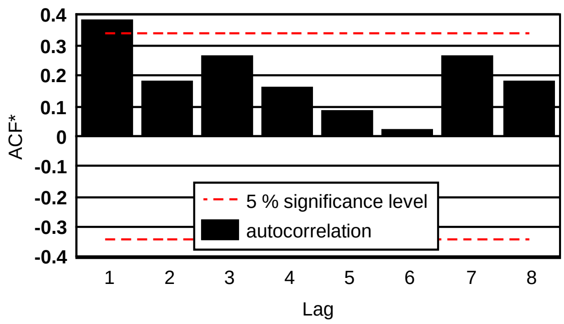
Wilgarup River (GS607 144)



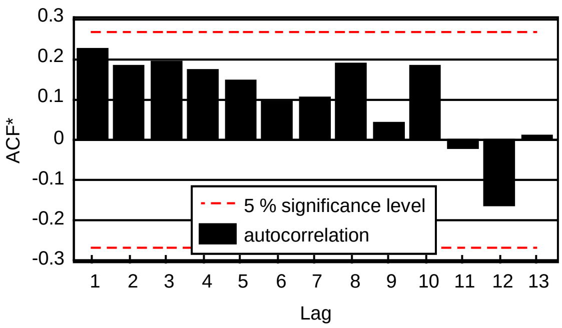
Donnelly River (GS608 151)



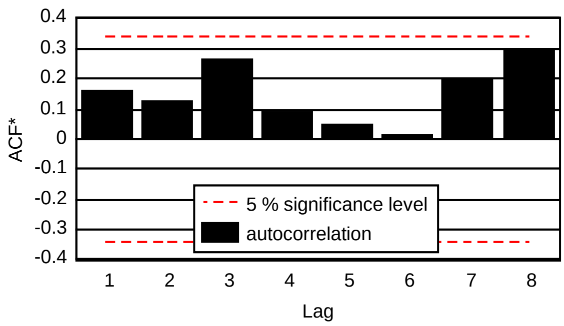
Dombakup River (GS607 155)



Barlee Brook (GS608 148/001)

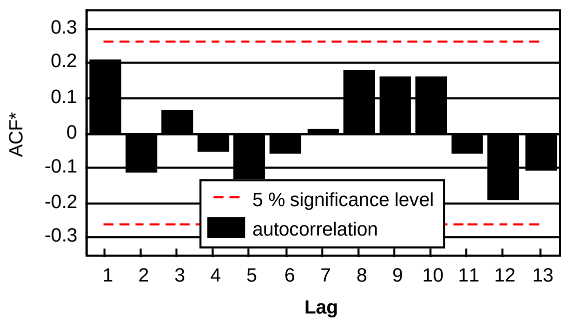


Lefroy Brook (GS607 001/009/013)

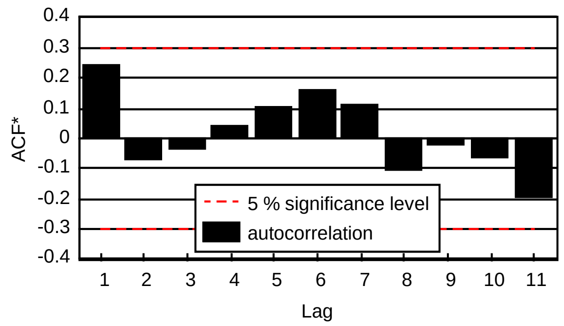


Fly Brook (GS608 171)

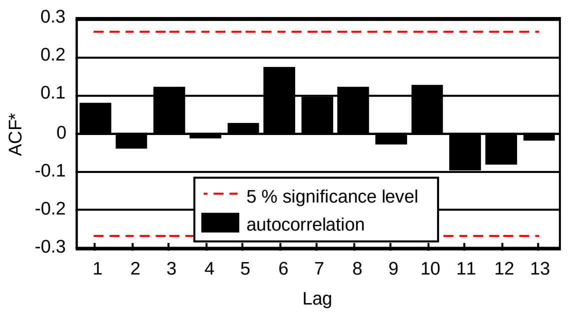
Basin 609 to 613



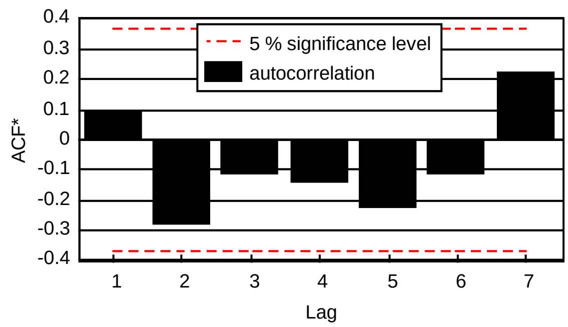
Blackwood River (GS609 025/007)



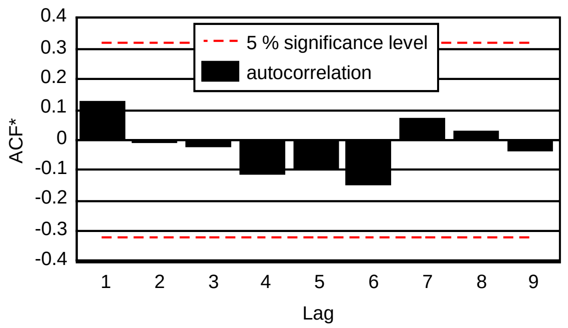
Collie River South Branch (GS612 034)



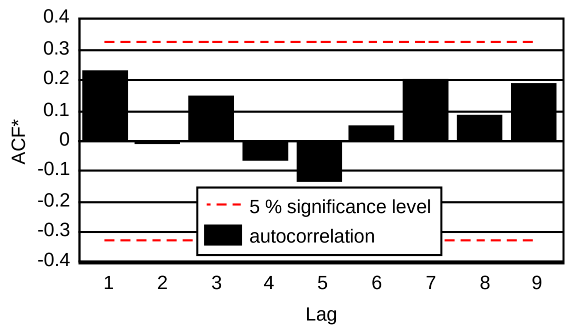
Margaret River (GS610 128/001)



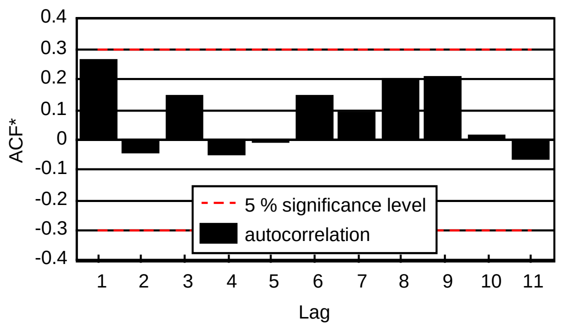
Collie River East (GS612 001)



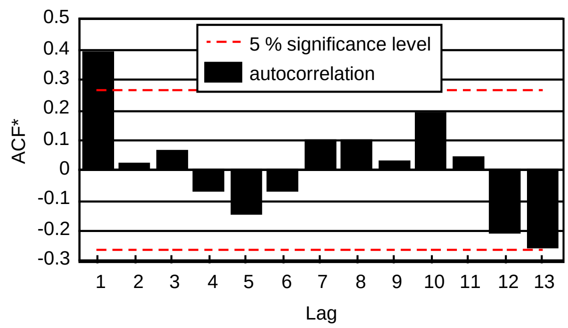
Thomson Brook (GS611 111)



Harris River (GS612 017/036)

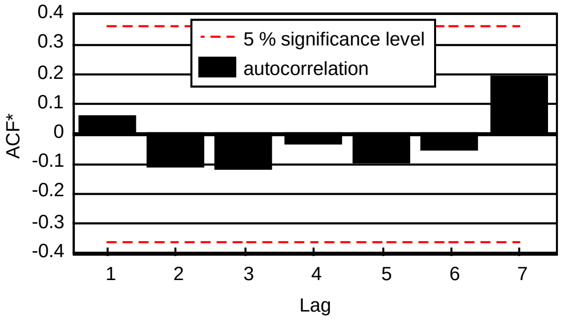


Bingham River (GS612 014/037)

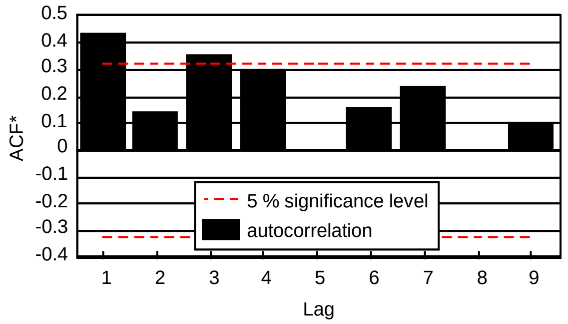


Bancell Brook (GS613 007/013)

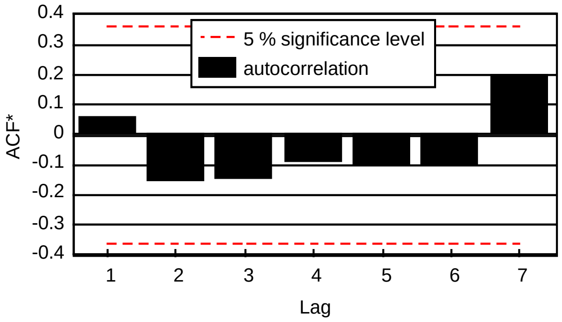
Basin 614 to 617



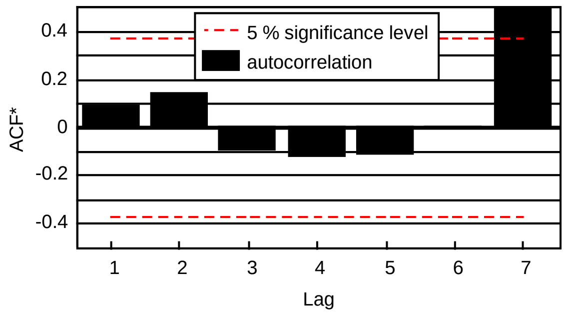
Williams River (GS614 196)



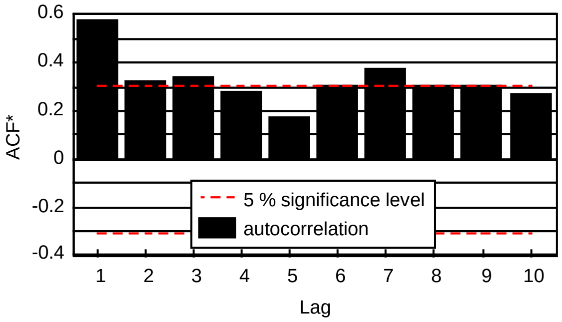
Yarragil Brook (GS614 044)



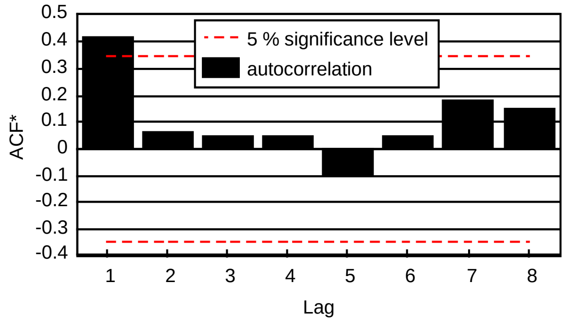
Murray River (GS614 006)



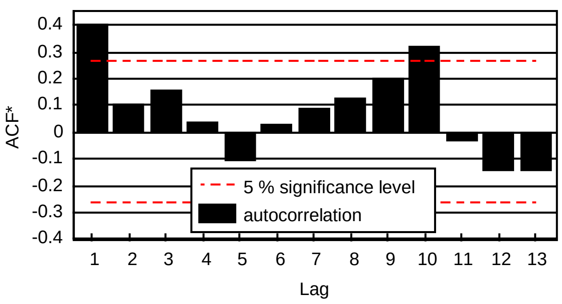
Helena River (GS616 216)



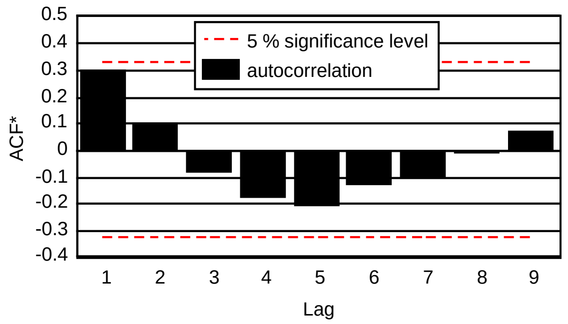
Davies Brook (GS614 047)



Lennard Brook (GS616 165)



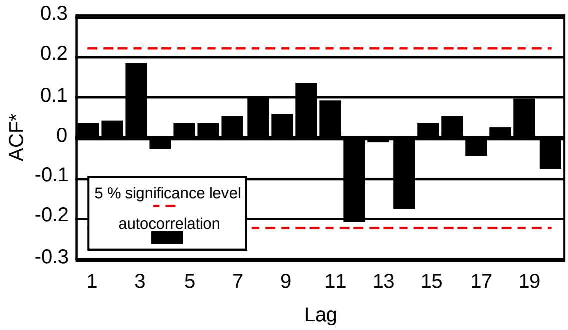
North Dandalup River (GS614 016)



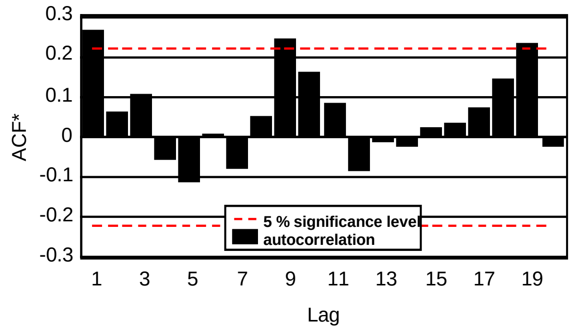
Gingin Brook (GS617 058)

MODELLED ANNUAL INFLOWS TO THE METROPOLITAN RESERVOIRS:

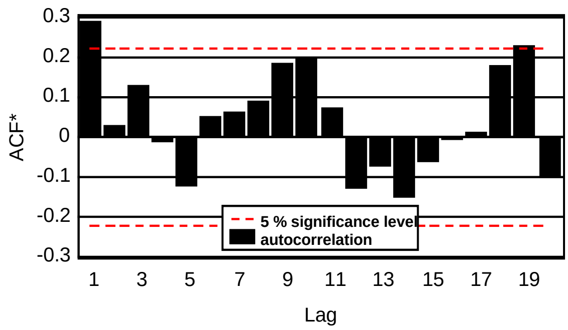
Bickley Pipehead



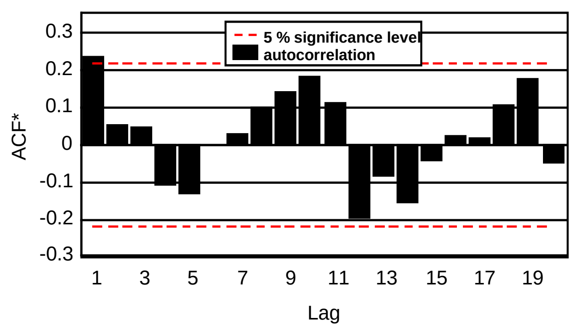
Helena Reservoir



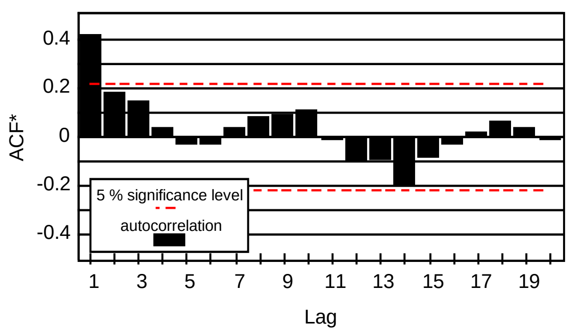
Canning Reservoir



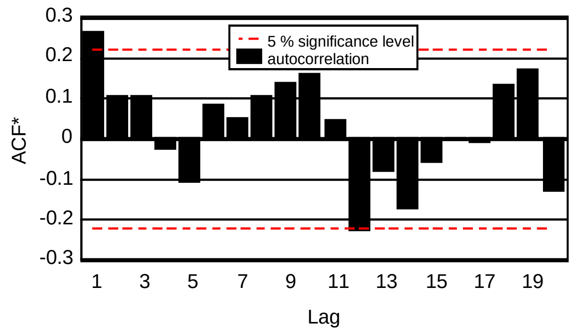
Lower Helena Pipehead



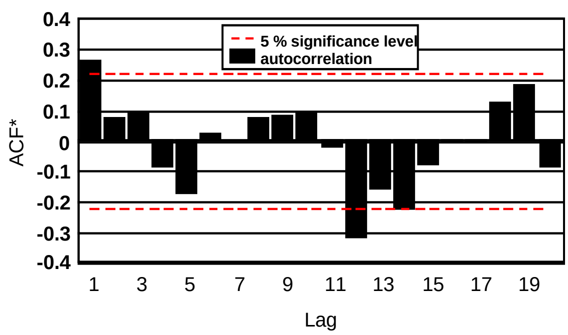
Churchman Brook Pipehead



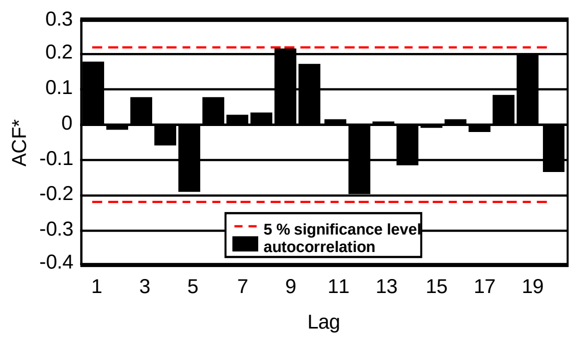
North Dandalup Reservoir

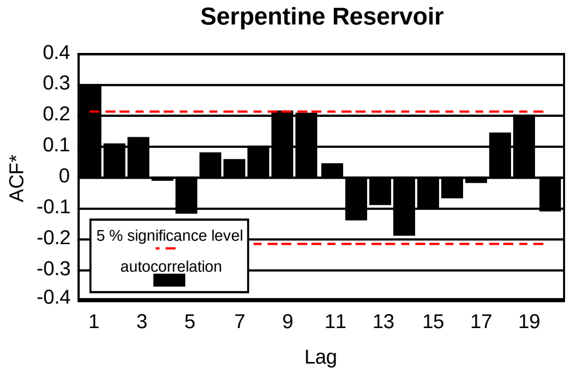


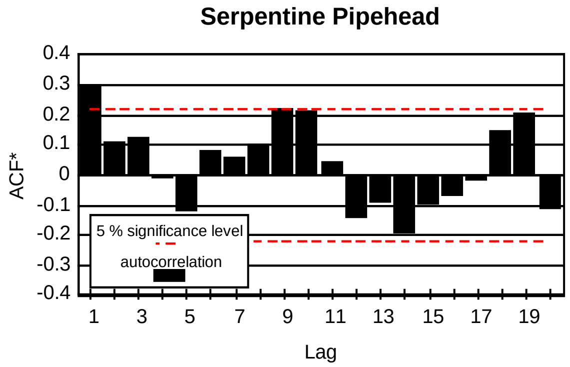
Conjurunup Pipehead

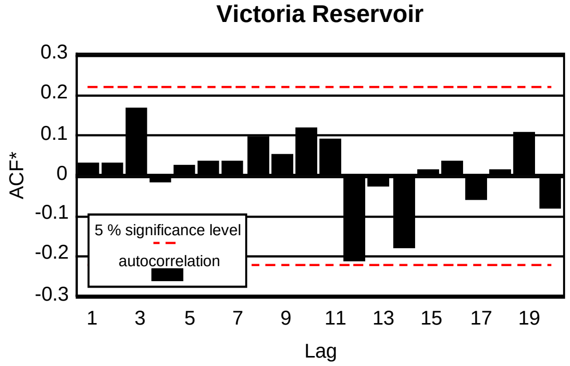


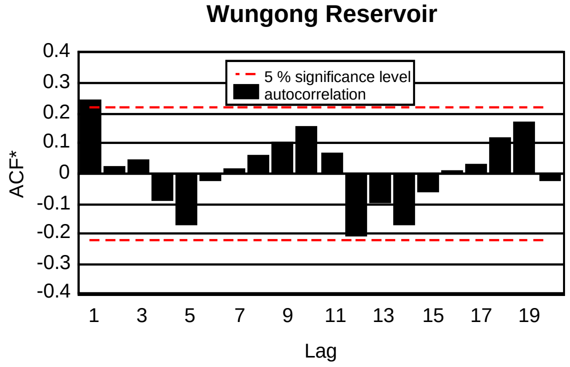
South Dandalup Reservoir




Serpentine Reservoir
ACF*
5 % significance level
autocorrelation
Lag


Serpentine Pipehead
ACF*
5 % significance level
autocorrelation
Lag

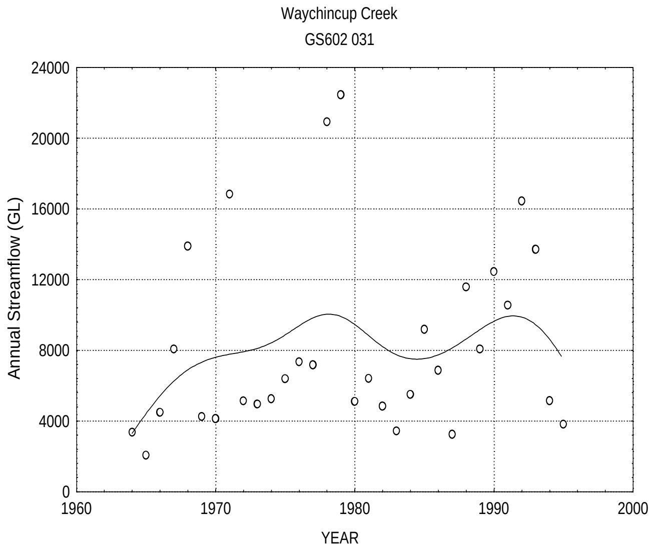

Victoria Reservoir
ACF*
5 % significance level
autocorrelation
Lag

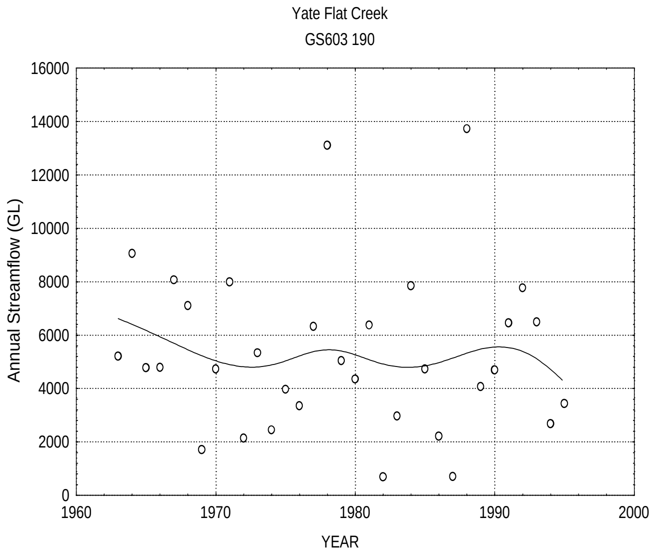

Wungong Reservoir
ACF*
5 % significance level
autocorrelation
Lag

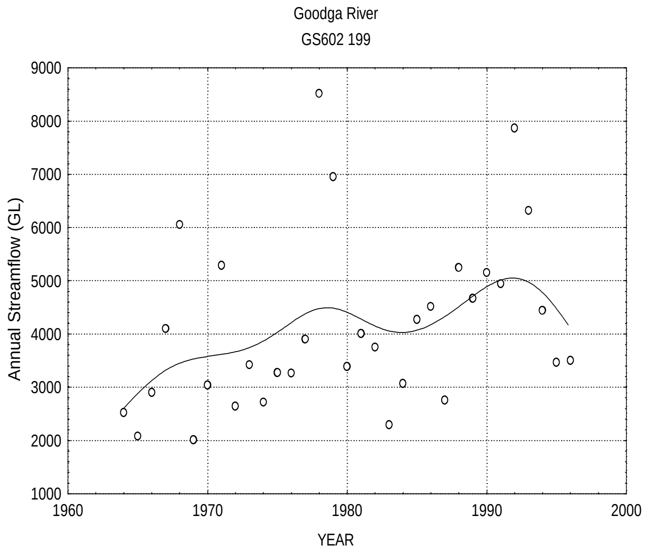
Appendix D: Loess and Alternative Smoothing

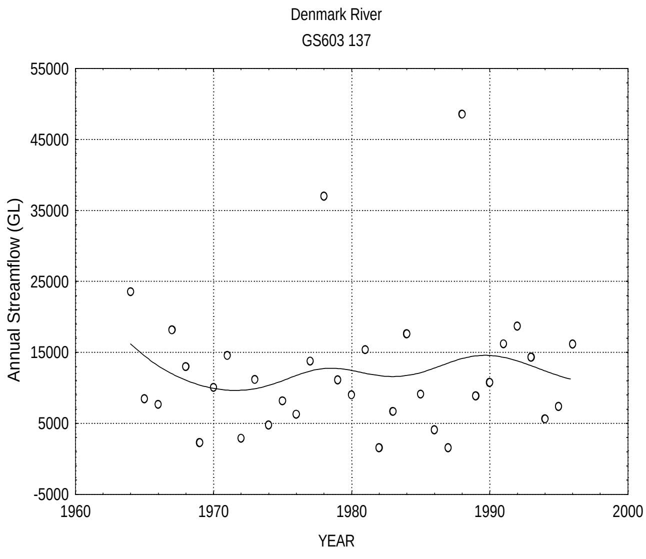
As discussed in Section 3.1.3, both the Loess smooth in the MHTS PC Package (McLeod and Hipel, 1995) and the Least square regression in STATISTICA was used to smooth the raw data. The following plots summarise the results from the Least square regression in STATISTICA.

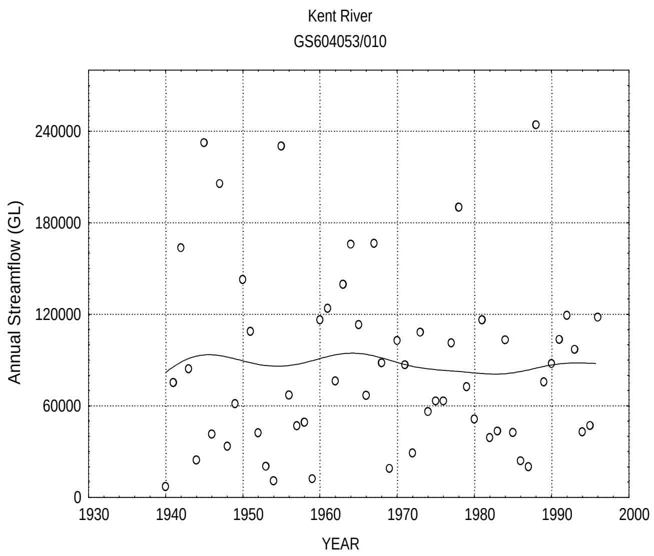
GAUGED DATA:

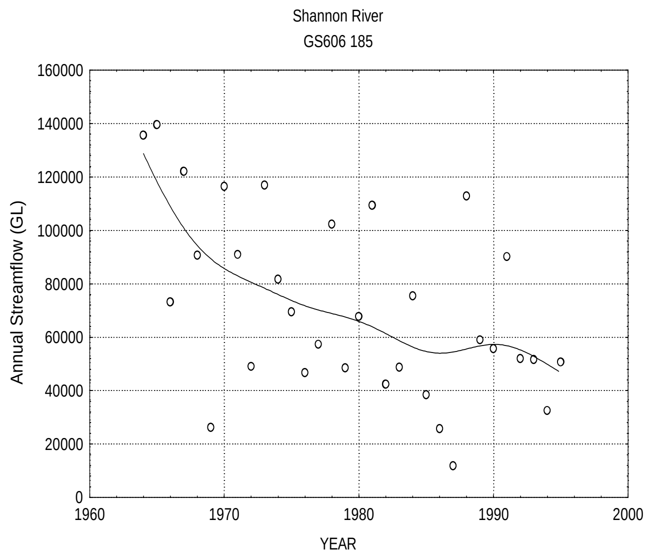


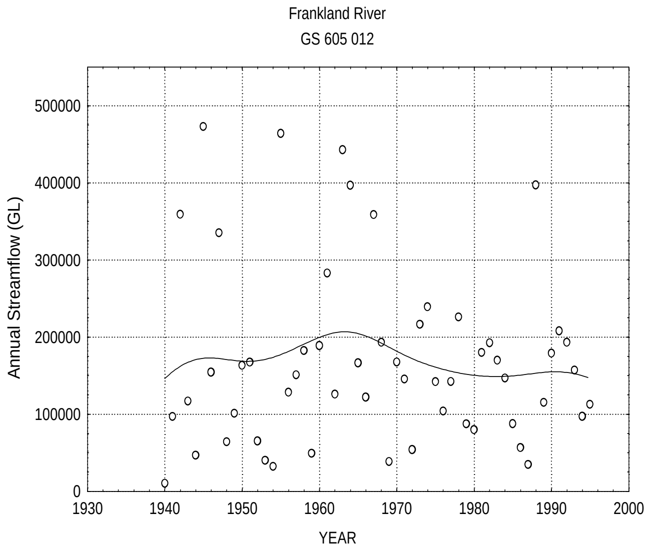


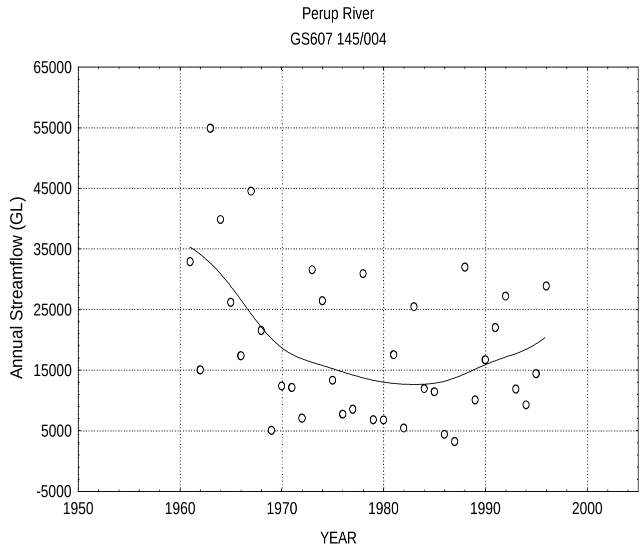


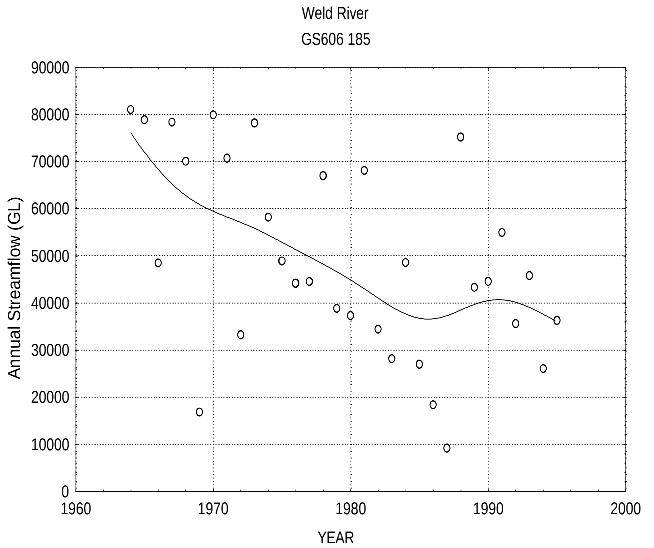


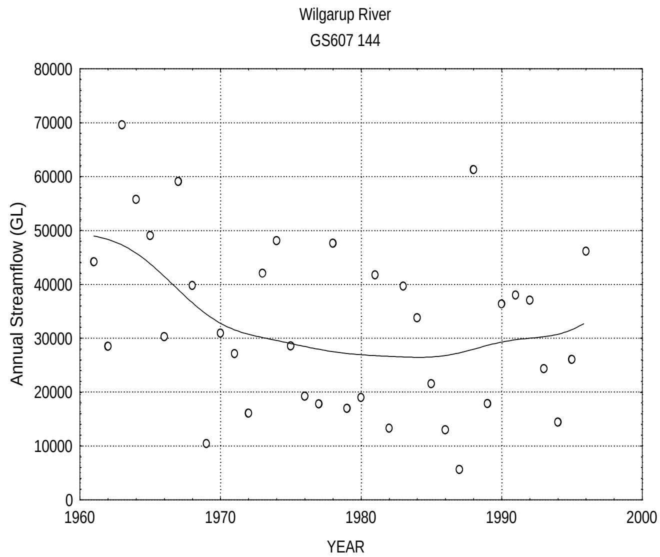

Kent River
GS604053/010
Annual Streamflow (GL)
YEAR

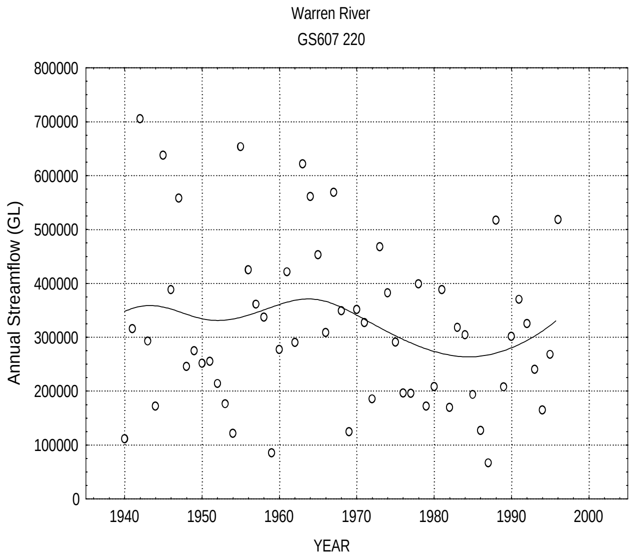

Shannon River
GS606 185
Annual Streamflow (GL)
YEAR

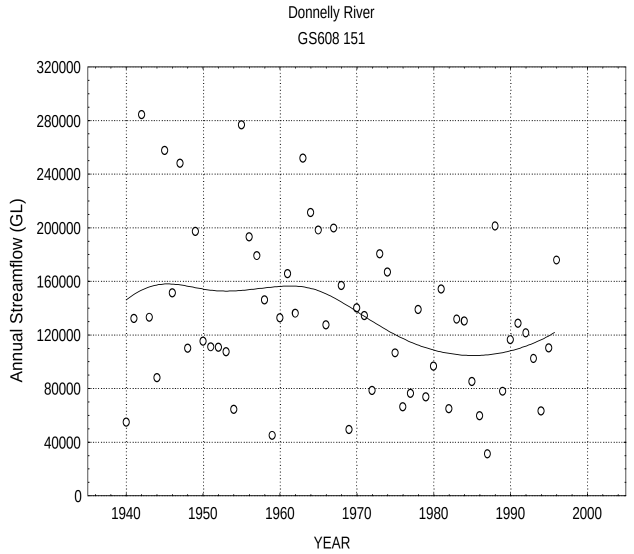

Frankland River
GS 605 012
Annual Streamflow (GL)
YEAR

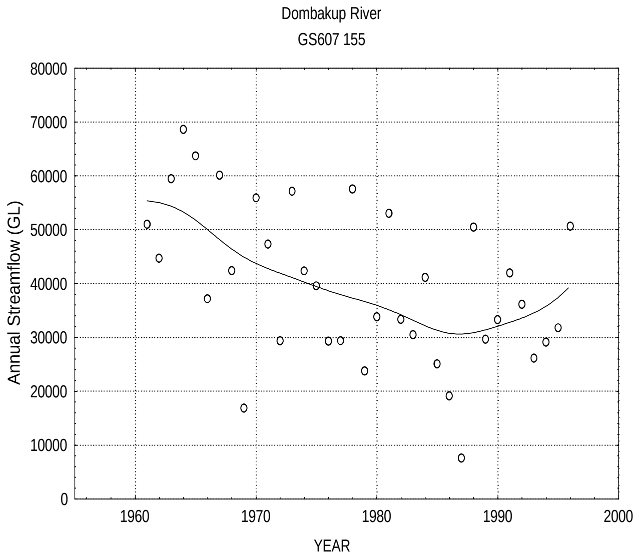

Perup River
GS607 145/004
Annual Streamflow (GL)
YEAR

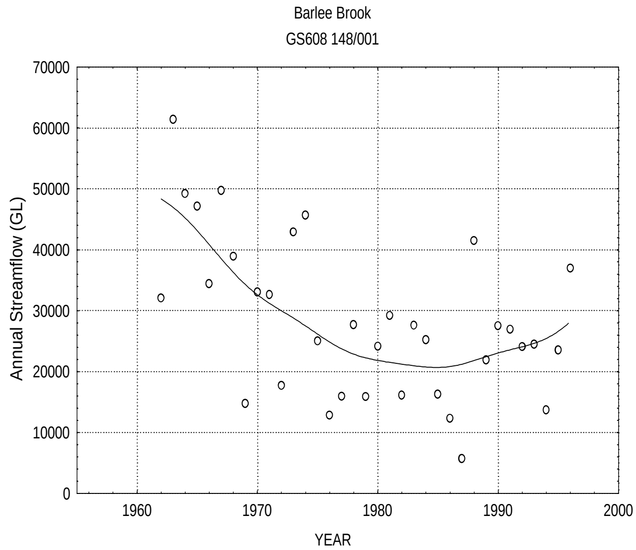

Weld River
GS606 185
Annual Streamflow (GL)
YEAR

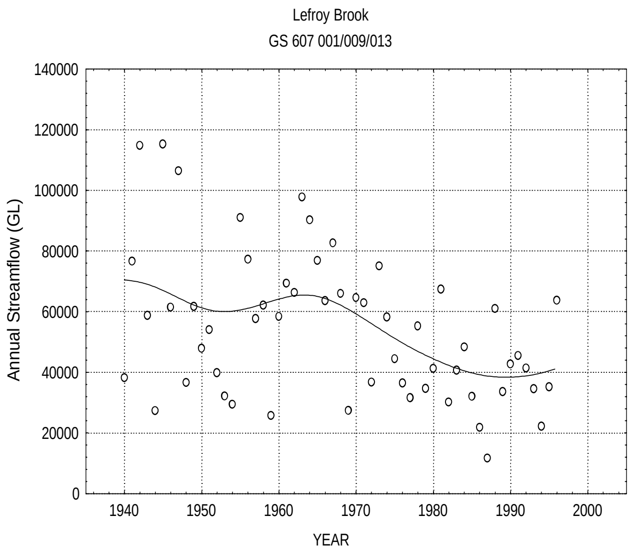

Wilgarup River
GS607 144
Annual Streamflow (GL)
YEAR

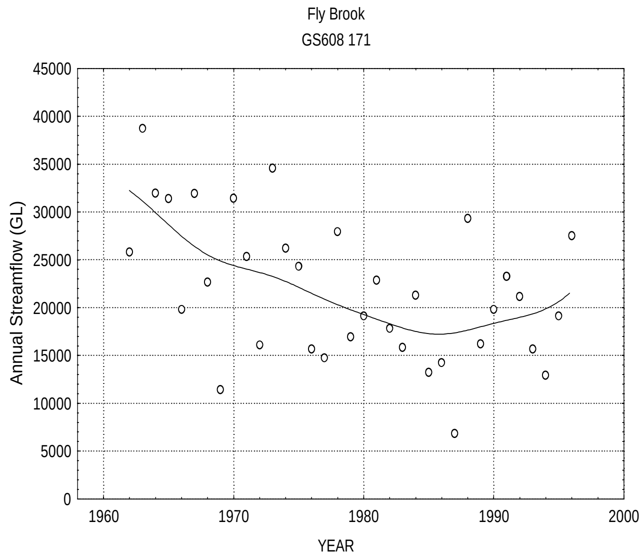

Warren River
GS607 220
Annual Streamflow (GL)
YEAR

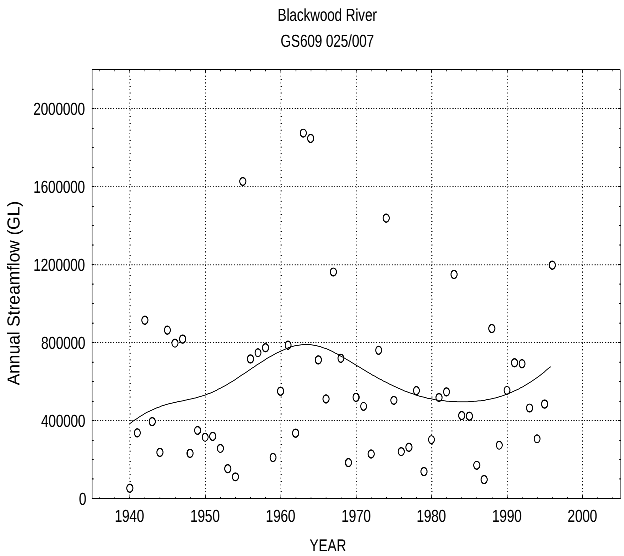

Donnelly River
GS608 151
Annual Streamflow (GL)
YEAR

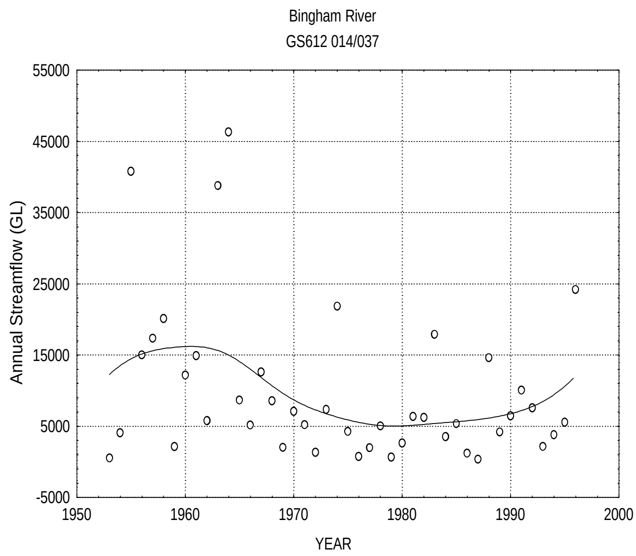

Dombakup River
GS607 155
Annual Streamflow (GL)
YEAR

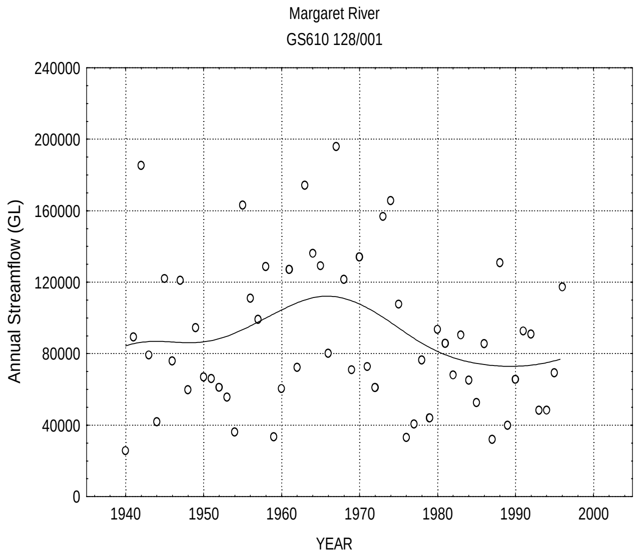

Barlee Brook
GS608 148/001
Annual Streamflow (GL)
YEAR

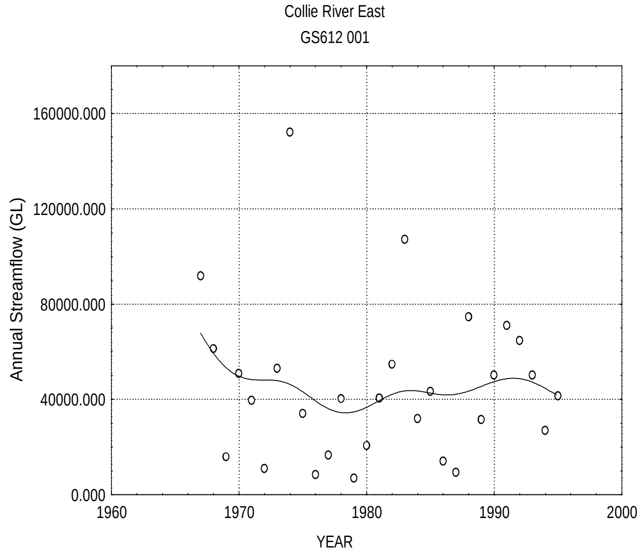

Lefroy Brook
GS 607 001/009/013
Annual Streamflow (GL)
YEAR

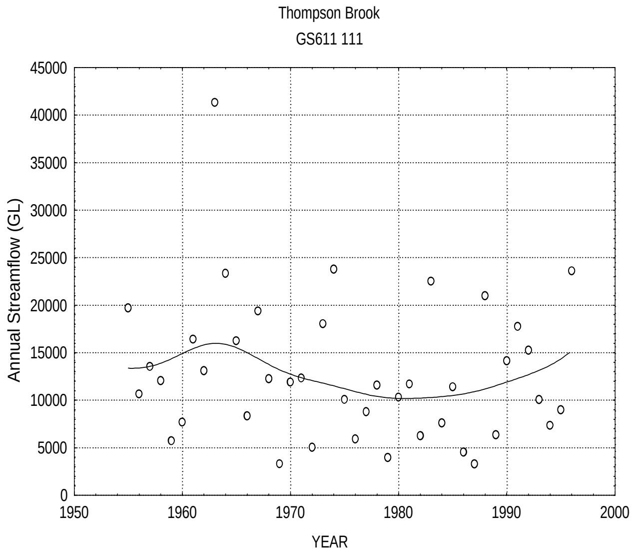

Fly Brook
GS608 171
Annual Streamflow (GL)
YEAR

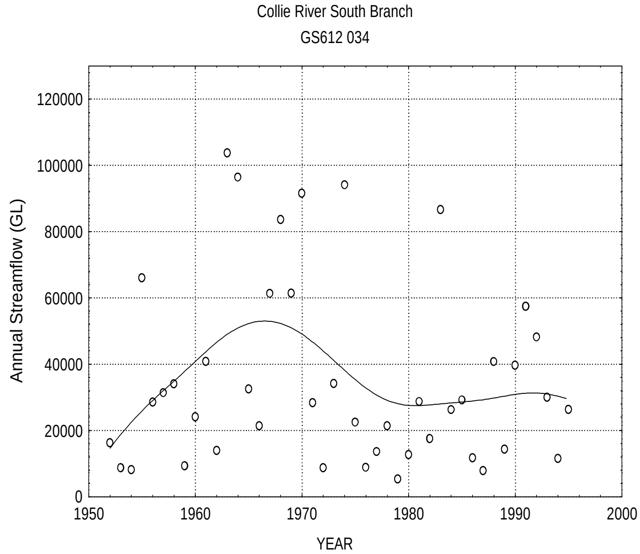

Blackwood River
GS609 025/007
Annual Streamflow (GL)
0
400000
800000
1200000
1600000
2000000
1940
1950
1960
1970
1980
1990
2000
YEAR


Bingham River
GS612 014/037
Annual Streamflow (GL)
-5000
5000
15000
25000
35000
45000
55000
1950
1960
1970
1980
1990
2000
YEAR


Margaret River
GS610 128/001
Annual Streamflow (GL)
0
40000
80000
120000
160000
200000
240000
1940
1950
1960
1970
1980
1990
2000
YEAR

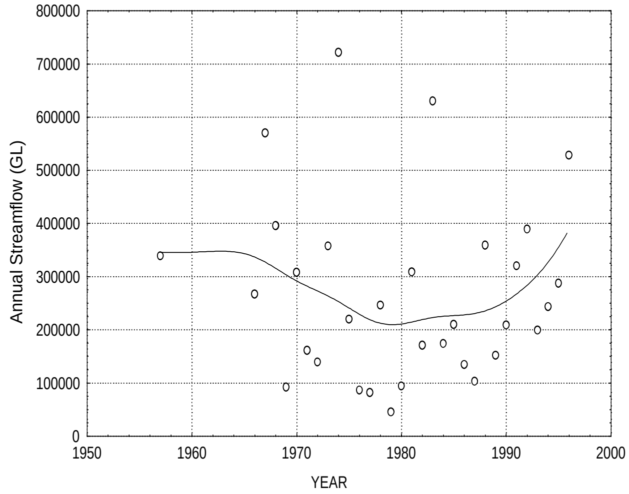

Collie River East
GS612 001
Annual Streamflow (GL)
0.000
40000.000
80000.000
120000.000
160000.000
1960
1970
1980
1990
2000
YEAR


Thompson Brook
GS611 111
Annual Streamflow (GL)
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
1950
1960
1970
1980
1990
2000
YEAR

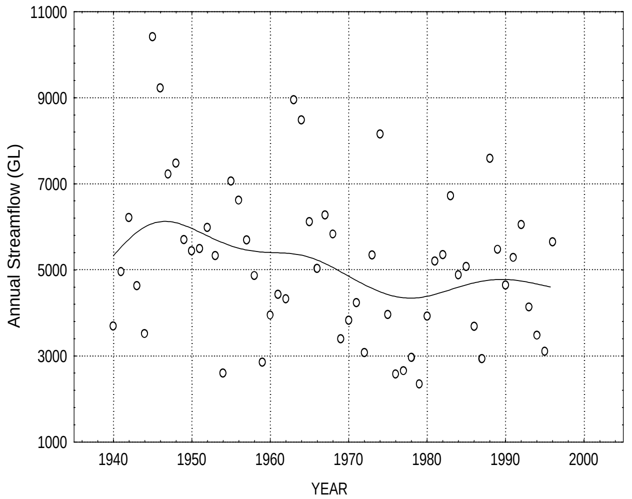

Collie River South Branch
GS612 034
Annual Streamflow (GL)
0
20000
40000
60000
80000
100000
120000
1950
1960
1970
1980
1990
2000
YEAR

Harris River
GS612 017/036

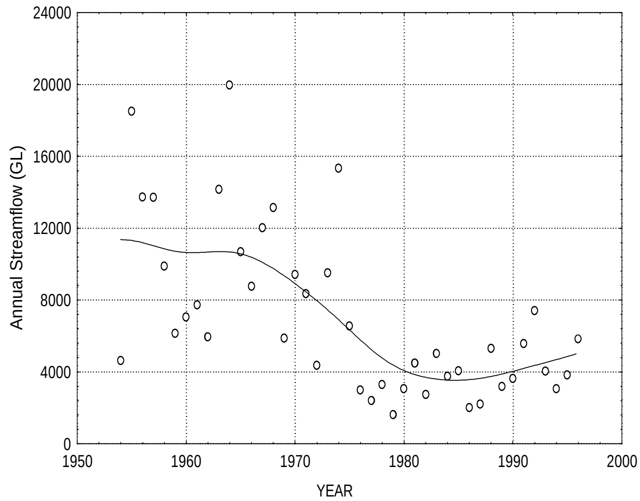
Murray River
GS614 006



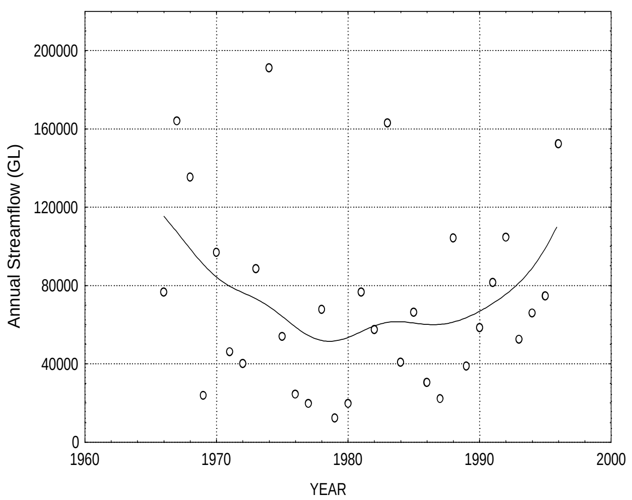
Bancell Brook
GS613 007/013



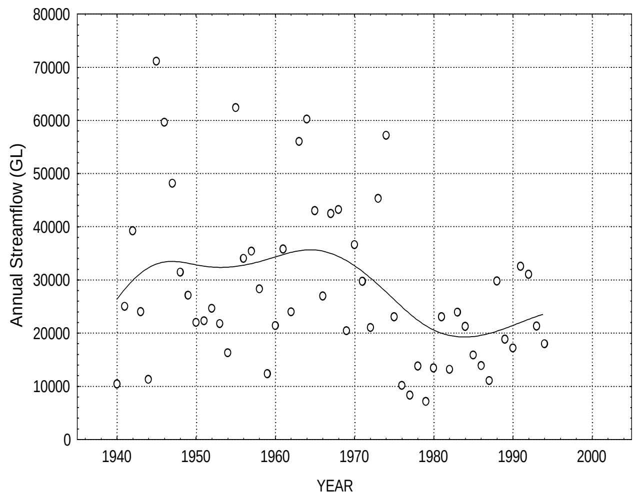
Davies Brook
GS614 047

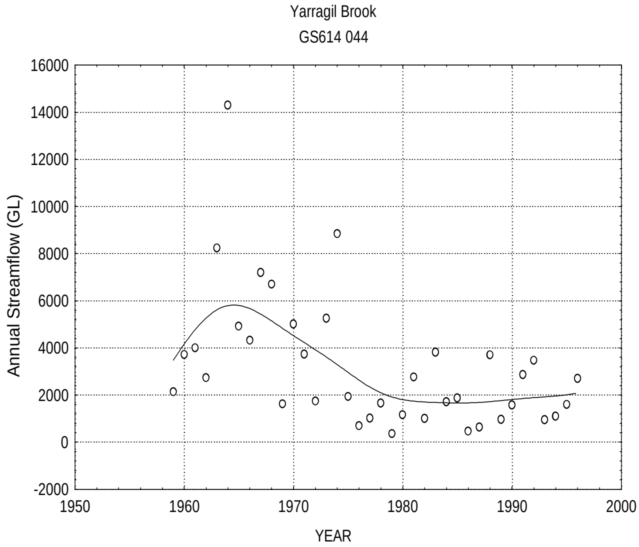


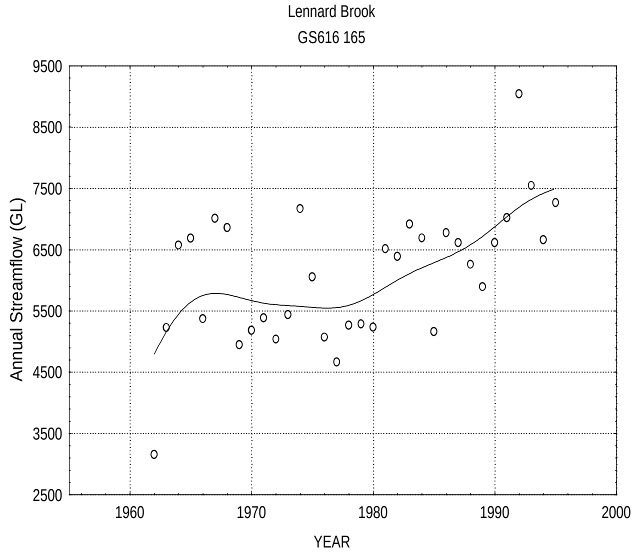
Williams River
GS614 196

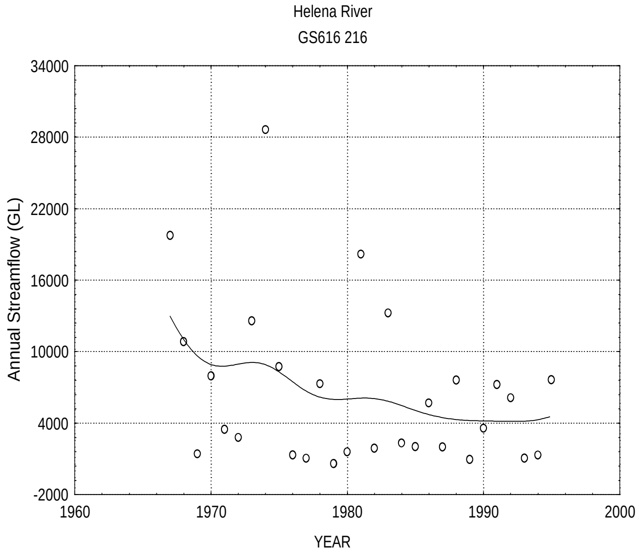


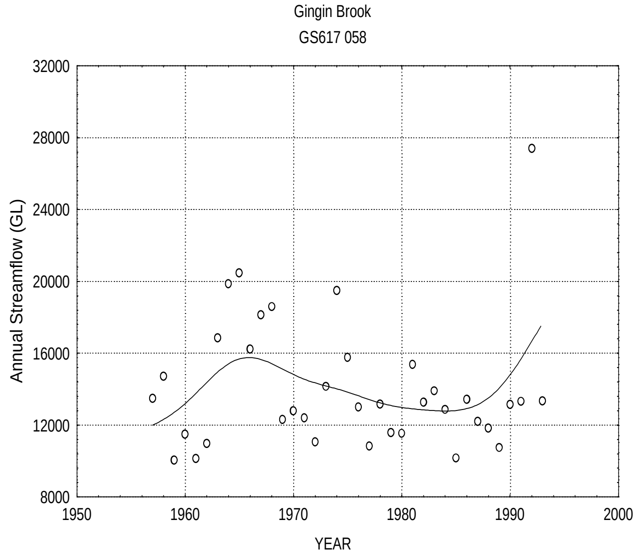
North Dandalup River
GS614 016



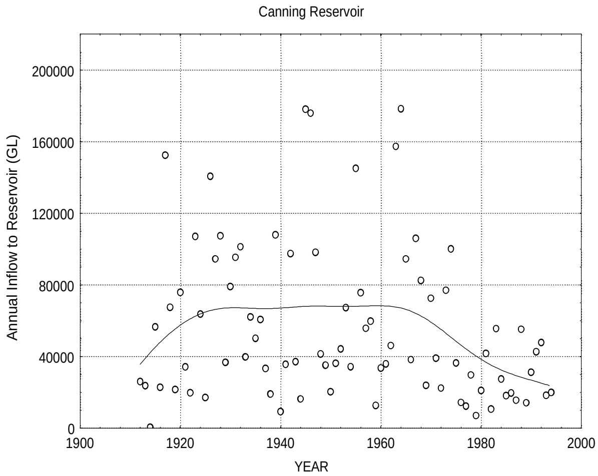


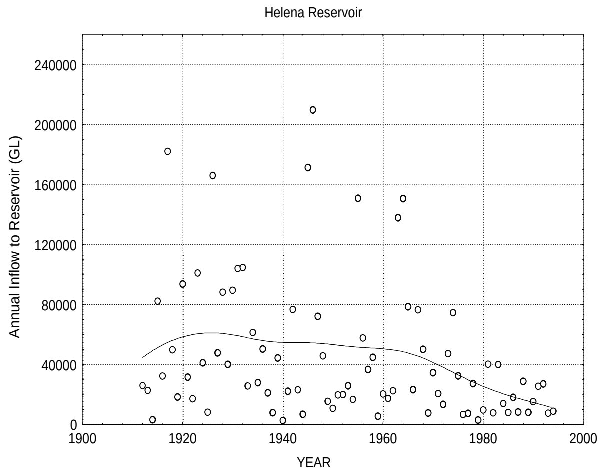


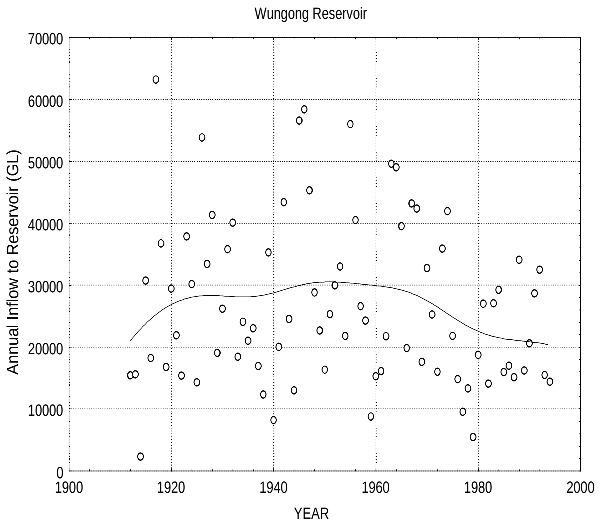


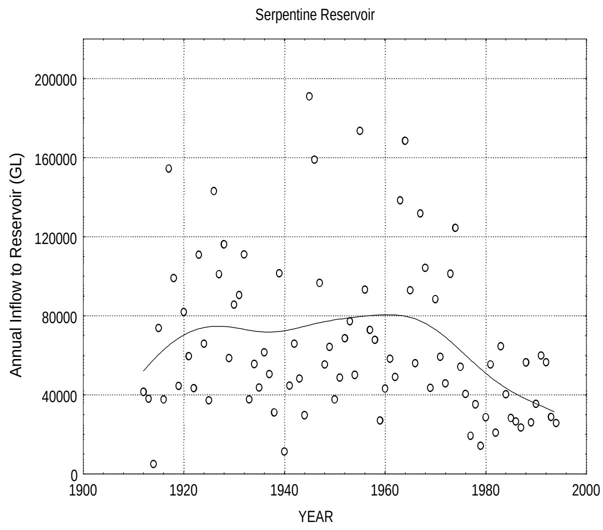


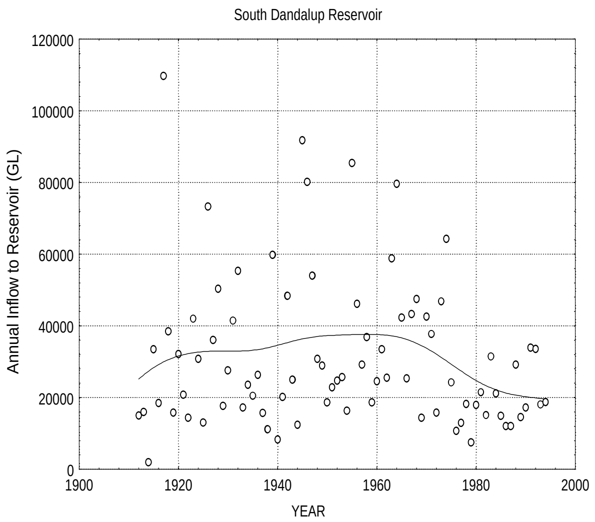
MODELLED INFLOW DATA:

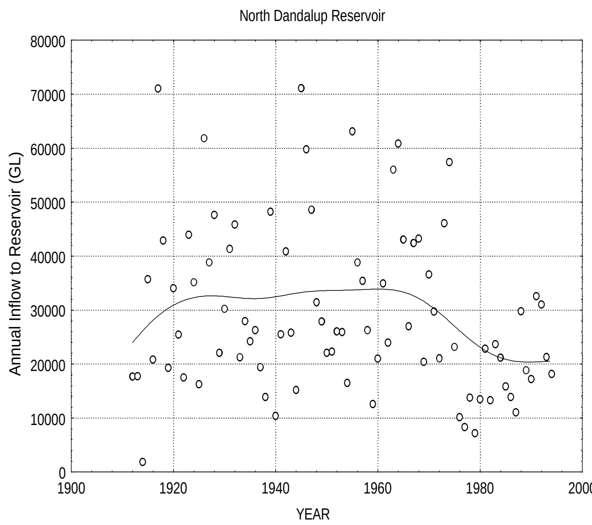


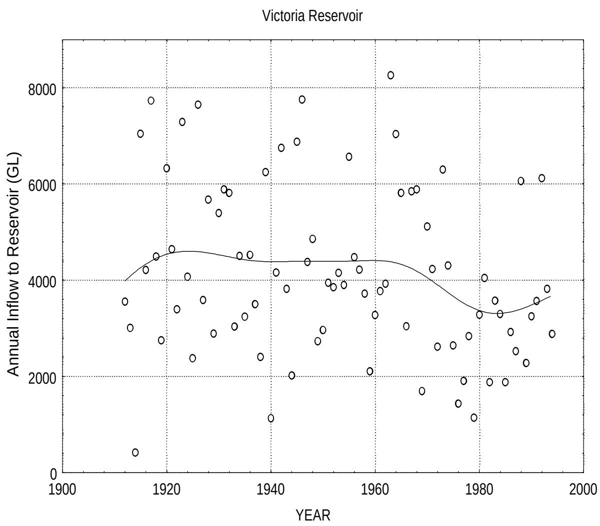


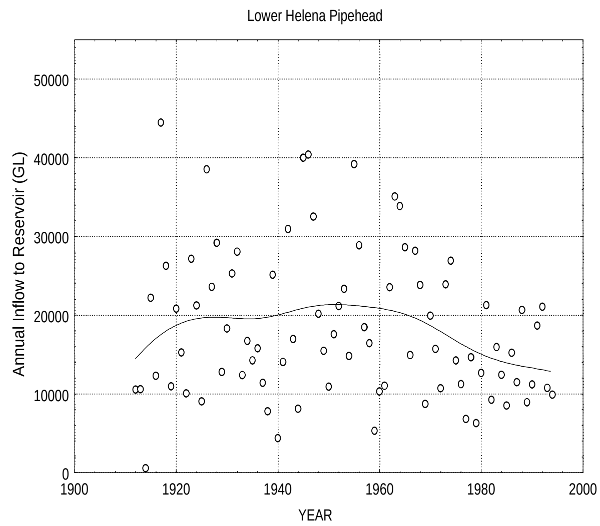

Wungong Reservoir
Annual Inflow to Reservoir (GL)
YEAR

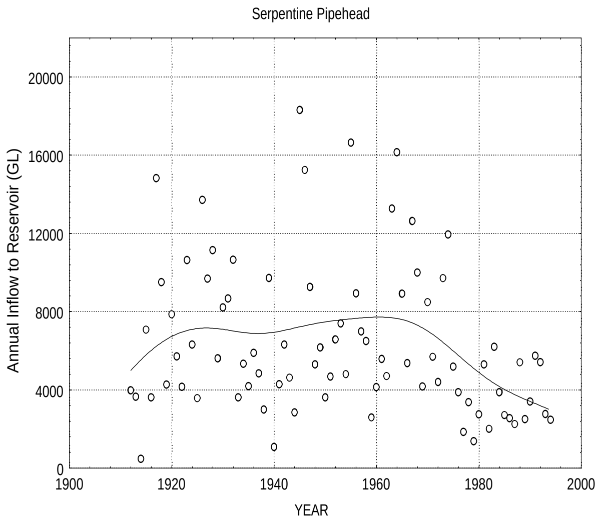

Serpentine Reservoir
Annual Inflow to Reservoir (GL)
YEAR

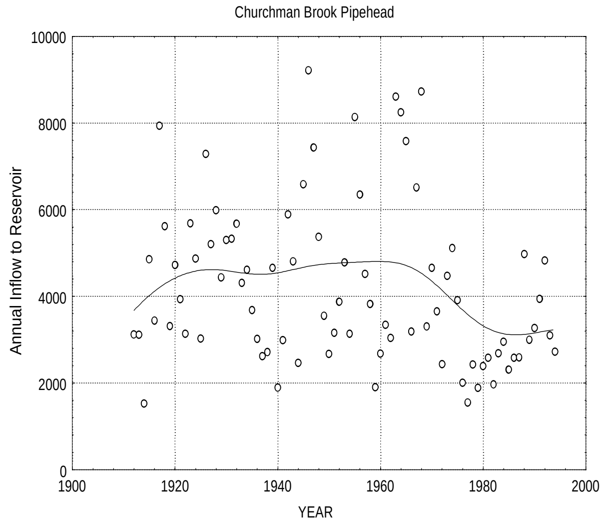

South Dandalup Reservoir
Annual Inflow to Reservoir (GL)
YEAR

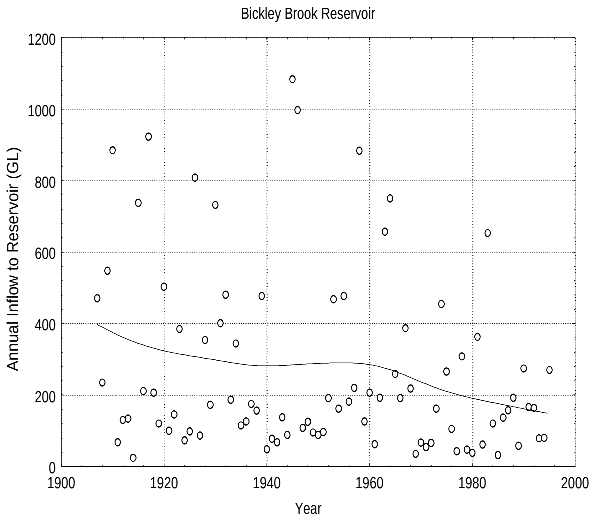

North Dandalup Reservoir
Annual Inflow to Reservoir (GL)
YEAR

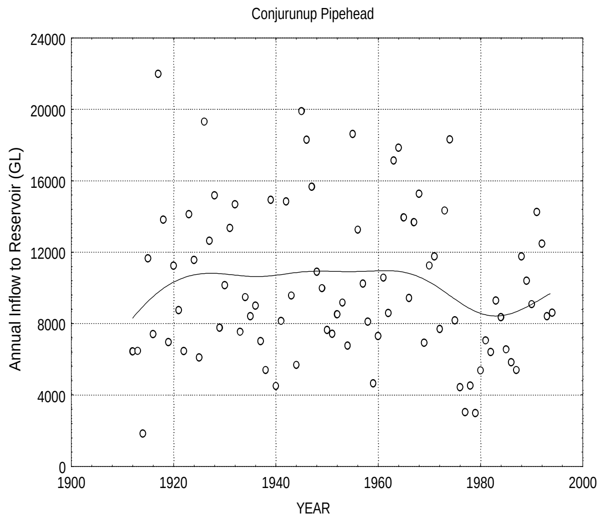

Victoria Reservoir
Annual Inflow to Reservoir (GL)
YEAR


Lower Helena Pipehead
Annual Inflow to Reservoir (GL)
YEAR

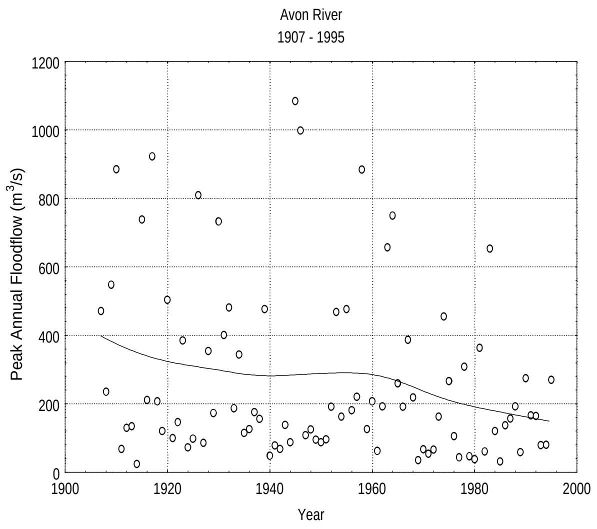


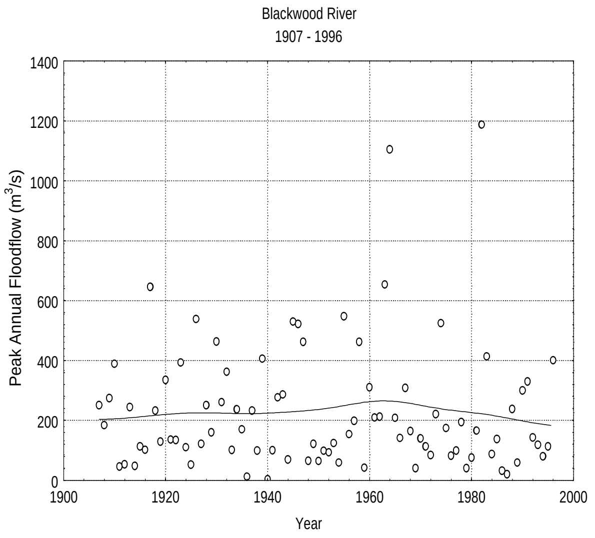






MODELLED FLOODFLOW DATA:





Appendix E: Statistical Tests

Rank-Sum Test

The rank-sum test was used to determine whether the annual streamflow data for the selected south-west gauging stations when divided into two groups (pre 1976 and post 1976) tended to produce higher flows during one of the periods. The test is based on the null hypothesis (Ho) that the median annual streamflow since 1976 is equal to the median annual flow prior to 1976. This implies that flows since 1976 have a fifty percent probability of exceeding, and of being less than, annual flows prior to 1976.

H_0: Median annual flow post 1976 = Median annual flow prior to 1976

H_1: Median annual flow post 1976 ≠ Median annual flow prior to 1976

The alternative hypothesis (H_1) is that the median of an annual flow since 1976 does not equate to the median annual flows prior to 1976.

The rank-sum test procedure, described in detail in Helsel and Hirsch (1992), involved ranking the annual streamflow data in order of increasing flows, dividing the flow into the two groups described above, and the test statistic Wrs is calculated simply by summing the ranks of the smaller of the two groups. For large sample sizes, greater than 10 observations in each data group, the test statistic Wrs closely approximates a normal distribution. The mean (μ_W) and standard deviation (σ_W)of Wrs is given by:

$$\mu_W = n(N+1)/2$$

$$\sigma_W = \sqrt{n \bullet m \bullet (N+1)/12}$$

where n,m = sample size of each group

N = n+m

The test statistic is then standardised (Zrs) and compared to a table of standard normal distribution for evaluation of he test results.

Hodges Lehmann Indicator

One nonparametric estimate of the difference between two independent groups is a Hodges-Lehmann estimator. This estimator is the median of all possible differences between two groups of data points. It relates to the Rank-Sum Test, in that if the estimator was subtracted from all of the observations in the larger of the groups, the rank-sum statistic (W) would provide no evidence for rejection of the null hypothesis. In other words, a shift of the same size as the estimator makes the data appear devoid of any evidence of a difference between two groups of data points when viewed by the Rank-Sum Test.

The rank-sum test is very similar to the Mann test which similar to the Worsley likelihood ratio, Kruskal-Wallis and Cumulative Deviation Test are selected by the World Meteorological Organisation (1988) as standard procedures for detecting trend or change in long time series hydrological data.

The purpose of the cumulative deviation test is to detect the existence of a change in the mean after m observations.

$$E(X_i) = \mu \qquad i = 1, 2, \ldots, m \qquad (3.5)$$

$$E(X_i) = \mu + \Delta \qquad i = m+1, m+2, \ldots, n \qquad (3.6)$$

where μ is the mean prior to the change and Δ is the change in mean.

The test statistic is the maximum value attained by calculating the cumulative deviations from the mean, at each observation to the first observation, and then dividing by the standard deviation. The critical values of this test statistic are shown in Grayson et al. (1996).

The Worsley likelihood ratio test is similar to Student's t-test. It provides an alternative to the t-test when information about the change point is not known. The Worsley likelihood ratio test is also similar to the cumulative deviation test except that it weights the cumulative deviations according to their location in the time series prior to dividing by the standard deviation producing a test statistic that has the critical values detailed in Grayson et al. (1996).

The Kruskal-Wallis test ranks the observations and the time series is divided into a number of sub periods. The sum of the ranks for the observations in each sub period is then used to calculate a test statistic which follows the Chi-square distribution. In this study sub periods of five and ten years have been used.

The Rank-Sum and Krukal-Wallis are both non-parametric tests, where the calculations are based on the ranks and not on the actual values of the observations. The reliability of these two tests and the distribution-free CUSUM test does not depend on the underlying distribution of the observations (Chiew and McMahon, 1992). The cumulative deviation and Worsley likelihood ratio tests assume that the observations are independent and normally distributed, although they can still be applied when there are slight departures from normality.

Results

Critical values for two-sided probability were used in all the five tests. The statistics test the null hypothesis (Ho) that the observation are randomly ordered versus the presence of either an increasing or decreasing trend or a change in the mean, as opposed to the one sided probability which tests against either an increase, or a decrease, in the data sequence. The null hypothesis is rejected only if a change or trend is detected above the 90 per cent confidence level. The results of the tests are given in Table E.1.

All five tests indicate no significant trend or change in the mean annual flow for nine of the twenty-two stations investigated. Seven stations showed significant evidence of a trend or change in the mean annual flow when all tests were applied to the data. These stations all had high lag-one autocorrelation coefficients and the catchments are situated in the high rainfall zones (>1,100 mm/year catchment centroidal rainfall) and are free from significant amounts of clearing (<10 % in most cases). This suggests that the presence, and the significance, of a trend or change in the mean annual flow appears to increase with increasing catchment rainfall and decreasing clearing. This builds on the results from the Loess Smoothing analysis discussed in Section 3.1.3. The timing of the apparent trend or change in mean during the trend tests analysis is focussed on the years of 1974-76 which fall in the centre of the decreasing flow period observed in the Loess smoothing where the gradient of the regression curve was at a maximum.

The seven stations that indicated the presence of a trend or change in mean in all of the tests, and four other stations that indicated the presence of a trend or change in mean in 3 or more of the tests, generally have longer period of records than the other stations investigated. Therefore, the length of record of the available data for a number of the remainder of the stations may be too short (typically 30 to 35 years) to detect any trend or change in the mean. However, this may not be the case as the period of record for some of the other stations in the south coastal area of Western Australia, for which no trend in annual streamflow was indicated, is greater than fifty years.

In order to investigate the effect of the period of record on the results from the trend tests the annual data for the Frankland River gauging station (GS605 012) was analysed over different lengths of record. The results indicate that the Kruskal-Wallis and Distribution free CUSUM Tests are the least sensitive to the length of record while the Cumulative Deviation and Worsley Likelihood Ratio Tests are quite sensitive (Table E.2).

Table E.1. Results of Statistical tests carried out to detect change or trend in historical annual streamflow

Station Number	Record Length (years)	Mean Annual Flow (ML)	Catchment Rainfall (mm)	Catchment Clearing (%)	Lag-one Auto correlation Coeff.	Rank-Sum Test	Hodges Lehmann Indicator	Cumulative Deviation Test	Worsley Likelihood Ratio Test	Kriuskal-Wallis Test subperiods		Distribution free CUSUM Test
										5 year	10 year	
602 199	33	4,130	870	10	0.35*	95%	1.13	90 %	NS	NS	NS	NS
603 190	33	5,130	780	60	-0.11	NS	-0.26	NS	NS	NS	NS	NS
603 136	38	31,300	800	20	-0.05	NS	0.57	NS	NS	NS	NS	NS
604 010/053	57	87,400	800	40	-0.18	NS	0.24	NS	NS	NS	NS	NS
605 012	57	168,800	600	56	-0.07	NS	-11.4	NS	NS	NS	NS	NS
606 195	32	49,100	1,275	0	0.06	95 %	-24.6	95 %	90%	90 %	95 %	95 %
607 220	31	292,200	800	40	-0.08	NS	-80.3	NS	NS	NS	NS	NS
607 155	35	39,300	1,430	16	0.18	99 %	-15.3	90 %	95 %	90 %	95 %	99 %
608 151	57	134,200	1,110	22	0.09	99 %	-44.3	99 %	95 %	90 %	NS	95 %
608 001	35	28,400	1,160	0	0.38*	99 %	-16.5	99 %	99 %	95 %	95 %	95 %
608 171	35	21,800	1,420	25	0.16	99 %	-8.7	99 %	95 %	90 %	90 %	90 %
609 025	42	643,500	550	85	0.23*	90 %	-607.8	90 %	90 %	NS	NS	90 %
611 111	39	12,600	960	30	0.12	NS	-2.44	NS	NS	NS	NS	NS
612 001	28	42,200	710	28	0.09	NS	-0.68	NS	NS	NS	NS	NS
612 017/036	37	36,000	1,000	5	0.23	95 %	-23.1	95 %	95 %	NS	NS	95 %
613 013/007	57	5,160	1,225	20	0.39*	90 %	-0.26	95 %	90 %	95 %	90 %	NS
614 196	31	72,600	600	80	0.06	NS	-22.4	NS	NS	NS	NS	NS
614 006	31	267,100	650	50	0.06	NS	-67.5	NS	NS	NS	NS	NS
614 047	43	7,090	1,215	5	0.58*	99 %	-5.7	99 %	99 %	99 %	99 %	99 %
614 016	55	28,300	1,300	0	0.40*	99 %	-13	99 %	99 %	99 %	99 %	99 %
614 044	38	3,220	1,090	0	0.44*	99 %	-3	99 %	99 %	99 %	95 %	95 %
616 216	29	6,300	680	10	0.09	95 %	-5.4	NS	NS	NS	NS	NS

- indicates that the lag one autocorrelation coeff. Is outside the 95% confidence limits of the expected value. NS indicates that no trend or change in mean (above 90% confidence level) is detected. Numbers indicate the level of significance (90, 95 or 99 per cent) in the trend detected. A negative Hodges-Lehmann indicator implies a trend to decreasing flows and vice-versa.

Table E.2. Investigation into the effect of the length of record at GS605 012 on trend tests results.

Period of Record (year –1995)	Cumulative Deviation Test	Worsley Likelihood Ratio	Kruskal-Wallis Test		Distribution free CUSUM Test
			5 yr sub-periods	10 yr sub-periods	
1940-1944	NS	NS	NS	NS	NS
1945	NS	90 %	NS	NS	NS
1946-1954	NS	NS	NS	NS	NS
1955	90 %	90 %	NS	NS	NS
1956-1959	NS	NS	NS	NS	NS
1960	90 %	90 %	NS	NS	NS
1961	90 %	95 %	NS	NS	NS
1962	NS	90 %	NS	NS	NS
1963	90 %	99 %	NS	NS	NS
1964	NS	90 %	NS	NS	NS
1965-68	NS	NS	NS	NS	NS

Modelled Data

The trend tests, which were applied to the gauged data for the longer term streamflow gauging stations in the south-west, were also applied to the modelled inflow data for the metropolitan sources in Table E.2. The results, shown in Table E.3, indicate the presence significant trend or change in mean is observed at least two of the tests for each of the metropolitan sources. However, only four of the sources exhibit a significant trend or change in mean in all of the tests. The rank-sum and cumulative deviation tests indicate the presence of a trend or a change in mean for all of the modelled inflow data sets. The Worsley Likelihood Ratio and the Kruskal-Wallis test using five year sub-periods indicates the presence of a trend or a change in mean in 11 of the twelve modelled inflows and the total inflows. However the Kruskal-Wallis test using a ten year sub-period and the distribution-free CUSUM test did not indicate the presence of a trend or a change in mean for a number of the modelled inflow data sets (Table E.3).

Floodflow Data

The result of applying the trend tests to the peak annual floodflow data is illustrated in Tables E.4 and E.5. There is little to indicate the presence of a significant trend in the gauged peal annual floodflow data for the long term gauging stations in the southwest of Western Australia. There is some possible evidence of a trend in the floodflow data for the Murray River (614 006), North Dandalup River (614 016) and Bancell Brook (613 013) in the trend test results (Table E.4). However, the gauged floodflows at none of the stations examined illustrated evidence of a trend for each of individual tests applied to the data. In fact, there was no evidence of a trend in any of the floodflow data sets using the Distribution-free CUSUM Test or for the Kruskal Walllis Test with a 5 year sub-period.

Similarly, there is no significant trend detected in the modelled floodflow data for the Avon and Blackwood Rivers except using the Rank Sum Test on the Avon River data where a a trend at a 90 % significance level is detected (Table E.5).

Table E.3. Trend test results for the modelled annual inflows between 1912 and 1994 to the metropolitan surface water sources.

Inflow site	River	Mean annual flow 1912-94 (GL)	Rank-Sum Test	Hodges Lehmann Indicator	Cumulative Deviation Test	Worsley Likelihood Ratio Test	Kruskal-Walllis Test sub-periods 5 year	Kruskal-Walllis Test sub-periods 10 year	Distribution free CUSUM Test
Mundaring Reservoir	Helena River	45.1	99 %	-20.1	95 %	95 %	95 %	NS	90 %
Canning Reservoir	Canning River	55.9	99 %	-26.0	95 %	95 %	95 %	90 %	NS
Wungong Reservoir	Wungong Brook	26.6	99 %	-7.7	90 %	NS	90 %	NS	NS
Serpentine Reservoir	Serpentine River	66.4	99 %	-30.4	99 %	99 %	99 %	95 %	90 %
South Dandalup Reservoir	South Dandalup River	31.2	99 %	-10.8	90 %	90 %	99 %	NS	NS
North Dandalup Reservoir	North Dandalup River	29.4	99 %	-12.4	99 %	99 %	99 %	90 %	95 %
Victoria Reservoir	Mundays Brook	4.1	99 %	-1.24	95 %	95 %	90 %	NS	95 %
	SUB - TOTAL	258.5	99 %	-111.2	95 %	95 %	90 %	95 %	NS
Lower Helena Pipehead	Helena River	18.3	99 %	-5.6	90 %	90 %	NS	NS	NS
Serpentine Pipehead	Serpentine River	6.4	99 %	-2.9	99 %	99 %	99 %	95 %	90 %
Churchman Brook Pipehead	Churchman Brook	4.2	99 %	-1.5	99 %	99 %	99 %	95 %	90 %
Bickley Pipehead	Mundays Brook	2.8	99 %	-0.9	95 %	95 %	90 %	NS	90 %
Conjurunup Pipehead	Conjurunup Creek	10.1	99 %	-2.9	90 %	90 %	99 %	NS	NS
	SUB-TOTAL	41.8	99 %	-13.6	95 %	95 %	95 %	NS	90 %
	TOTAL	300.3	99 %	-123.6	95 %	95 %	95 %	NS	NS

NS indicates that no trend or change in mean (above 90% confidence level) is detected. Numbers indicate the level of significance (90, 95 or 99 per cent) in the trend detected. A negative Hodges-Lehmann indicator implies a trend to decreasing flows and vice-versa.

Table E.4. Summary of trend analysis results for gauged floodflows at selected south-west gauging stations.

Station Number	Mean Ann. Floodflow (m^3/s)	Rank Sum Test	Hodges-Lehmann Indicator	Cumulative Deviation Test	Worsley Likelihood Ratio Test	Kruskal-Wallis Test sub-periods 5 year	Kruskal-Wallis Test sub-periods 10 year	Distribution CUSUM Test
604 053	35.8	NS	1.14	NS	NS	NS	NS	NS
605 012	69.9	NS	2.09	NS	NS	NS	NS	NS
608 151	36.25	NS	6.38	NS	NS	NS	NS	NS
613 013	1.58	NS	0.04	NS	95%	NS	90 %	NS
614 006	163.6	NS	24.8	NS	NS	NS	95 %	NS
614 016	10.46	95 %	3.26	95 %	90 %	NS	NS	NS

Table E.5. Summary of the trend tests results for the modelled Blackwood and Avon River floodflows.

River	Mean Ann. Floodflow (m^3/s)	Rank Sum Test	Hodges Lehmann Indicator	Cumulative Deviation Test	Worsley Likelihood Ratio Test	Kruskal-Wallis Test Sub-period 5 years	Kruskal-Wallis Test Sub-period 10years	Dist. Free CUSUM Test
Blackwood	227.5	NS	40.2	NS	NS	NS	NS	NS
Avon	267.1	90 %	62	NS	NS	NS	NS	NS