THE EFFECT OF CLEARING OF NATIVE FOREST ON FLOW REGIME

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December 2004

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The Effect of Clearing of Native Forest on Flow Regime

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Preface

There is now widespread awareness of the problems of land and stream salinity in the Australian community. The community understands the impacts to agricultural productivity, and the vision of white salt scalds spreading across the landscape, especially in Western Australia. However, the accompanying modifications to streamflow, length of wet period, and potential increase in flooding are less widely understood. This report investigates changes to flow regime, in particular the frequency distribution of flow in the streams, using data from experimental catchments in southern Western Australia.

These catchments have the best record in Australia, and one of the best in the world demonstrating the link between clearing forest, the rise in stream salinity, and change to flow. It is therefore an important proving ground for our understanding of streamflow and salinity in catchments. For this reason, this report will be valuable reading for specialists managing salinity throughout Australia. It will also be a valuable resource for those interested in catchment flow responses to climate and deforestation.

This work has been conducted by the Cooperative Research Centre for Catchment Hydrology's Land-use Impacts on Rivers research program. This program is focused on the impact of human activities upon the land and stream environment and the physical attributes of rivers. We are concerned about managing impacts for catchments ranging in size from a single hillslope to several thousands of square kilometres. Specifically our interest is focussed on changes in streamflow, changes to in-stream habitat by the movement of coarse and fine sediment, as well as changes to water quality (sediment, nutrients and salt). If you wish to find out more about the program's research, I invite you to first visit our website at http://www.catchment.crc.org.au/programs/projects

Peter Wallbrink
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CRC for Catchment Hydrology

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Executive Summary

This report discusses the changes that have taken place to flow regime as a result of clearing for agriculture, and the associated implications for stream salinity. The focus of this report is analysing data from several well-instrumented experimental catchments in the Collie River Basin, in the south-west of Western Australia.

This project has three key complementary aims:

- To quantify the change in flow regime resulting from clearing through analysis of flow, baseflow, discharge ratio, and number of zero flow days.
- To explore existing methods for separating the influence of climate from vegetation on the flow duration curve.
- Develop a model structure that has the potential to:
  - (i) separate the influence of climate from vegetation change over the entire flow duration curve (FDC); and,
  - (ii) predict the impact of vegetation change on the FDC, based on physically measurable properties.

Rainfall and streamflow data from five small catchments through a 24 year period have been analysed for trends in changes to flood frequency and duration. The catchments were set up as clearing experiments in the Collie River Basin in the early 1970s. A catchment pair was instrumented in the high rainfall zone (1100 mm/yr), and three catchments in the intermediate rainfall zone (700 mm/yr). Following clearing the discharge coefficient has risen by a factor of 5 in the wetter catchments, and about 10 in the intermediate rainfall catchments. Some of this increase occurs almost immediately following clearing, before there is a significant rise in the watertable. When the watertable reaches the surface in some parts of the catchment there is a second increase in discharge coefficient and in baseflow index. Our work shows that clearing 50% of a catchment as one large block has a significantly different effect than clearing in patches. The watertable has risen substantially and reached a new equilibrium level in the catchment cleared as a block, while groundwater is still rising across the catchment that was cleared in patches. The watertable is rising only under the cleared areas and adjacent forest. Salinity of this stream has just started to increase (2000-2003) and it is not yet clear whether the groundwater will stabilise at a level deep enough to prevent major salinisation of the stream. Annual average rainfall and proportion of catchment cleared both have an influence on response time of catchments to clearing. Because we lack replicates of treatment and rainfall we cannot separate the two, but we observe that the response of the high rainfall catchment was very rapid, with discharge coefficient increasing immediately on clearing, stream salinity increasing within a year of the treatment, and baseflow index increasing four years later.

The land-use change studied here was the opposite of that studied by Lane *et al*., 2003, who found afforested streams that had begun as perennial became ephemeral. In this study, two of the catchments that were forested, in different rainfall regimes, began as ephemeral streams, but rapidly became perennial streams after clearing. The methodology outlined by Lane *et al*., 2003 for separating climatic and vegetation influences on the percentiles of the FDC has been tested in three deforested catchments and has proved to be appropriate in catchments undergoing a large percentage change in forest cover with rapid response times. However, the methodology does not appear to work in catchments where the observed response to vegetation change is small and, or, time for response is longer than the observed period of record. Following the method outlined by Lane *et al*., we develop a description of individual percentiles of the FDC in terms of their dependence on annual rainfall, and representing the change from one flow regime to another following clearing. This gives a useful description of data, but it does not provide a method for predicting changes to the FDC in a new catchment. The analysis shows that, for catchments subject to clearing, the vegetation effects dominate the response and the rainfall influence is hidden within the statistical variability from year to year. We found that the number of zero flow days exhibits binary behaviour, with a sharp change between the forested

intermittent state and perennial flow. We show that a sigmoidal relationship can be used to describe the dependence of number of zero flow days on annual rainfall. This relationship may be used to separate the climatic influence on a catchment, independently of treatment for land-use change. The analysis of Lane *et al.*, 2003 assumes that the climate dependence of individual percentile flows, $Q_{\%}$, and of the number of zero flow days, N_{zero}, is a linear function of annual total rainfall. We discuss the limitations of this assumption.

We then approach the problem from a different perspective, to try to characterise the entire FDC with a single function that would allow development of a predictive model. We explore a set of models of the FDC, as functions of the flow, q:

$$F(q) = 1/(\exp(g(q))+1)$$

where:

$g(q)$ is a polynomial or fractional power function of q. The analysis required the removal of zero flow days and normalisation by the maximum flow in the recorded series. This normalisation of the FDC therefore specifies two parameters needed in order to apply the model to new catchments, but we have not managed to specify the dependence of the parameters of the model on independent catchment and climate characteristics. By developing the normalised approach we have a way of moving towards a more generic model that would be predictive, however there is still a way to go.

Our exploration of fractional powers of flow in the FDC model produced more promising fits to the FDC, without being materially different in substance – that is they still had some parameters that changed through time and some that did not. It appears that a fractional power of flow, specifically ½, is more likely to produce a good result and future work should focus on this. This project aimed to develop a predictive framework for the flow duration curve of catchments subject to land-use change – specifically clearing of forest for pasture. While we have not completed the task, we have made progress, and identified areas for the focus of future work. The first step is to remove the climate signal, similar to Lane *et al.*, but we broaden the approach by normalising the FDCs and seek a function that describes the whole distribution, rather than individual percentile flows. While demonstrating that some of the parameters of the FDC functions change in time and others do not, we show that it is possible to separate out the climatic and vegetation influences. For this work to reach a practical use, we need to link to more sophisticated climate statistics to the FDC parameters. We also need to be able to generalise the functions to include catchment characteristics, and some of these are discussed. The intermittency of flow is a strong component of the flow frequency distribution, and intermittent streams need different approaches to perennial streams. As discussed by others, most recently Cigizoglu and Bayazit (2000), there is a great need for more data from a large number of catchments to understand the physiographic controls on FDCs.

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1. Introduction

Flow in a river is the result of a complex array of natural and anthropogenic influences. A river network can be perceived as a collection of inter-linked reservoirs, some cascading to others, and some discharging directly to the stream. Each reservoir has a water balance governed by components of input (recharge) and output (discharge), moderating its storage. The input is largely controlled by precipitation, but discharge and storage are functions of catchment physiographic characteristics and vegetation. Over very long time scales the physiography, climate and vegetation are explicitly linked in the development of the catchment form and function (Eagleson, 1982). Climate gives the major driver for the weathering of basement material to soil, but the vegetation that develops in this environment itself influences the weathering process by contributing carbon to the soil, and thereby carbonic acid and other active chemicals. However, for most purposes of management the vegetation is considered primarily dependent on the soil and topography, with the latter considered largely static. This presumption is not true when active land-use is invoked. For example, forest soils are known to have much higher infiltration capacities than soil under agriculture after clearing. This occurs because stock and machinery compact the surface and breakdown the soil structure. It is also highly likely that preferential flow pathways through the regolith occur partly through old root channels (for example, Johnston *et al*., 1983). Over time these collapse, from soil movement and, if watertables rise, dispersion, especially in the presence of saline groundwater.

Previous analysis has identified an impact on streamflow regimes in agricultural catchments by rising watertables, as saturated areas increase and infiltration is reduced (Silberstein *et al*., 2003; Bowman and Ruprecht, 2000; Lane *et al*., 2003). The result is increased rapid flow responses in affected catchments and increased total flow through longer duration of baseflow. The rising watertables are also the source of the increased salinity in streams, through direct discharge of saline groundwater and by supplying the salt that rises through capillary action and is then available to be washed off the surface by rainfall. This increases the total salt load of streams, the average stream salt concentrations, and changes the timing of salt input to streams, and its conjunction with flow events.

The massive land-use change in Australia associated with agricultural development has caused an imbalance in catchment hydrological regime, leading to increased land and stream salinisation. The recent Prime Minister's Science, Engineering and Innovation Council (PMSEIC, 1999) report "Dryland Salinity and its Impacts on Rural and Industries and the Environment" estimated that each year the total cost of salinity to the nation is about $270 million including cost of lost production, damaged infrastructure, and environmental assets. The area affected by dryland salinity is about 2.5 million hectares and it is expected to increase to more than 15 million hectares over coming decades. Dryland salinity has become a major natural resource management issue and its most damaging impact is on our environment (e.g. terrestrial and in-stream ecological processes and biodiversity).

Under native vegetation over much of Australia, groundwater is below the root zone and runoff is generated only after significant rainfall events. The native vegetation has evolved to survive long drought periods, maintaining water use at a low rate throughout the dry season, with the result that it used almost all the rain that fell. Clearing of the native vegetation since European settlement has tipped this delicate balance and caused increased recharge, leading to rapid rise in watertables and increased permanently saturated areas. This has accompanied an increased groundwater discharge, which is often salty, to streams. The result has been a dramatic change in flow regime of the rivers affected, from ephemeral mainly fresh streams to perennial saltier ones. Understanding of the processes responsible and developing applicable knowledge is an important step toward sustainable management strategies.

Dryland salinity has been recognised as a catchment scale problem developed over a period of decades. Any actions to control salinity will have to take place at appropriate scales (e.g. catchment scales) and their effects may not be noticeable for some time. The main emphasis of current salinity control strategies is to reduce groundwater recharge and to minimise the mobilisation of salt in the landscape. Among the proposed land management initiatives, plantation forestry is likely to be a major land-use change in southern Australia and its impact on water yield and salinity could be significant (Vertessy and Bessard, 1999).

Afforestation will affect stream salinity in two ways. The first is to reduce water yield and decrease the dilution of the salt loads. This effect occurs in the first five years of the plantation as water is taken up by the trees. The second is to decrease recharge and hence the salt discharge that occurs from groundwater. The response time for this may be several decades or longer (Cook *et al*., 2002). The discrepancies in time scales of response mean that large scale afforestation could initially lead to increased salinity and in the longer term decreased salinity. The water yield impacts would occur from the higher rainfall zones, whereas the salt load reductions would occur from the medium to low rainfall zones (Vertessy *et al*., 2003). This discrepancy in space means that from a salinity perspective, it is advantageous for plantations to occur in the medium rainfall zones and not in the higher rainfall zones.

From both water quantity and quality perspectives, the preferred siting of plantations is opposite that from a commercial perspective. It is important to understand the water balance-vegetation relationships through the different parts of the landscape to determine the trade-offs between economic viability, environmental sustainability and water resource security. Thus, in order to determine the trade-offs, it is highly desirable to develop predictive capability at regional scales to quantify these impacts and to better plan the siting of increased areas of plantations and water allocations.

We have already seen a major change in flow regime as a result of clearing for agriculture in Australia, and the introduction of large scale plantations would mean another major change. This report discusses the changes that have taken place to flow regime as a result of clearing and discusses the associated implications for stream salinity. The focus of this report is analysing data from several well instrumented experimental catchments in the Collie River Basin, south-west Western Australia.

This project has three key complementary aims:

- To quantify the change in flow regime resulting from clearing through analysis of flow, baseflow, discharge ratio, and number of zero flow days.
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The aim is to generate a set of explanatory variable relationships that relate the FDCs and peak flow intensities to catchment conditions and rainfall. These are of the form:

$$F(Q)=G(\text{Climate})H(\text{Catchment})I(\text{Vegetation}) \qquad (1)$$

where $F(Q)$ is the cumulative frequency distribution of flow, and G,H,I are (as yet arbitrary) functions of climate, catchment and regolith properties and vegetation cover, respectively. These may be rearranged to give occurrence of a specific flow frequency as, for example, was done by Lane *et al.,* 2003:

$$Q_{\%}=A+b(\text{Climate})^{n}+c(\text{Time})^{m} \qquad (2)$$

The key is to determine these functional forms, and to do this in such a way as to preserve as much physical information as possible.

2. Literature Review

Zhang *et al.,* 1999 enabled the estimation of the impact of vegetation changes on long-term average water yield, based on factors that are easily measurable at catchment scales. The basis of the method is an empirical observation (Holmes and Sinclair, 1986) that the proportion of rainfall that becomes runoff, on an annual basis, can be plotted against potential evaporation as a smoothly varying curve. Zhang *et al.* developed a rational function that characterised the shape of the curve and represented it in terms of vegetation rooting depth and potential evaporation. The method has been applied to the Murrumbidgee catchments by Vertessy and Bessard (1999) and used to explore the impact on stream water yield under a range of plantation scenarios within the catchment. While the results have been useful in an exploratory sense, the basic parameters of the representative model are yet to be physically demonstrated, and it only gives a prediction of average annual water yield, when there is often a need for inter-annual variability and seasonal or event based predictions.

While the process of runoff generation has been the subject of study over a long period, (infiltration excess - Horton, 1933; partial area contribution – Betson, 1964; variable source area – Hewlett and Hibbert, 1963; variable source area-overland flow – Dunne and Black, 1970) little has been carried out in the south-west of Western Australia. Work done in the 1980s in the forested catchments south of Perth identified throughflow from shallow perched aquifers as the major proportion of streamflow, dominating the contribution from overland flow and deep groundwater (Stokes and Loh, 1982; Loh *et al*., 1984; Stokes, 1985; Turner *et al*., 1987). Ruprecht and Schofield (1989) showed that after clearing in a high rainfall catchment (1100 mm yr^{-1}) streamflow increased by 30% within about six years. Streamflow increased in the first year as a result of a reduction in interception and transpiration, and subsequently as the watertable rose and the groundwater contribution to streamflow increased. They determined that a new hydrological steady state between the streamflow and rainfall had been reached within about six years. The subsequent increase in runoff/rainfall ratio was closely correlated with the expansion in groundwater discharge area, which appeared to reach a new recharge-discharge steady state.

George and Conacher (1993a,b) identified the pathways for runoff generation and salt mobilisation in a small (12 ha) catchment with a saline seep in the wheatbelt in Western Australia. They determined that the majority of runoff was generated by throughflow (including “return-flow” or exfiltration) and saturation excess overland flow in winter and infiltration excess in summer.

There have been many intensively studied catchments in Australia, however, because of the variation in function of these catchments, particularly with respect to salinity development, it is not easy to integrate understanding of processes and hence appropriate management between them. The recent development of a catchment categorisation approach in the study of hydrogeological controls and salt mobilisation (Coram, 1998; Petheram *et al*., 2000) should enable further developments, by giving a framework for developing common approaches to catchments with similar characteristics.

2.1 Flow Duration Curves (FDCs)

A flow duration curve (FDC) represents the relationship between the magnitude and frequency of streamflow events on an annual, monthly, daily (or any time interval) basis for a particular river basin (McMahon and Mein, 1986). The curve gives the time a given streamflow was equalled or exceeded over the historical period of record for which the curve is constructed. As such it gives a clear graphical view of the variability of flow associated with the particular river basin. The FDC should be normalised by some suitable units to enable comparison between catchments and possibly between different time periods. Primarily flow should be normalised by catchment area, and then by some measure of flow such as the (Mean Daily Flow) MDF, or (Maximum Flow) MF. This removes some of the scale issues from the analysis, and leaves most of the characteristics of the FDC as a function of geology, geomorphology, climate and anthropogenic factors. Naturally the shape of the FDC is subject to issues of measurement error and sample period (Vogel and Fennessy, 1994; Hughes and Smakhtin, 1996; Smakhtin *et al*., 1997)

As described by Vogel and Fennessey (1994), each value of flow, Q, has a corresponding exceedence probability, p, and a FDC is simply a plot of Q_p, the p^{th} quantile of streamflow against its probability of exceedence, p, where p is defined by:

$$p = 1 - P\{Q<q\} \qquad (3)$$

$$p = 1 - F_Q(q) \qquad (4)$$

The FDC is therefore the complement of the cumulative distribution function of streamflows over the given time interval. The quantile, Q_p, is a function of the observed streamflows, and is therefore an empirical function. If an independent functional representation can be found for the FDC, then we have a powerful tool for characterising catchments and generalising process understanding across catchment boundaries. Whatever functional representation we derive for the FDC, to be useful it must have parameters that are estimated independent of the actual FDC. Ultimately, we seek a functional form that has parameters only dependent on some catchment and climate characteristics.

A number of low-flow indices may be estimated from the FDC, over whatever flow period is taken in the FDC data. These may be $Q_{75}(7)$ (using the notation of Smakhtin (2001) as the 7-day flow exceeded 75% of the time), $Q_{90}(7)$, $Q_{95}(7)$, or $Q_{75}(10)$, etc. Arihood and Glatfelter (1991) proposed Q_{20}/Q_{90} as a measure of flow variability, while Q_{50}/Q_{90} may be taken as a measure of low-flow variability. These measures may be particularly useful for comparing one catchment with another or for comparing flow periods driven by different climate or land-use conditions. Additionally, Q_{90}/Q_{50} may be taken as an estimate of the proportion of total flow that originated as groundwater, somewhat as the Baseflow Index (BFI) but avoiding the necessity to perform hydrograph separation, with its inherent problems subjective estimate of parameters.

The Low-flow Frequency Curve (LFFC) differs from the FDC in that it shows the proportion of time that a stream falls below a given discharge, and may be constructed from records with averaging period of any length, but typically 1, 7, 10, 30 or 365 days. Probability distributions used in the literature to fit low-flow data have been Weibull, Gumbel, log Pearson type III and log-normal (Maidment, 1992), however, it is quite possible that a universally accepted distribution for low-flows will never be identified. Certainly, it is likely to be more fruitful that a generally accepted model of catchments be found than necessarily a distribution of what are inherently random events.

2.2 Modelling the Flow Duration Curve

Afforestation will result in a reduction in quantity and duration of flow (Bosch and Hewlett, 1982; Brown *et. al.,* 2005; Vertessy and Bessard, 1999; Vertessy, 2001; Vertessy *et al*., 2003). Afforestation has a greater impact on low-flows than on the total flow (Smith and Scott, 1992; Scott and Smith, 1997; Scott *et al*., 1998). The enhanced transpiration by trees over that of herbaceous communities is greatest when soil moisture is available to the deeper rooted trees that was not available to the shallower rooted plants. The low-flows generally occur in seasons when transpiration is water limited and water formerly unavailable to (shallow rooted or annual) plants flowed to the stream. There are also impacts from groundwater abstraction in the catchment or in the vicinity of the stream, or diversions from dams built on the river. Lane *et al.,* 2003 recently examined the impact of afforestation on flow duration curves, generating a sigmoidal model, similar to that of Scott and Smith (1997), to represent the temporal change in flow frequency curves as plantations grow, and hence reduce flow generally. Lane *et al.,* defined a function of the form:

$$Q_{\%} = a + b(\Delta P) + A_{sig}/\{1+\exp[(t-t_{\frac{1}{2}})/N_{sig}]\} \qquad (5)$$

where:

$Q_{\%}$ is the percentile flow of interest, (i.e. Q_{50} is the 50th percentile flow), ΔP is the deviation of annual rainfall from the average through the period of record, A_{sig} and N_{sig} are coefficients of the sigmoidal function, essentially defining the shape of the curve, t is time since the land change (afforestation) was implemented, and $t_{\frac{1}{2}}$ the time for half the effect of the land change to take effect.

Lane *et al.* discussed the impact of afforestation on low-flows and noted that the impact was greatest on the low-flow end of the flow duration curve. In particular, the number of days of zero flow can increase significantly. They found the same shaped sigmoidal function also represented the relationship between number of zero flow days, rainfall and the time since the impact of the land-use change. In this case, instead of $Q_{\%}$, the dependent variable is the number of zero flow days, N_o.

Jothityangkoon *et al.,* (2001) explored a hierarchy of model structures to determine the level of complexity required to satisfactorily reproduce the inter-annual, seasonal, and daily variability of streamflow at a range of sub-catchment scales within the Collie River Basin in south-west Western Australia. Their approach was to focus on the key process controls using summary signature plots, that is annual flow exceedence, average monthly flows and daily flow duration curves. The benefits of this approach, at least in principle, are that the emphasis is on building a model with important physical processes, rather than a focus on hydrograph fitting that requires extensive parameter calibration. Starting with a simple bucket model, complexity was progressively built into the model as required to meet more rigorous analysis criteria. They used parameters estimated *a priori* from field data reported in the literature, with only two out of ten parameters requiring streamflow data. These two were estimated from the recession curves. The conclusions reached were that:

1. At the annual time scale, a simple bucket model including saturation excess overland flow and evaporation was adequate, provided that spatial variability in soil storage was introduced.
2. At the monthly time scale, subsurface runoff was a necessary additional process, but they also partitioned evaporation into bare soil and transpiration components.
3. At the daily time scale, it was critical to include a deep groundwater store to capture the prolonged periods of low-flow, especially in the absence of rain. A non-linear storage-discharge relationship for subsurface runoff generation dramatically improved the model's monthly average streamflow and the daily flow duration curve.

The results of Jothityangkoon *et al.,* 2001 give useful insights in how to approach this perennial problem. Some of their model representations were over simplified, particularly the partitioning of evaporation between bare soil and vegetation components, as were parameter values representing the catchment, however, their analysis led to some useful conclusions. Spatial variability in and distribution of soil water storage capacity, and hydraulic conductivity, were found to be the critical parameters for large scale modelling. They also found, unsurprisingly, that for large catchments streamflow routing is important for representation of high flows. These notions are not new, but in the running debate between detailed reductionist approaches, that require small scale representations of catchments, and larger scale emergent property approaches, clear statements of how much process detail is required at a given scale of interest are a most welcome contribution.

2.3 Low-flow Characteristics

Smakhtin (2001) has given an excellent review of recent (last twenty years) literature on the processes controlling low-flow conditions. His discussion on the meaning of "low-flow" reaches the inevitable conclusion that it depends on the hydrologic and climatic environment. Low-flows are normally derived from groundwater discharge or surface discharge from storages that release water over extended periods of time. Hence, substantial retention of groundwater from year to year can result in annual low-flows being correlated from one year to the next.

Lowest annual flow usually occurs during the same (driest) season each year, and these have been characterised by a number of flow statistics, including magnitude of annual lowest flow, variability of flow and rate of flow recession in absence of rain, length of period of continuous low-flow, proportion of total streamflow made up of low-flow periods. These temporal characteristics require considerable streamflow records for their analysis, but the spatial extrapolation from one catchment to another without data poses a serious challenge to hydrology (and not just for low-flow statistics) (see for example, Jothityangkoon, *et al*., 2001). This is the so-called “regionalisation” problem discussed by Nathan and McMahon (1990). The temporal and spatial characteristics of flow regimes both require an understanding of physiographic and climatic factors, as well as anthropogenic influences on stream hydrology. In many parts of the world, frequency and magnitude of low-flows are important for water resources planning and management, but in Australia, in agricultural catchments, the focus is usually on water quality because it is the low-flows that carry the highest concentrations of pollutants and especially salt. In the context of this report, low-flows are critical because in many cases they represent the most significant change to the streamflow regimes resulting from vegetation changes accompanying human land-use.

This “low-flow” is different from so-called “base flow” which refers to a low frequency component of a streamflow hydrograph. Base flow is generally considered to be derived mainly from groundwater but may include slow components of surface or shallow subsurface stormflow. Most methods used to estimate it are done as graphical interpretations or digital filters on total streamflow data, and the actual source cannot be discerned without independent measurements of stream and groundwater chemistry. streamflow during a “low-flow” period may be virtually entirely groundwater discharge, either directly to the base of the stream or from seepages, or may be due to a slow rate of discharge from a lake or reservoir.

Existing techniques of low-flow analysis include flow duration analysis, low-flow frequency, flow recession and storage-yield analyses (see for example, McMahon, 1976; McMahon and Arenas, 1982). Low-flows may come from lakes feeding into streams, especially in glaciated landscapes with lakes formed at high elevations, where they may also be fed by snow and ice melt (Gustard *et. al.,* 1992). However, in Australia, river flows at “low-flow” conditions generally derive from groundwater discharge. This occurs where the watertable intersects the surface, and to be maintained for any length of time requires that seasonal recharge is adequate to maintain a shallow watertable and the transmissivity of the aquifer is low enough that discharge rate is low relative to the aquifer storage. Clearly these characteristics are a function of catchment geology and erosion history. However, human activities, most notably agriculture and similar enterprises, can have a major impact on the input (recharge) side of this balance.

River flow can reduce to “low-flow” conditions because of “transmission” losses from the stream by direct evaporation from the river body, and from seepages that would otherwise drain into the stream, by drainage out of the stream into dry soil beside the river bank or to an aquifer below or beside the streambed. Whatever analysis is undertaken to quantify and characterise the low-flow conditions of streams, the relative importance of the contributing processes needs be identified as part of the analysis.

The focus of this report is the effect of clearing of native vegetation on river flow. The major effect in Australia is that clearing for agriculture has resulted in greatly increased quantity and duration of streamflow (Holmes and Sinclair, 1986; Schofield *et al*., 1988). With agriculture come a range of land modifications that affect soil structure (infiltration capacity, macro-porosity, and surface roughness), evapotranspiration losses and water quality, either directly through nutrient and pesticide runoff or indirectly through changes to watertable levels, thereby changing the solute concentrations reaching the streams. Generally these water quality changes are detrimental. While improved farming practices such as minimum tillage and contour ploughing may have impacts on streamflow and quality, these effects have not been quantified. Flow may also be enhanced when artificial drainage is constructed to dry saturated areas, like swamps or seepages, and discharge these to streams. Once again, the effect of these structures is likely to be greater on the low-flow conditions than total flow, and may have a great impact on stream quality depending on the quality of the groundwater.

2.4 Low-flow Indices

A number of measurement techniques have been used to quantify low-flow characteristics of streams, mainly based on analysis of streamflow data, flow duration data and low-flow temporal sequences. An arbitrary measure that sets an upper bound on low-flow conditions is the Mean Annual Runoff (MAR) or, MAR divided by 365, Mean Daily Flow (MDF) (Smakhtin, 2001). However, especially for ephemeral streams, or streams with long periods of low-flow, the daily Median Flow (MF) may be significantly smaller than MDF, and serves as a much better measure. Dracup and Painter (1979) discussed a selection of flow statistics in order to improve definition of drought periods. They found that the definitions are affected by sample size, serial correlation, drought severity, magnitude and duration, and areal extent. However, definition of drought as an "exceptional" prolonged reduction in rainfall is being questioned in some regions of the world in the context of changing climate. Certainly in Australia, the impact of El Niño and La Niña sequences on rainfall is now recognised, and with the prospects that what used to be regarded as drought is now becoming more frequent we are revising our definitions (McVicar and Jupp, 1998; White, 2000).

In perennial streams, the lowest daily discharge may be referred to as the Absolute Minimum Flow (AMF) but the usefulness of such a measure is questionable unless it is accompanied by a time period and record length, particularly since for ephemeral streams this will be always at the natural minimum of zero. The proportion of time that a catchment is at zero flow gives a straightforward measure of flow variability for comparison between catchments, or periods under different climates or land-uses (Smakhtin *et al*., 1995). The longest recorded period with zero flow may be used as an indication of most severe drought, but is clearly dependent on the period of record (Smakhtin, 2001).

A key issue in the analysis of low-flow hydrology is the occurrence of zero-flow data. These should not be ignored, but may be taken into account by use of a "conditional probability model" (Maidment, 1992). In this case, if the probability that a data point is zero is p_o, and $G(X)$ is the continuous distribution for the non-zero values, X, then the unconditional cumulative distribution function (cdf) $F(X)$ for any value $x>0$, is:

$$F(x) = p_o + (1-p_o)G(x) \tag{6}$$

3. Data Sources

In the work that follows, we have taken an empirical approach, similar to that of Lane *et al.,* 2003, and Silberstein *et al.,* 2003. Data from five research catchments in the Collie River Basin, south-west Western Australia have been analysed (Figure 1). The analyses presented in this report are all from daily rainfall, streamflow, and salinity data, through a 28 year period from 1974-2002 or 2003, with data ceasing in 1998 in one catchment (see Table 1). In addition we used piezometric levels from bores across the catchments taken regularly every few months throughout the period. Daily pan evaporation at Collie taken from the Bureau of Meteorology Patched Point Dataset (http://www.bom/gov.au/silo) has been used to estimate evaporation across the catchments.

The Collie research catchments were established in the early 1970s and provide a tremendous source of data for this exercise. The results presented in this report are all from the five catchments whose details appear below, but future work will also analyse data from a number of other catchments of different sizes for which there is similar data.

Table 1. Catchment Details.

Stream	Station Name and Number	Catchment Area (km^2)	Area Cleared (%)	Mean Annual Rainfall (mm) 1974-2003	Period of Record
Bingham River Tributary	Don 612007	3.50	40 (strip and parkland cleared)	670	1974-2003
Bingham River Tributary	Ernie 612008	2.68	0	710	1974-2003
Pollard Brook Tributary	Lemon 612009	3.46	40 (lower half cleared)	710	1974-1998, 2002-2003
Salmon Brook Tributary	Wights 612010	0.826	95	1100	1974-2002
Salmon Brook	Salmon 612011	0.933	0	1100	1974-1998

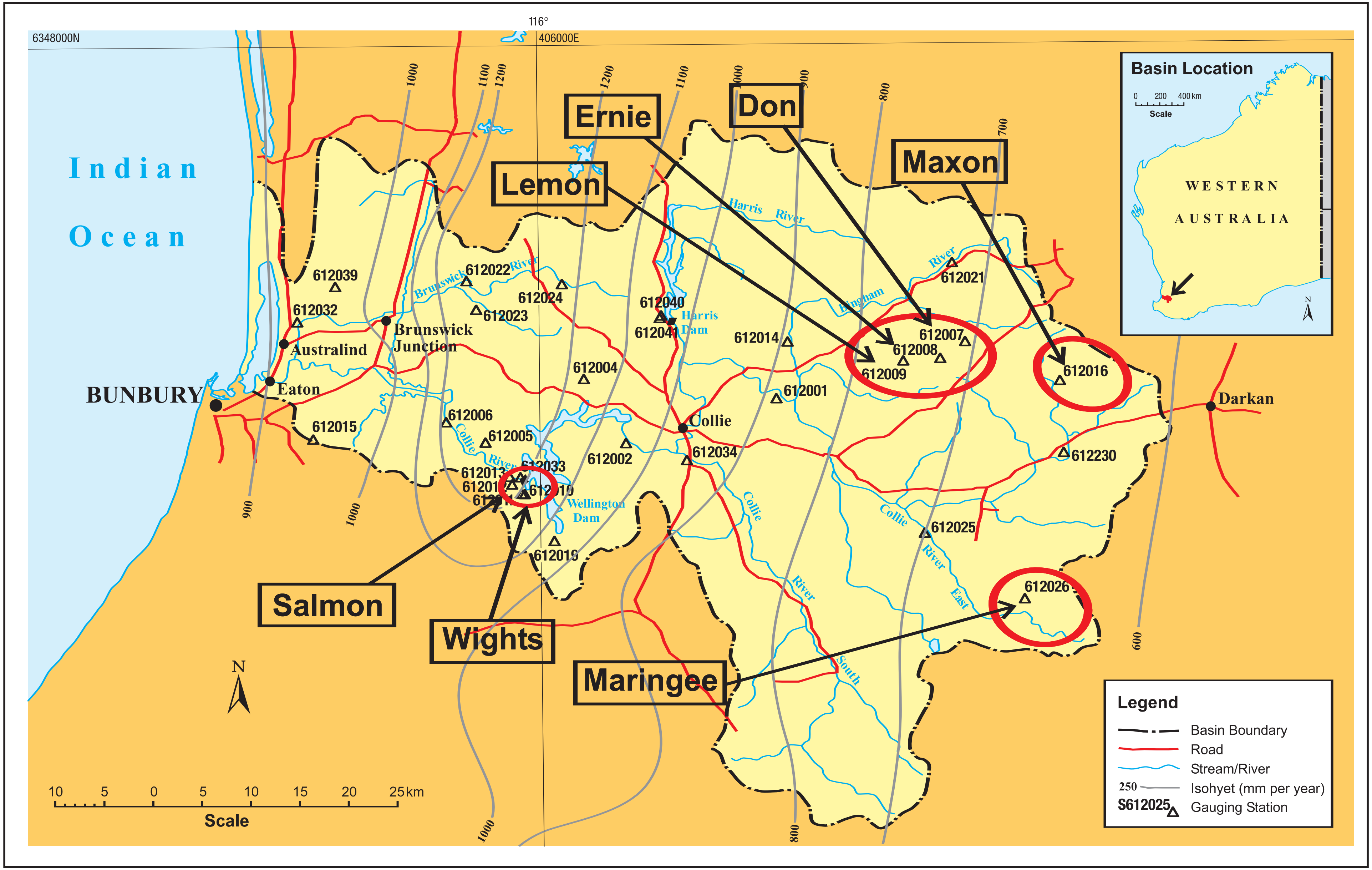

Figure 1. Location of Collie River Basin in Western Australia, and the Research Catchments used in this Study. Insets show the clearing layout of catchments. Note that the isohyets are long-term values and a generally higher rainfall period than that analysed in this report.

(Figure compiled courtesy of Water and Rivers Commission).

4. Quantifying the Change in Flow Regime – Simple Statistics

For the purpose of this study, flow regime is taken as the combination of the proportion of rain that becomes streamflow (discharge coefficient), the period of zero flow, the baseflow component of streamflow (as defined by hydrograph separation), stormflow recession period, and daily flow cumulative frequency distribution or flow duration curve. This section discusses the first four of these, with the major discussion of flow frequency distribution given in Sections 5 and 6.

4.1 Methodology

4.1.1 Discharge Coefficient (or Runoff Ratio)

The first change that is noticed following major clearing in a rural catchment is generally the proportion of annual total rainfall that becomes streamflow. This is often referred to as *runoff ratio* or *runoff coefficient*, but this term is also used specifically in stormflow dynamics as being distinct from the baseflow component. For this reason we have used the term discharge coefficient as a more suitable generic term for the longer term streamflow analysis. We adopt a simple empirical approach to examine the *discharge coefficient* of the stream over time, comparing the treated catchments with their forested control counterparts.

4.1.2 Baseflow analysis

Baseflow separation on the daily hydrographs is undertaken using the method outlined by Chapman (1999) with the parameter k = 0.98. This is used to identify changes in baseflow component through time as the watertable rose following clearing. The change in baseflow has been represented using the Base Flow Index (BFI), which is the ratio of baseflow to total flow. The BFI is a measure of the contribution that groundwater discharge makes to total streamflow. Stream salinity is also used to get an independent estimate of baseflow component. The salt is used as a groundwater tracer, assuming all salt comes from the groundwater. Groundwater salinity is estimated from piezometers, and from salinity measurements in the stream at low-flows. The salinity of the stream is then used to determine the quantity of groundwater inflow on the assumption of dilution by rain water. This method is likely to overestimate the groundwater component of streamflow because the salt load includes a component from surface accumulations from evaporated groundwater over dry periods. We are exploring ways of compensating for this.

4.1.3 Zero Flow Days

As with the work of Lane *et al.,* 2003, an observed feature of the flow regime in the Collie Basin catchments following clearing is the change in the number of zero flow days. Lane *et al.,* used a model (Eq. 7) to separate the impacts of climate and vegetation on the number of zero flow days. In this model N_{zero} is the number of zero flow days and the sigmoidal function is used to represent the impact of the vegetation change on zero flow days, and $b(\Delta P)$ can be used to represent the climate.

$$N_{zero} = a + b(\Delta P) + A_{sig}/[1+\exp((t-t_{\frac{1}{2}})/N_{sig})] \qquad (7)$$

where:

ΔP is the deviation in precipitation from the mean, A_{sig} gives the magnitude of vegetation change influence on N_{zero}, $\mathrm{N_{sig}}$ gives the shape of the response, b is the magnitude of the dependence on precipitation, and $t_{\frac{1}{2}}$ is the time for half the change in N_{zero} to take place and t is the time in years since the vegetation change. For an average year, ΔP=0, $a+A_{sig}$ is the number of zero flow days under the current steady state, and a is the number of zero flow days once the new steady state is reached. In this context the term "steady state" refers to a catchment in hydrologic equilibrium with its climate, that is two years with similar climatic distributions will produce similar streamflows. It was assumed by Lane *et al.,* 2003 that there is a smooth transition between the pre-treatment and post-treatment steady state conditions that justifies the use of the sigmoidal function.

4.1.4 Stormflow Recession Time Constants

The rate of dissipation of a stormflow is related primarily to the topography and vegetation cover of a catchment as they control the overland flow, and to a lesser extent by the soil properties and watertable through their influence on shallow subsurface flow. The storm recession time is defined as the time taken for stormflow to diminish by half, and is obtained by fitting an exponential decay to the shape of the declining hydrograph at the end of the storm. Every storm event in the record for each catchment was analysed for recession in flow after rain ceased, to investigate the lag time and storage of water within the catchments.

4.2 Results

The dependence of streamflow data on rainfall is, of course, critical. In the discussion that follows, all our analysis is dependent on the isolation of the climate signal from the other influences on catchment discharge. The rainfall in the period of data was highly variable, and historically low, on average. This is now recognised as part of a fundamental change in the rainfall regime of the south-west of Western Australia. Figure 2 shows the annual total rainfall for the catchments through the period of record, and Figure 3 the cumulative deviation from the mean within that period. This second trace illustrates the periods of persistent wetter and drier climates more readily than the simple annual totals.

4.2.1 Discharge Coefficient (or Runoff Rates)

The cleared catchments all show an increase in discharge coefficient immediately following clearing (Figures 4 and 5), and well before there is any groundwater impact near the surface. This was discussed by Ruprecht and Schofield (1989) and is likely due to a reduced interception loss and reduced evapotranspiration loss from the pasture. The discharge coefficient has remained reasonably constant over time in the forested catchments, Ernie and Salmon. While Don shows an initial increase in runoff similar to Lemon following clearing, the runoff coefficient does not increase further. This indicates that the initial effect is virtually entirely due to a lack of surface cover and a decrease in infiltration capacity at the surface, but not to increasing groundwater which commenced after clearing. The rise in groundwater in Don (Figure 6) occurred much more slowly than in Lemon. This can be attributed to the strip and parkland clearing, and indicates that the trees that remain in the catchment have greater access to soil water because they are distributed around the catchment and are not in a large contiguous block like those in Lemon.

From 1987 onwards there was a dramatic increase in discharge coefficient in Lemon – significantly more than Don. This timing coincided with the watertable reaching the surface in the lower part of the catchment, producing a permanent saturated area, which expanded over the subsequent years. The discharge coefficient of the low rainfall control catchment, Ernie, has stayed at around 0.01 throughout the period of record. The discharge coefficient of Don rose to 0.04 after clearing and has stayed there since. The discharge coefficient of Salmon has remained around 0.1, but shows a slight rise towards the end of the period of record, while for Wights it has risen up to around 0.4. The drier control catchment (Ernie) has, if anything, shown a slight decline over the same period.

4.2.2 Baseflow

The BFI has greatly increased following clearing, especially in the lower rainfall catchments (Figures 7 and 8), and the rate of increase has two clear stages. The BFI began increasing at clearing, in 1977, but the rate of increase in BFI increased again around 1988, when the groundwater reached the surface at the bottom of the catchment. It appears to have started to flatten out in the last two or three years of record, but unfortunately data collection ceased in 1998, and we cannot be certain of the trend after this time. The BFI in Don follows that of Ernie reasonably closely, perhaps a little higher after clearing. Clearly even before clearing (Figure 8) the small seepage area in Wights was contributing a significant proportion of the flow. The BFI has gradually increased from 1981 onwards, coinciding with the time that the seepage area began to expand up the catchment.

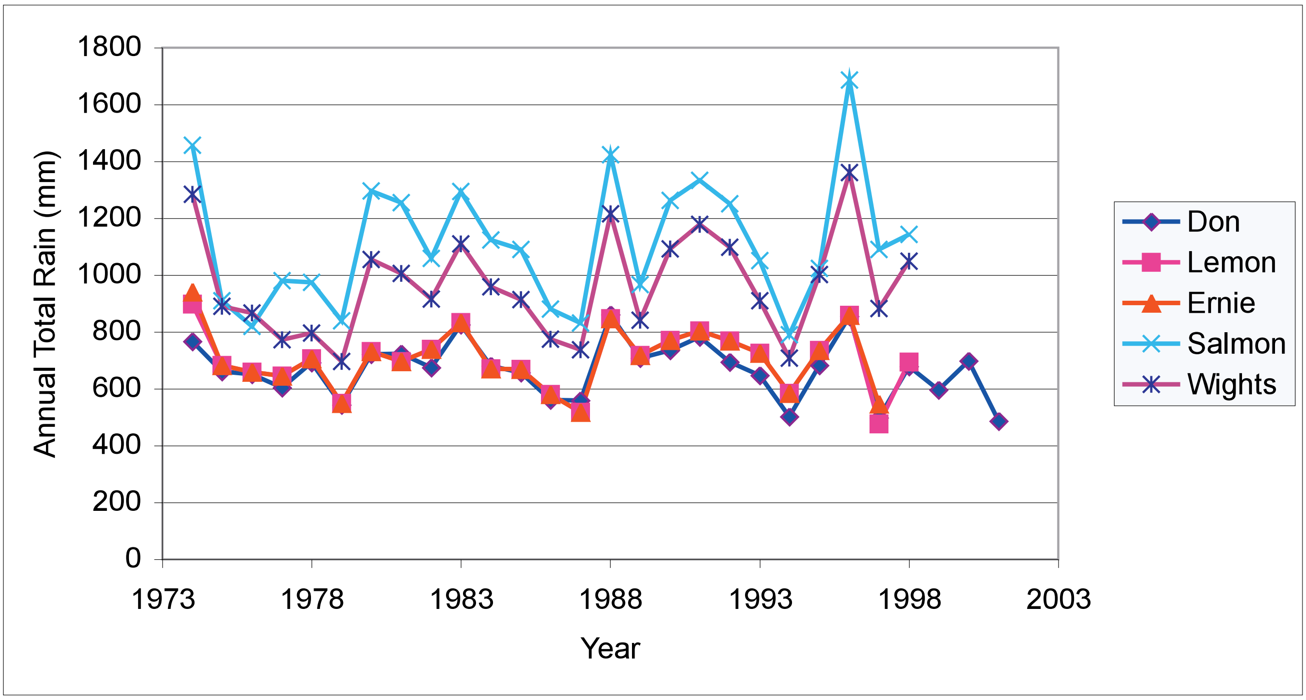

Figure 2. Annual Total Rainfall Recorded in each Catchment through the Period of Record. Note that Salmon and Wights are adjacent and are considered to have the same rainfall for the purposes of our analysis.

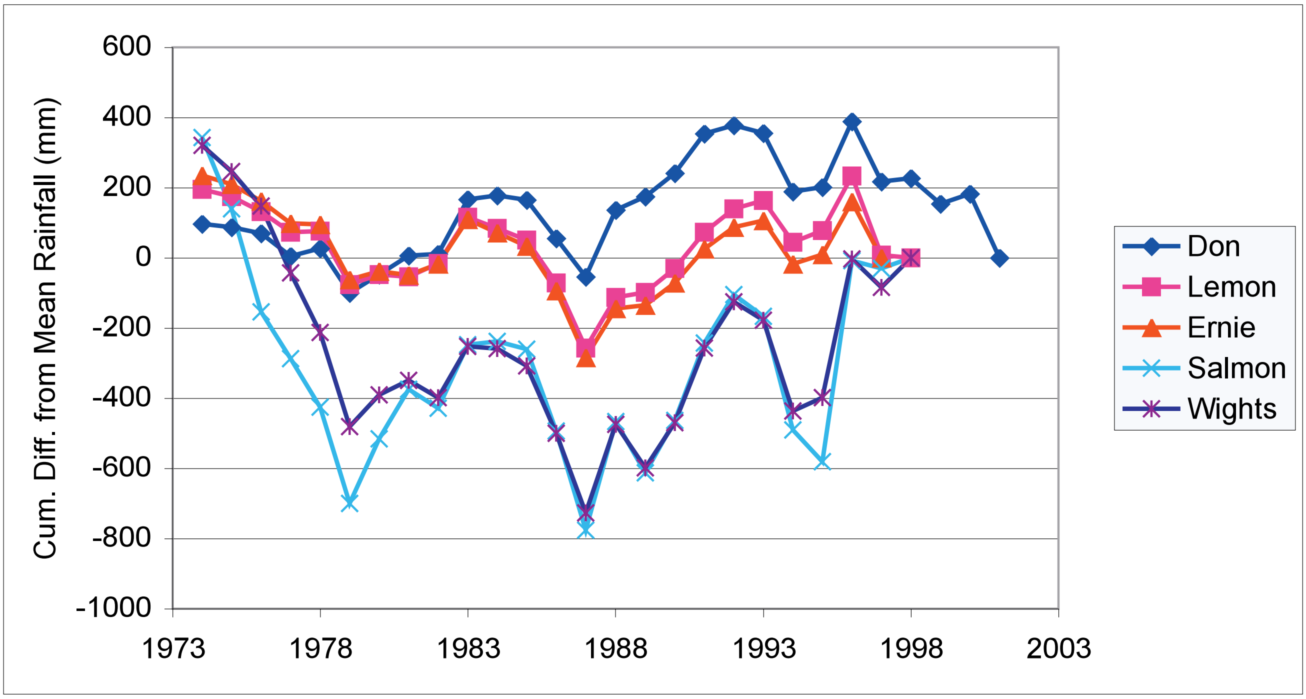

Figure 3. Annual Cumulative Deviation from the Mean Total Rainfall Recorded in each Catchment through the Period of Record. Note that Salmon and Wights are adjacent and are considered to have the same rainfall for the purposes of our analysis.

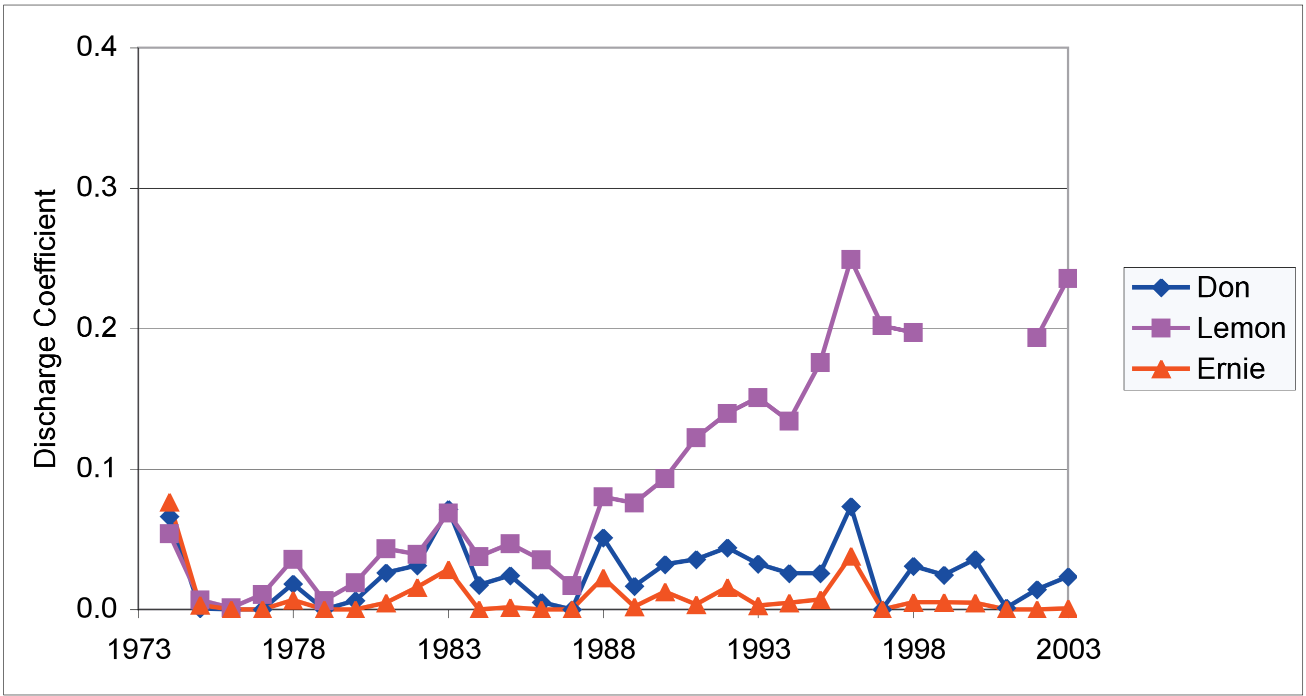

Figure 4. Discharge Coefficient in Don, Ernie, and Lemon Catchments.

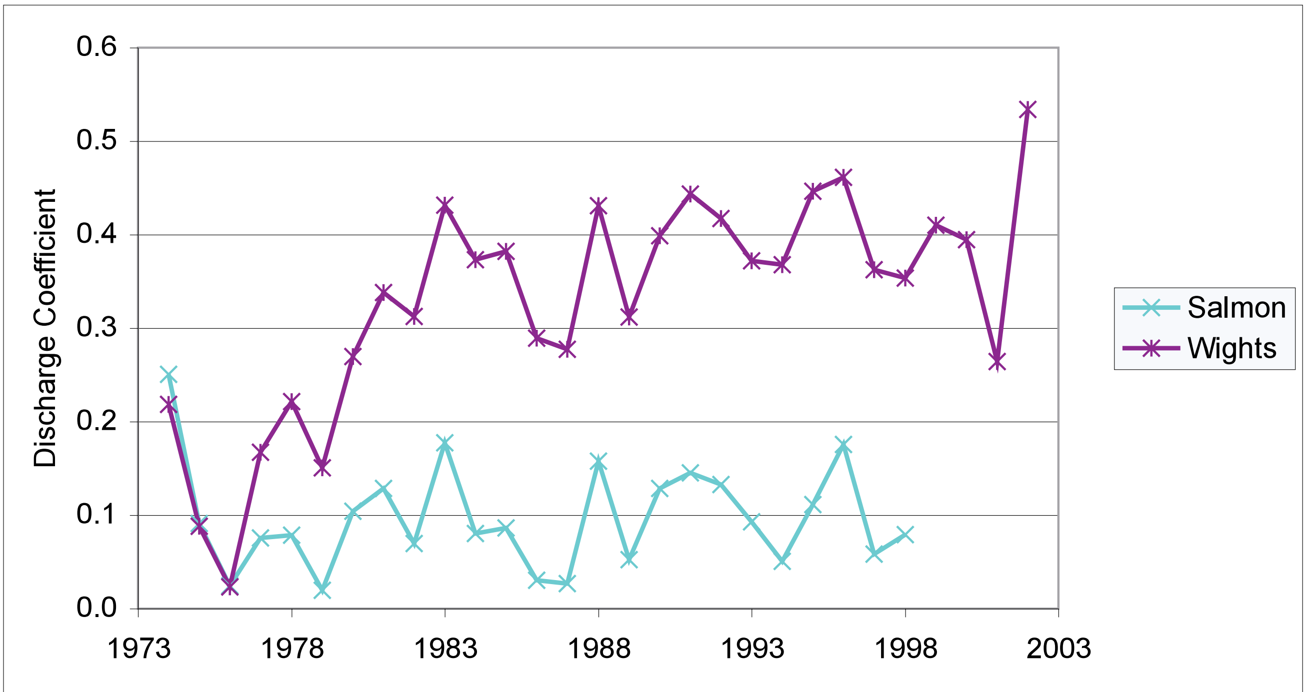

Figure 5. Discharge Coefficient in Salmon and Wights Catchments.

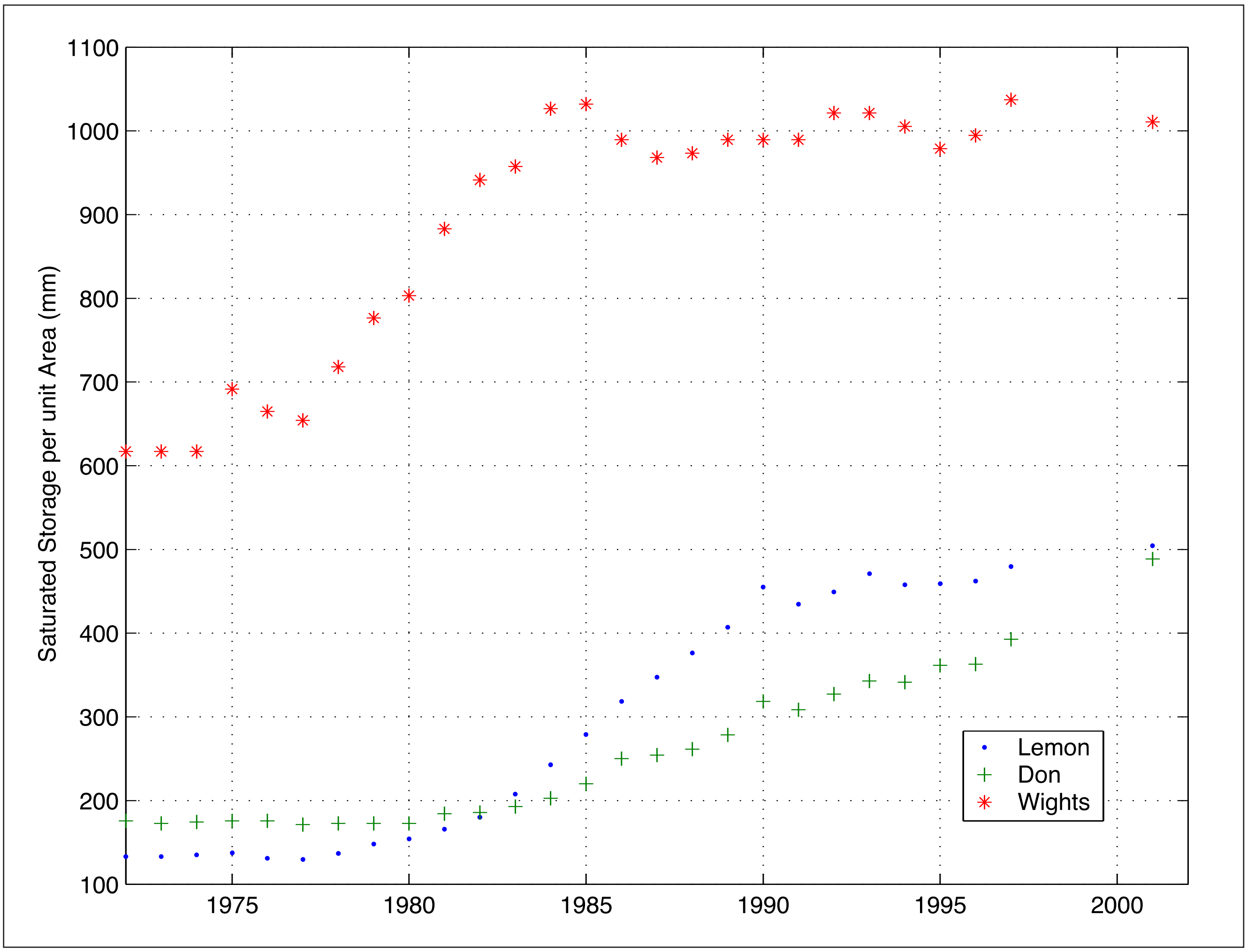

Figure 6. Estimated Water Storage per Unit Area in Three Cleared and Partially Cleared Catchments Over Time (taken from Silberstein *et al*., 2003).

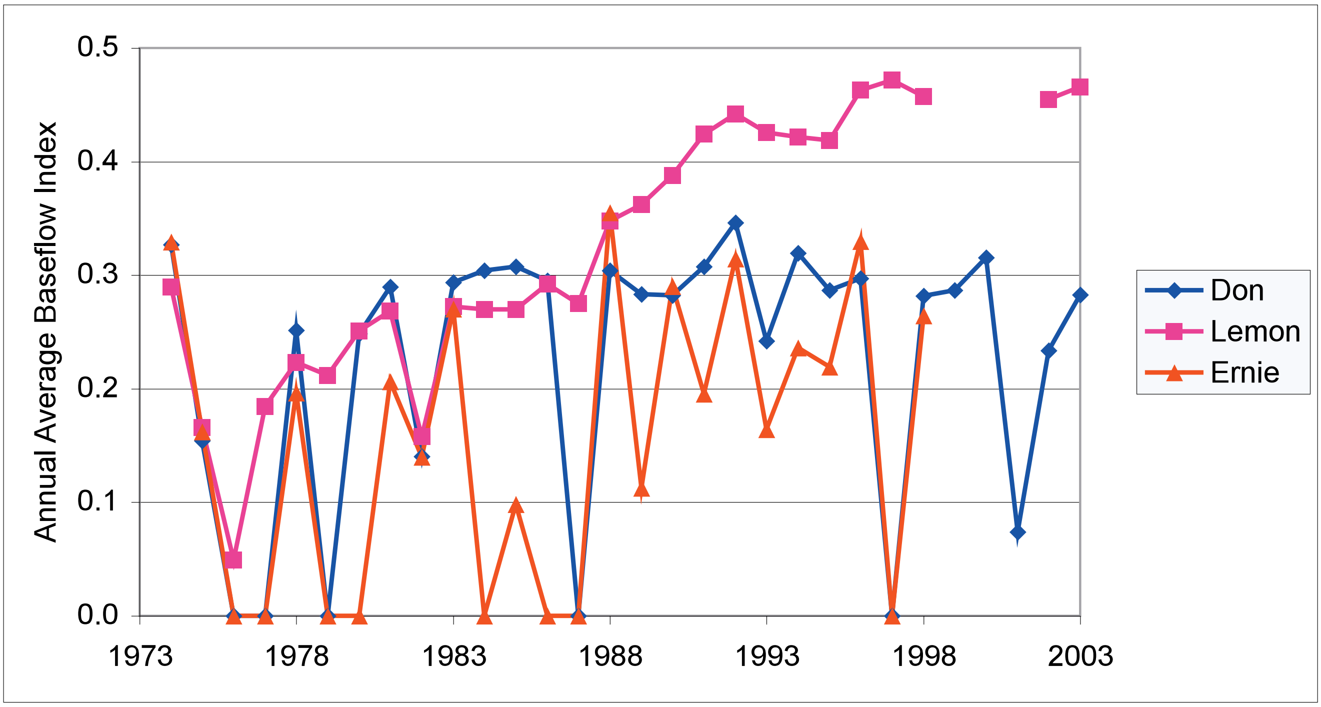

Figure 7. Proportion of Total Flow which is Baseflow at the Low Rainfall Catchments. (Clearing occurred in 1977, watertable reached the surface in lower areas in Lemon 1988, has not reached the surface in Don; there is no data for Lemon from 1999 to 2001, and Ernie after 1998).

There is a significant difference between the BFI of the wetter catchments and the drier catchments. The extra rain passes through the soil and eventually makes its way to the stream, consequently the BFI is much higher even for the forested catchments in the higher rainfall.

The impact of climate can also be seen here, with the BFI trend through time in both the forested catchments. At Salmon, it has shown a slight increase (from 0.33 to 0.35, although not statistically significant), but at Ernie the increase has been significant (0.10 to 0.22). The proportion of total flow that is baseflow has progressively increased in Lemon, relative to Don and Ernie, from a few years after the time of clearing, until about 1996 when it appeared to flatten out. This is somewhat similar to the stream salinity trend (Figure 9).

On this analysis it would appear that there has been no change in the baseflow component of the flow regime in Don since the initial increase after clearing, however, there has recently been an increase in stream salinity (Figure 9), that indicates a clear change has begun. This is useful as it gives us a timeframe for the effect of a different clearing regime to impact on the catchments.

It should be noted that if quick flow is increasing at the same rate (in the same proportion) as baseflow, then there will be no change to the BFI. However, although not stated like this, the analysis of Silberstein *et al.,* (2003) essentially concluded that the change to quick flow has not been as great as to baseflow, and we do see a progressive increase in BFI accompanying the increase in discharge coefficient.

4.2.3 Zero Flow Days

The biggest change to the flow regime following clearing is clearly the low-flow condition and the fact that intermittent streams have become perennial. This can be quantified as the number of zero flow days each year (Figure 10). The number of zero flow days in the uncleared catchments is clearly dependent on rainfall, both the total quantity and the distribution through the year.

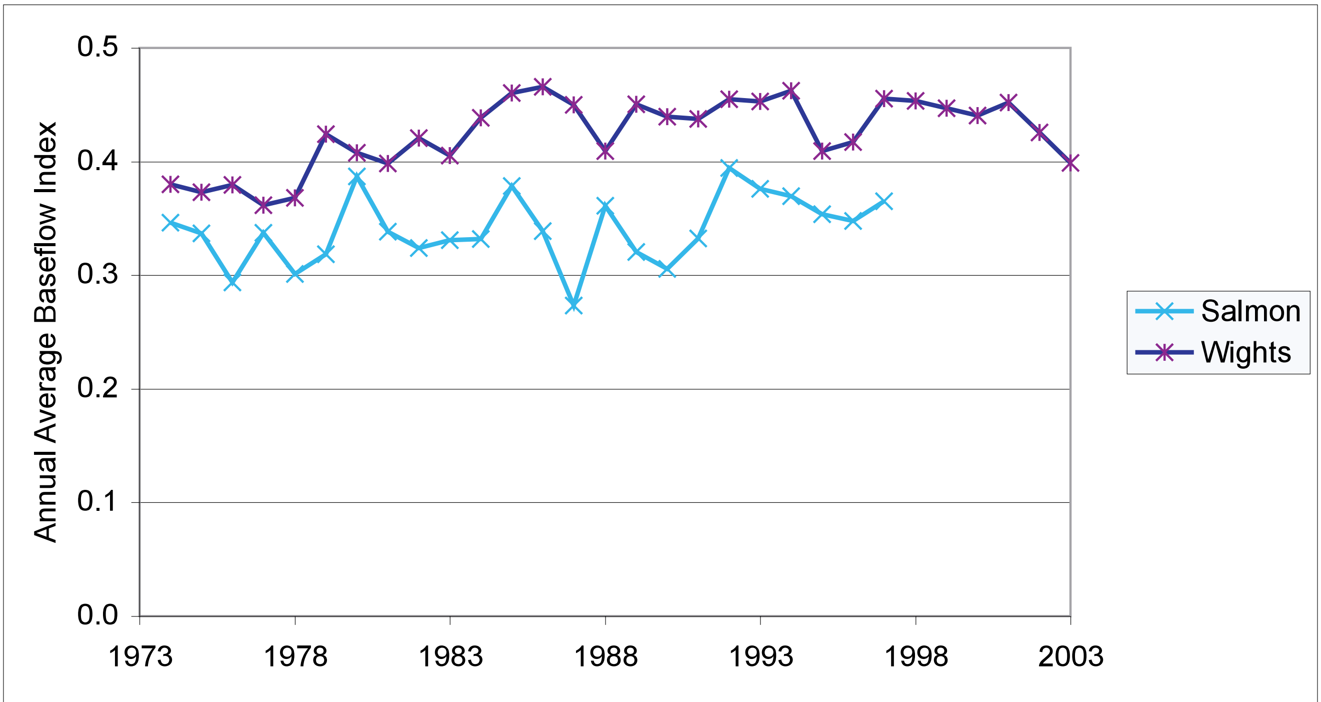

Figure 8. Proportion of Total Flow which is Baseflow at the High Rainfall Catchments. (Clearing in Wights occurred in 1977, watertable was already at the surface in lower areas in Wights in 1977.)

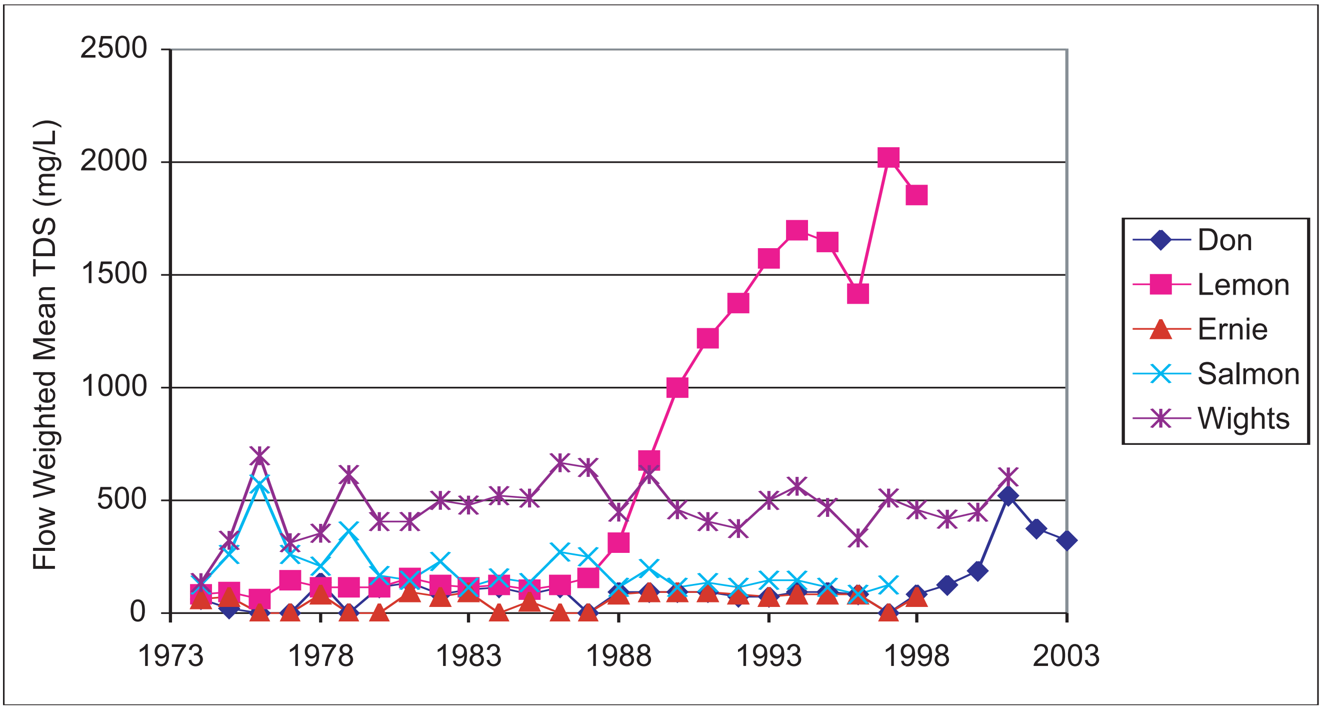

Figure 9. Flow Weighted Mean Salinity for the Collie Research Catchments (there is no salinity data for Salmon after 1997, and for Lemon after 1998).

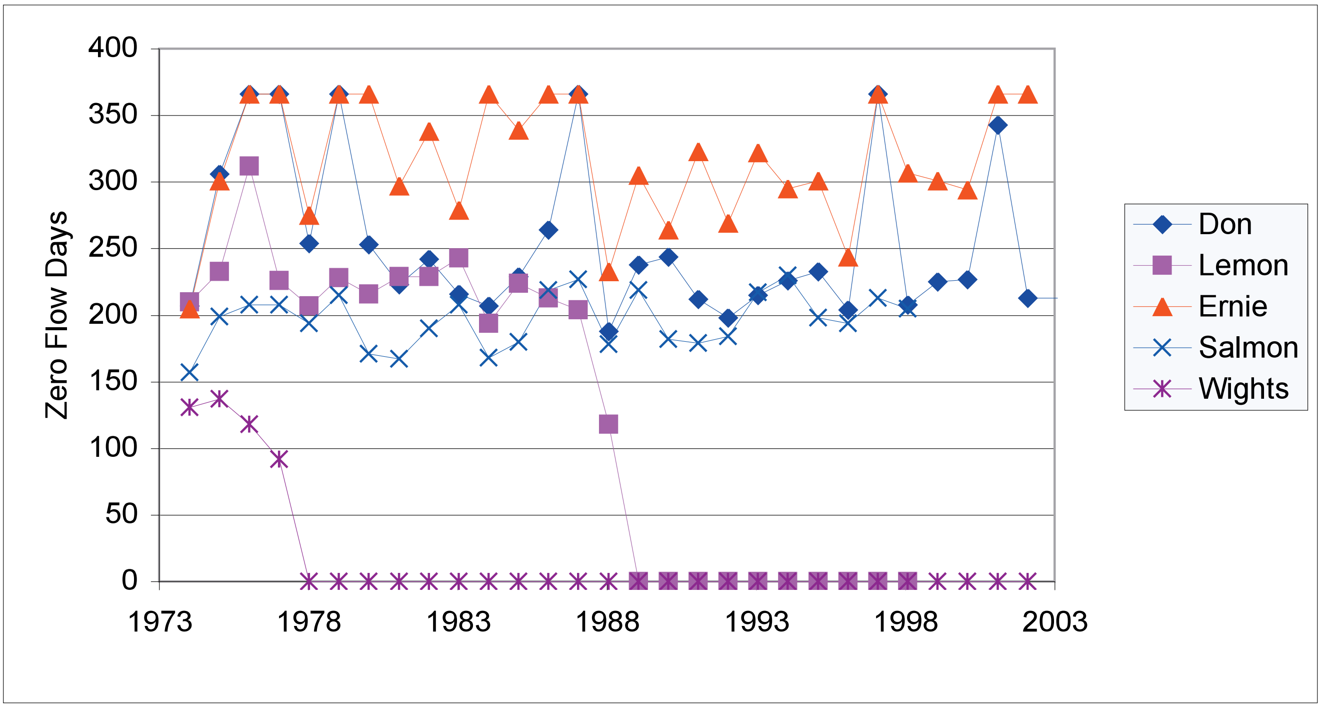

Figure 10. Number of Days of Zero Flow for the Collie Research Catchments through Time.

The zero flow day analysis outlined in Lane *et al.,* (2003) was carried out in an effort to separate the climate and vegetation effect on the number of zero flow days in the Lemon and Don catchments. This analysis was not undertaken on the Wights Catchment as the rapid response following clearing (Figure 10) does not conform to the model structure proposed by Lane *et al.,* 2003 which assumes a smooth transition between the pre-treatment and post-treatment equilibrium conditions. The observed response in the Wights catchment indicates immediate change in flow regime following clearing, with no zero flow days by the second year following treatment. The results for the Don catchment showed that, while the climate term is significant, the vegetation term in Equation 7 is not significant indicating that either we have been unsuccessful in separating the climate influence from the vegetation influence or the change in vegetation is having no impact on the number of zero flow days. Figure 11 shows the result of this analysis for the Lemon Catchment. The Lemon Catchment showed that while the vegetation term is significant the climate was insignificant. Given the results in the Don Catchment, this would indicate that the vegetation influence on the number of zero flow days is much greater than the impact of climate in this catchment.

The zero flow day analysis using the method of Lane *et al.,* 2003 (Figure 11) indicates that the number of zero flow days is clearly dependent both on climate and vegetation type. In order to assess the impact of climate on the number of zero flow days in the forested catchments in the Collie Basin the data from all catchments while under forest were used to construct a plot of rainfall against the number of zero flow days (Figure 12). The smooth line fitted to the data in Figure 12 is that given by Equation 7, but $t_{\frac{1}{2}}$ has been replaced by $P_{\frac{1}{2}}$ where $P_{\frac{1}{2}}$ is the precipitation rate that gives half the transition between a catchment that does not flow at all and one that has the minimum number of zero flow days. The fitting of the sigmoidal curve to the data in Figure 12 give values of $a = 180$ (the minimum number of zero flow days for the catchments), $A_{sig} = 365\text{-}a$, $P_{\frac{1}{2}} = 800$ mm, and $N_{sig} = 50$ mm, and N_{sig} is a scaling parameter that defines the rate of transition between maximum number of flow days and no flow at all.

It is likely that there is a relationship between the number of zero flow days and the saturated area of a catchment or the water stored within it. However, it can be seen that there is a very rapid transition between having the maximum number of zero flow days (about 140 for Wights and 200 for Lemon) and a permanently flowing stream (Figure 10). The transition takes only two or three years and occurs as the groundwater builds to the point where there is permanent saturated area in the catchment; it does not change slowly as might be expected analysing Figure 6. There is no apparent decline in zero flow days accompanying the rise in stream salinity in Don.

The number of zero flow days through time is clearly a very coarse representation of change in flow regime for these catchments. This is quite a contrast to the findings for the reafforested catchments by Lane *et al.,* (2003), and reinforces the general conclusion that impacts of clearing manifest much faster than those of reafforestation. This is due to the time taken for the trees to grow and reach maximum water use. Analysis of number of zero flow days with respect to saturated area or water storage within the catchments produces similar results, because the transition from ephemeral to perennial status seems to take only two or three years once the number of zero flow days starts to decline. As there has been no discernible change in number of zero flow days in Don to date (to end of 2003), it will be interesting to follow this development over the next couple of years as it would appear the rising stream salinity indicates a change in flow regime has just begun.

4.2.4 Stormflow Recession

The 'mean yearly recession time constants' for the catchments, that is the average of the recession times for each event in each catchment, were calculated on a yearly basis (Table 2, Figure 13). The time constants were calculated during the inter-storm period from the flow recession curves over the first five days after rain ceased. We used the first five days rather than longer periods, because otherwise the statistics were dominated by the extremely long recession time scales evident from the long summer periods without rain, especially in Lemon and Wights catchments.

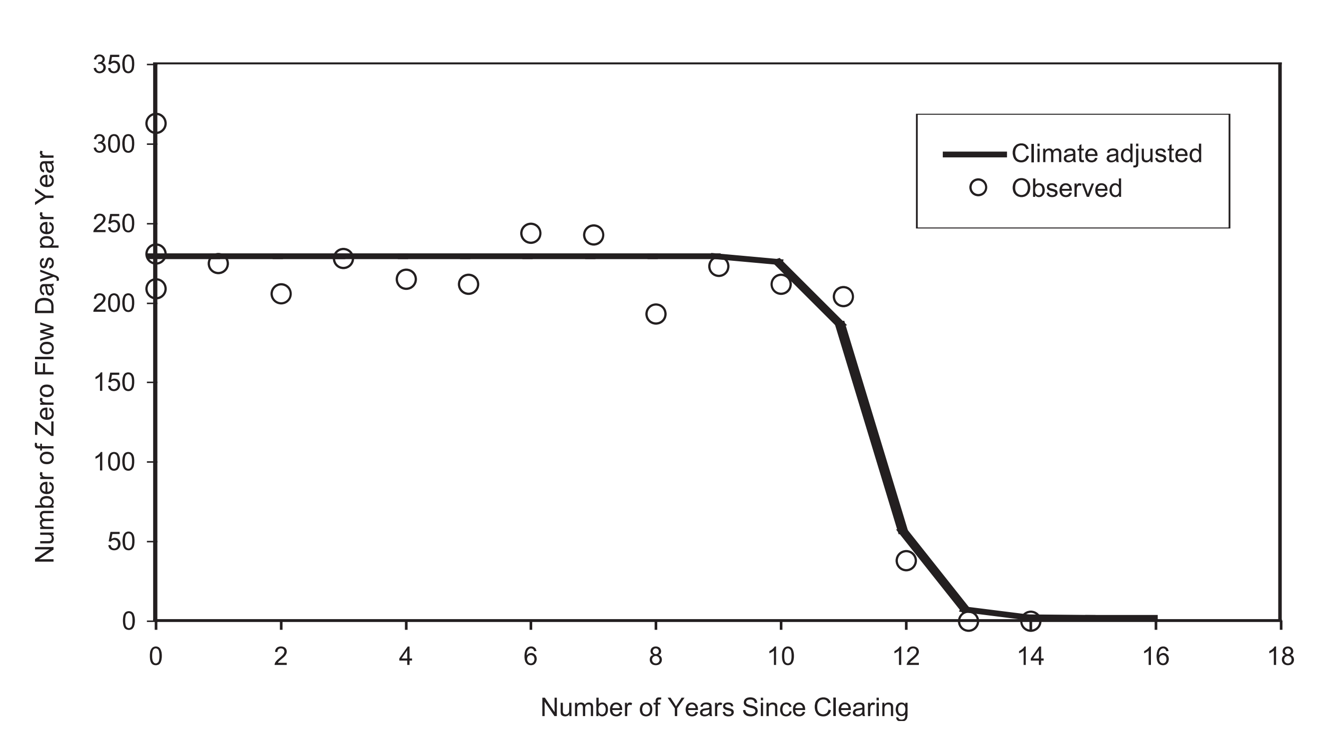

Figure 11. Climate Adjusted Number of Zero Flow Days for Lemon.

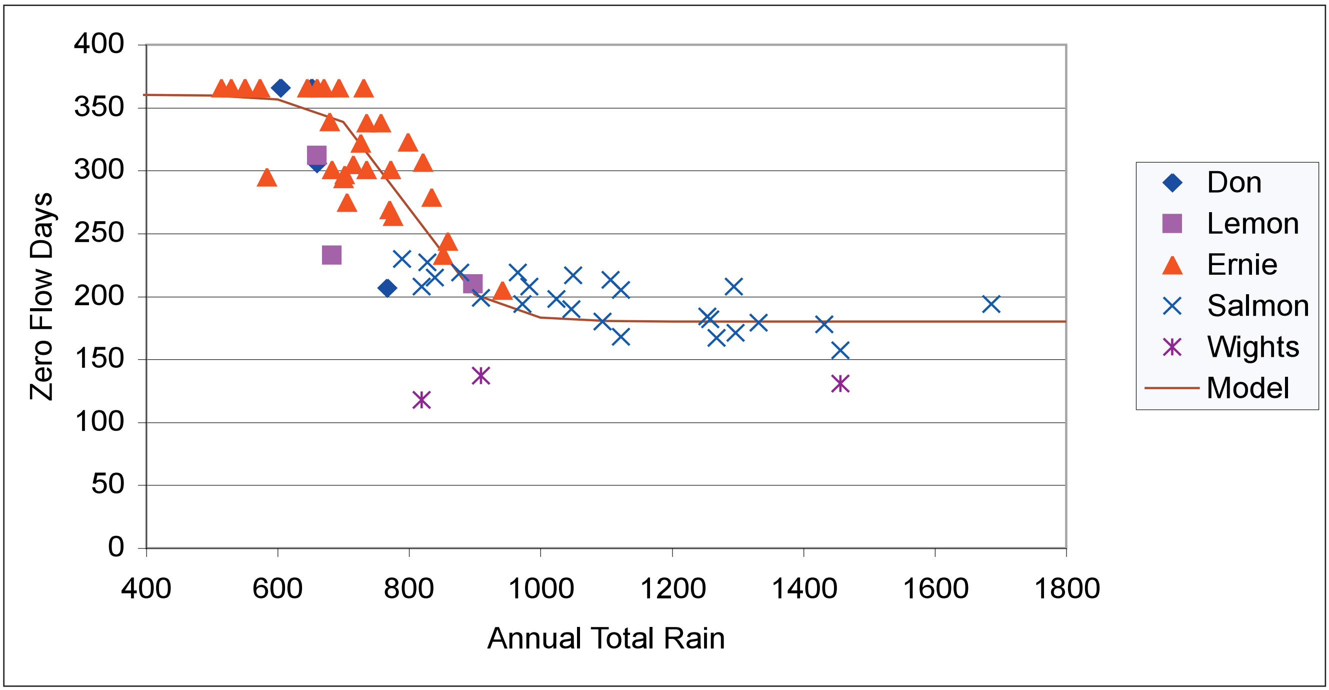

Figure 12. Number of Days of Zero Flow for the Collie Research Catchments. Data are shown for the two permanently forested catchments and for the treated catchments prior to clearing.

It is clear that the recession constants are highly variable, and there is an increase in time as the watertable rises. This shows the influence of permanent groundwater discharge to the streams, although the separation of stormflow from baseflow becomes more problematic under these conditions.

Table 2. Annual Average Recession Constants (days) Calculated from the Hydrographs for the First Five Days after Rain Ceased.

Year	Don	Ernie	Lemon	Salmon	Wights
1974	10.6	6.4	2.2	6.7	11.1
1975	1.5	4.3	1.5	5.3	6.5
1976	–	–	0.3	4.1	33.3
1977	–	1.1	4.7	12.9	–
1978	8.6	3.8	2.9	6.2	24.1
1979	–	–	3.0	5.0	48.6
1980	5.9	–	3.5	5.1	18.6
1981	3.9	3.0	2.1	4.3	26.6
1982	3.5	0	2.4	6.0	58.7
1983	5.8	5.0	4.9	4.9	40.9
1984	3.6		3.0	6.4	61.6
1985	4.0	2.5	3.2	5.6	23.8
1986	4.6	–	4.6	4.3	73.7
1987	–	–	4.5	14.7	26.6
1988	5.4	4.8	10.5	7.7	32.9
1989	8.7	0.3	26.1	4.3	64.6
1990	5.2	4.6	22.7	6.4	47.2
1991	4.4	2.4	28.7	5.5	36.9
1992	5.8	30.7	18.0	18.2	87.5
1993	6.9	1.6	24.1	16.1	93.4
1994	6.5	4.5	27.2	7.6	28.9
1995	4.5	1.6	34.1	6.2	28.2
1996	7.9	4.7	48.3	8.4	62.7
1997	2.2	–	31.7	7.9	115.1

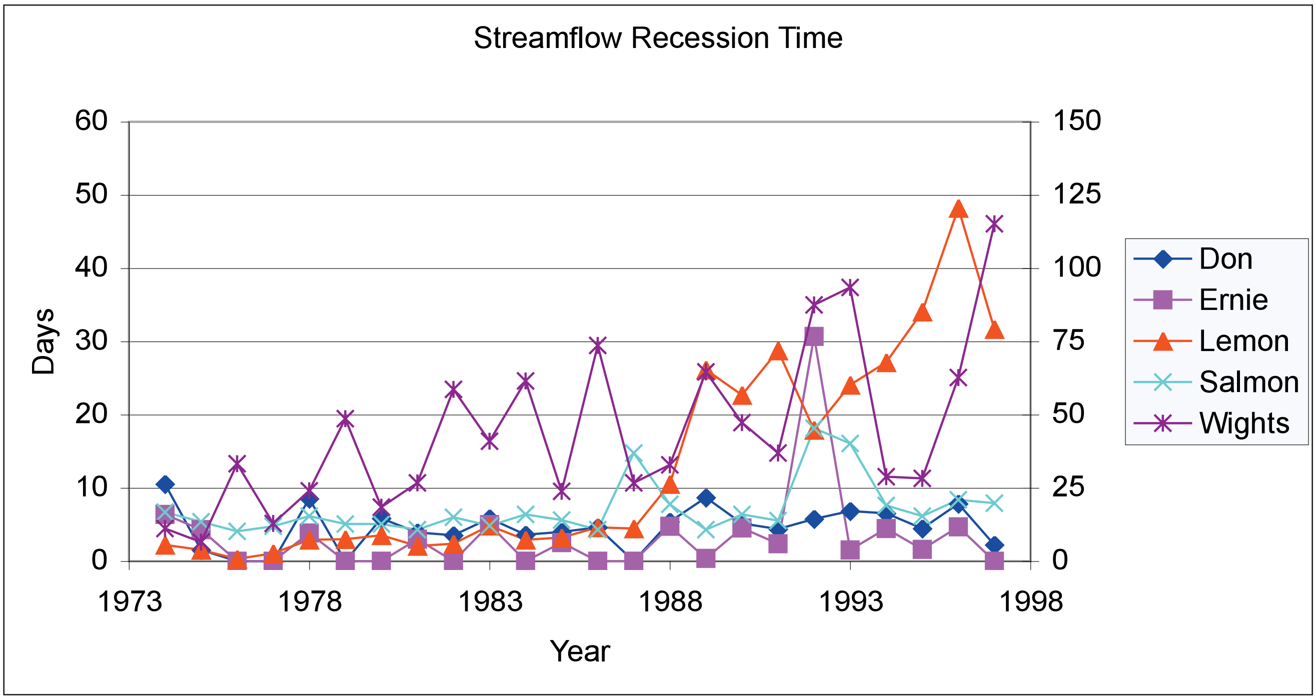

Figure 13. Yearly Average Recession Times for Each Catchment as Determined from Flow in First Five Days after Rain Ceased. (Trace for Wights uses right hand vertical axis.)

5. Flow Duration Curve Analysis

Flow duration curves are normally developed as a single response over a long period of record. The analysis usually assumes the catchments are in some kind of steady state and that the entire data series has the same statistical distribution. The flow frequency distribution can, of course, be taken for flows totalled over any time interval, and the interval chosen can have significant impact on the characteristics of the curve. There are consequences for the analysis of choosing a particular time interval, especially in relation to the size of the catchment in question and the rainfall intensity and distribution. In this study we focus on daily flow duration curves. Our data come from first order catchments, all of order 1 km^2 in area, and respond to rainfall on roughly one day to a few days time period.

Analysis of the flow duration curves (FDC) has focussed on:

1. Comparing the changes in observed flow duration curves with time (Sections 5.1.1 and 5.2.1); and
2. Separating the impact of climate and vegetation on individual percentiles of the FDC using the method outlined by Lane *et al.,* 2003 (Sections 5.1.2 and 5.2.2); and

Section 6 presents an analysis aimed at finding a generic functional form that can be used as a distribution model to represent the catchment behaviour under different climate and watertable conditions.

5.1 Methodology

5.1.1 Observed FDCs

In the case of the catchments considered here, the clearing of the catchments was undertaken three years after monitoring commenced, so this short period was the only measure of control, and comparison between the cleared and uncleared catchments. For the raw data analysis, data were grouped in three year periods to allow maximum statistical representation of the change in flow frequency distribution since clearing. This helps to smooth out the impact on the statistics of individual extreme years and also gives a more orderly progression as the FDC changes in response to the disturbance. The three year period of "calibration" coincided with the wettest year in the record (1974), followed by two of the driest. This was followed by an even drier 1977, so direct comparison between the pre- and post-clearing periods is problematic, however aided by the availability of data from the control forested catchments.

5.1.2 Adjusting Individual Percentiles of the FDC for Climate

While the aim of this project is to quantify the effect of clearing on flow regime, the analysis in Section 4 indicated that the climate influences must be removed first. Lane *et al.,* (2003) developed a methodology for separating the climate influences and vegetation impacts on the percentiles of the flow duration curve following the establishment of tree plantations. It is assumed in the model that rainfall and vegetation age are the principal drivers for evapotranspiration. The climatic influences on individual percentiles of the flow duration curve are represented as:

$$Q_{\%} = f(P) + g(t) \tag{8}$$

where:

$Q_{\%}$ is the percentile flow (i.e. Q_{50} is the 50% percentile flow), $f(P)$ is a function of rainfall and $g(t)$ is a function of the age of plantation.

Lane *et al.* argued that, to assess the impacts of afforestation, a sigmoidal function, similar to forest growth functions, was suitable to represent the impact of vegetation age on the percentiles of the FDC; and the deviation from mean annual rainfall over the period of record was used to represent the climate. Therefore, the model took the form:

$$Q_{\%} = a + b(\Delta P) + \frac{A_{sig}}{1 + \exp\left(\frac{t - t_{\frac{1}{2}}}{N_{sig}}\right)} \tag{9}$$

where:

ΔP is the deviation of annual rainfall from the period of record average, $t_{\frac{1}{2}}$ is number of years after treatment for half of the change in water yield to occurs, t is the time after treatment in years, A_{sig} and N_{sig} are coefficients of the sigmoidal function.

To normalise the percentile for average climatic conditions ΔP is set to zero. This leaves the $Q_{\%}$ that would be expected under average climatic conditions, t years after treatment. When ΔP is set to zero, a becomes the value of $Q_{\%}$ under equilibrium conditions for the new vegetation type, while A_{sig} becomes the magnitude of the change between equilibrium conditions under current vegetation and the new vegetation.

In order to assess the performance of the climate separation model on the Collie catchments the statistical analysis outlined by Lane *et al.,* 2003 was undertaken on the results from the Collie Basin. This allowed us to test for the statistical significance of the climate and vegetation terms as well as assess the model performance. This statistical analysis allowed us to determine how successful we had been in:

1. fitting the model to the time series of observed percentile flows; and
2. separating out the impact of climate from vegetation. If the climatic term in the model was not significant then the climatic and vegetation impacts have been separated out of that percentile flow.

While the response in deforested catchments is more rapid than for afforested catchments, it was considered that the model developed by Lane *et al.,* 2003 (Equation 9) should also be appropriate for separating the climate from the influences of deforestation on the FDCs for the catchments in the Collie Basin.

The model of Lane *et al.,* (2003) has been applied to the three deforested catchments (Wights, Lemon and Don) in the Collie Basin and the two control catchments (Salmon and Ernie) in order to develop climate adjusted FDCs, thus allowing us to assess the impact of clearing on the FDCs shown in Figures 14 to 18 without the influence of climate. The model was applied to the control catchments (using the same years as the treated catchments) in order to assess if the sigmoidal term is required to obtain a good fit in catchments undergoing no change in vegetation.

Each decile (i.e. 10th percentile, 20th percentile, etc.) for each of the catchments was extracted to generate a time series of percentile flows. The model (Equation 9) was then fitted to each of time series of percentile flows (ten for each catchment) using the optimisation procedure outlined by Lane *et al.,* 2003.

5.2 Results

5.2.1 Observed Flow Duration Curves

Clearing occurred after three years of gauging, nominally giving some pre-treatment comparison for the catchment groups. However, the climate for these three years was somewhat atypical for the whole period, complicating the signals which might otherwise be apparent due to the land clearing. The first year (1974) was the highest rainfall year for the entire 28 year record, and it was followed by two very dry years. As a result, over 90% of the flow recorded in the first three years in every catchment occurred in the first year. Some catchments did not flow at all in the second and third years. This has made the analysis of trends somewhat more challenging, but no less interesting.

In the figures that follow, flow duration has been grouped in three year lots, to remove some of the inter-annual rainfall variability, and to enable gross trends to emerge more distinctly.

The three figures illustrate a few clear features:

1. For all occurrence frequencies there is more flow in the cleared catchments than in the still forested catchments over the same time period.
2. There are far fewer no-flow-days in the cleared catchments than in the still forested catchments during the corresponding periods of time.
3. These trends increase in time.
4. There is much less variability in flow duration curves for Ernie than the other two catchments, although there are more zero-flow years.

There are more subtle features as well. The chart for Ernie, the forested catchment, shows the climate variability influence, and that there seems to be a trend in this. There is a set of curves (74-76, 89-91,92-94, 93-95) on the right of the plot showing fewer no flow days, and the sequence 77-79,80-82,83-85,86-88 progressively moving from left to right, as number of no-flow-days decreased during that period.

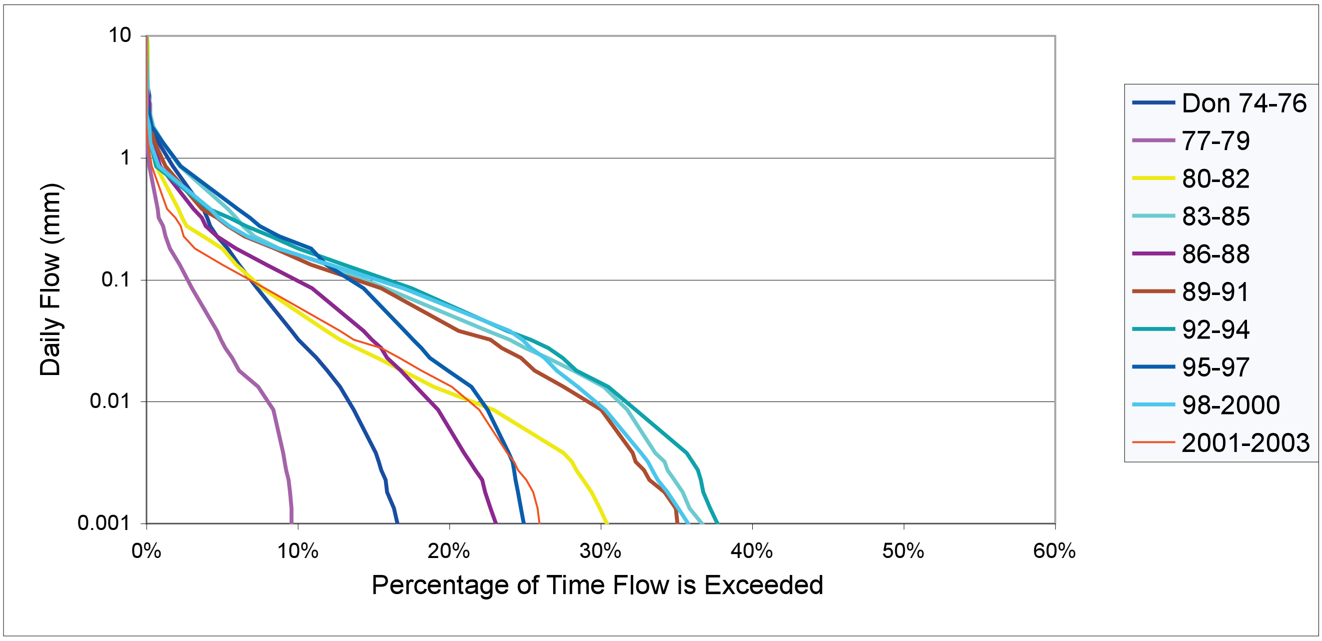

Figure 14. Flow Duration Curves for the Don (parkland and strip cleared) Catchment.

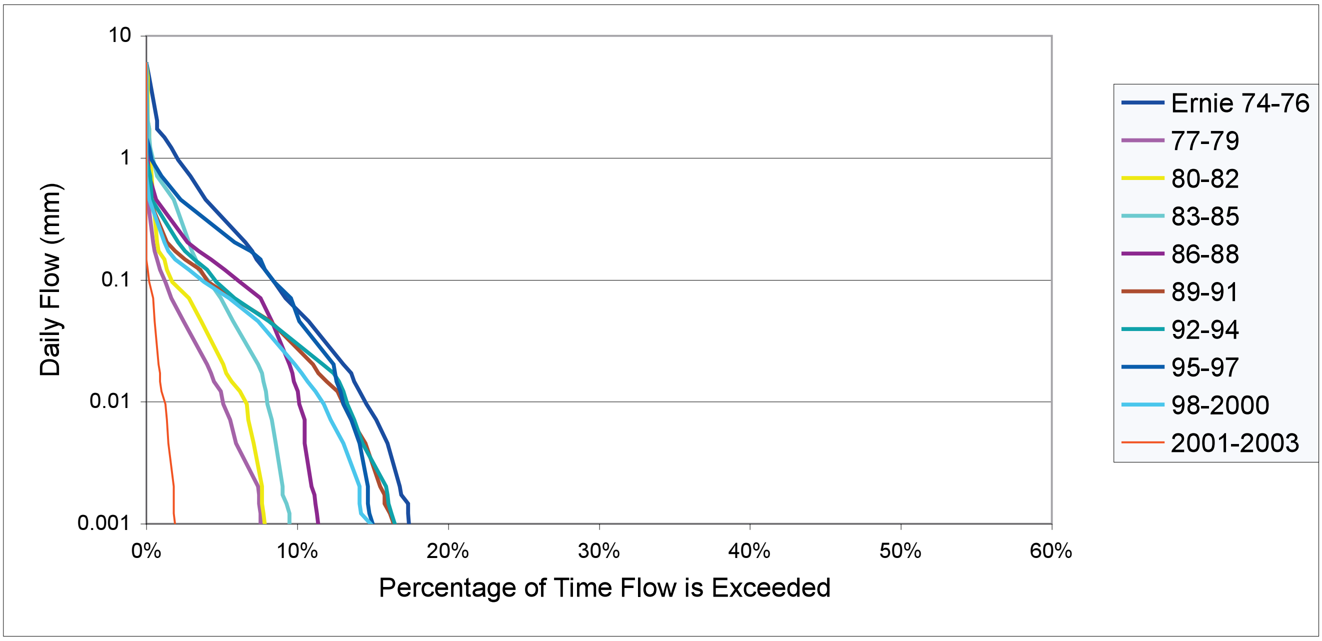

Figure 15. Flow Duration Curves for the Ernie (forested) Catchment.

The two cleared catchments both show a progression towards much longer baseflow periods, although this is much clearer in Lemon than in Don. By 1989, Lemon had reached a state where the stream was always flowing. Don, the parkland and strip cleared catchment, still had no flow 50% of the time by the end of the period recorded. The implication from this is that the distribution of clearing may have a significant influence on the rate of evolution of the hydrologic state of the catchment, if not the final state reached. It is too early to say whether Don will eventually reach the same state as Lemon, but Figure 9 clearly shows that the stream salinity started to rise in 2001. This timing coincides with the relative saturated groundwater storage reaching the same level as Lemon (Figure 6). The impact of climate is clearly evident for Don and Ernie, as the curves that cover the very dry years 2001 and 2002 show a much higher proportion of low or zero-flow days.

Because the higher rainfall is closer to the water demand of the forest in Salmon, there are no zero-flow years, and relatively, there is less variability in the FDC than for the lower rainfall control, Ernie. As with Lemon, the move from ephemeral to perennial streamflow at Wights is clearly illustrated in Figure 18.

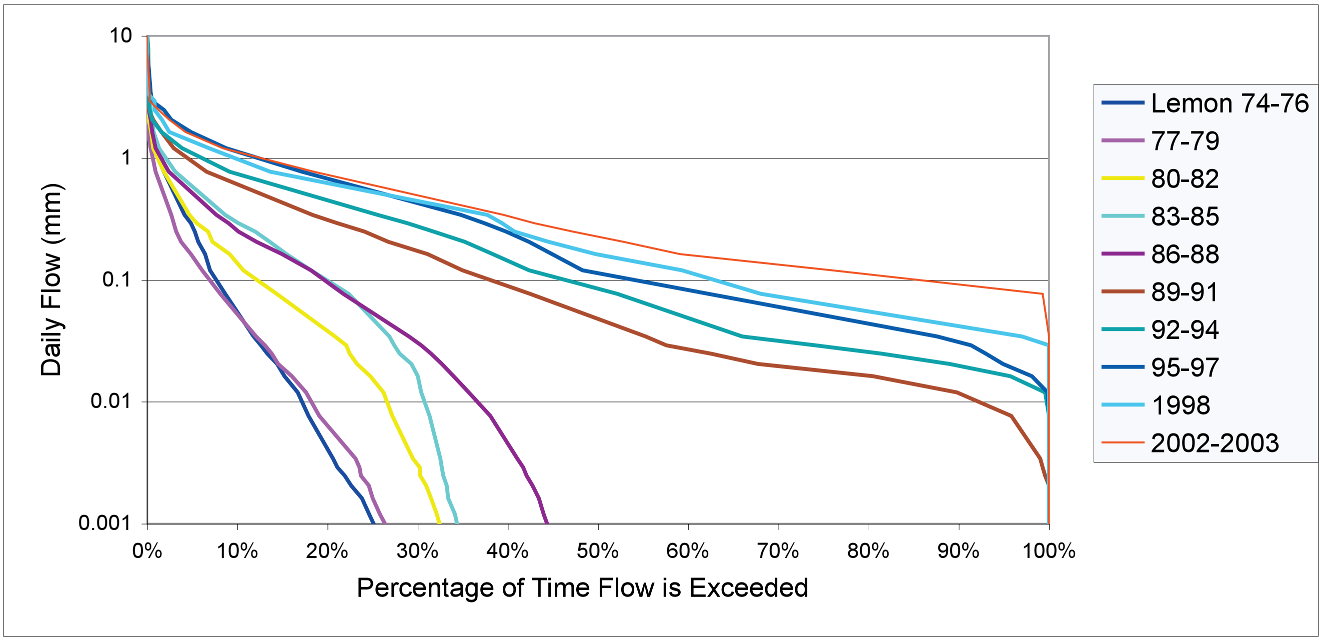

Figure 16. Flow Duration Curves for the Lemon Catchment (lower 50% clear-felled). No data recorded 1999-2001.

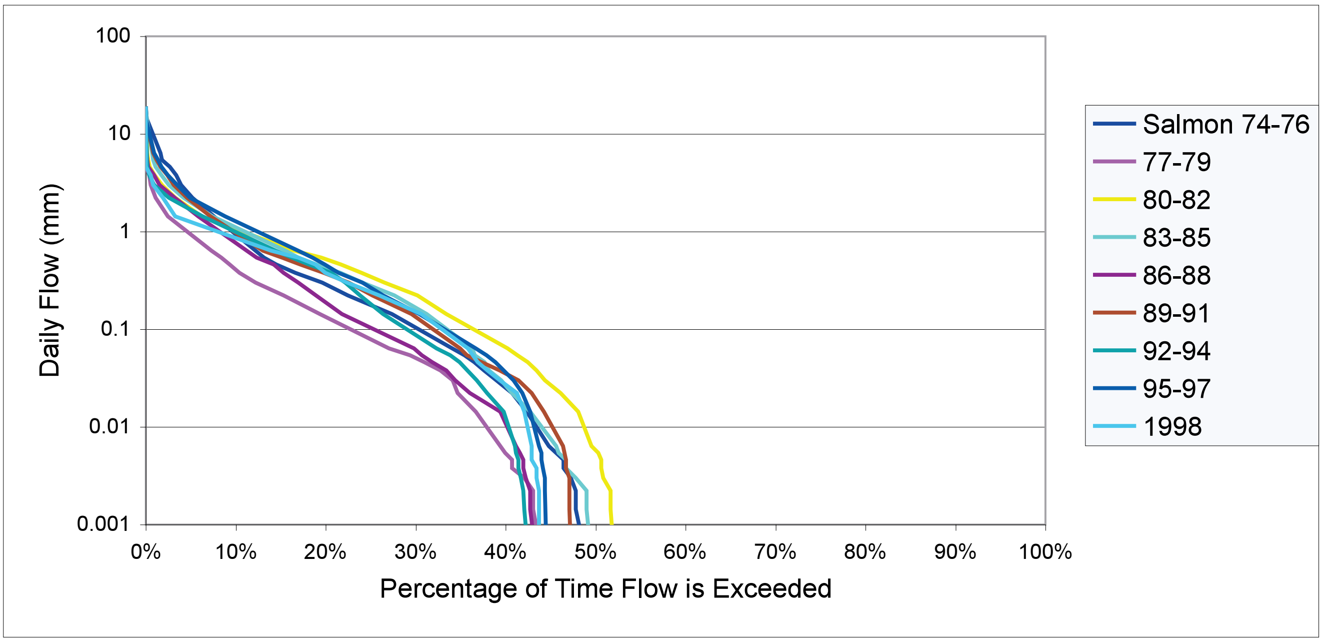

Figure 17. Flow Duration Curve for Salmon (forested) Catchment.

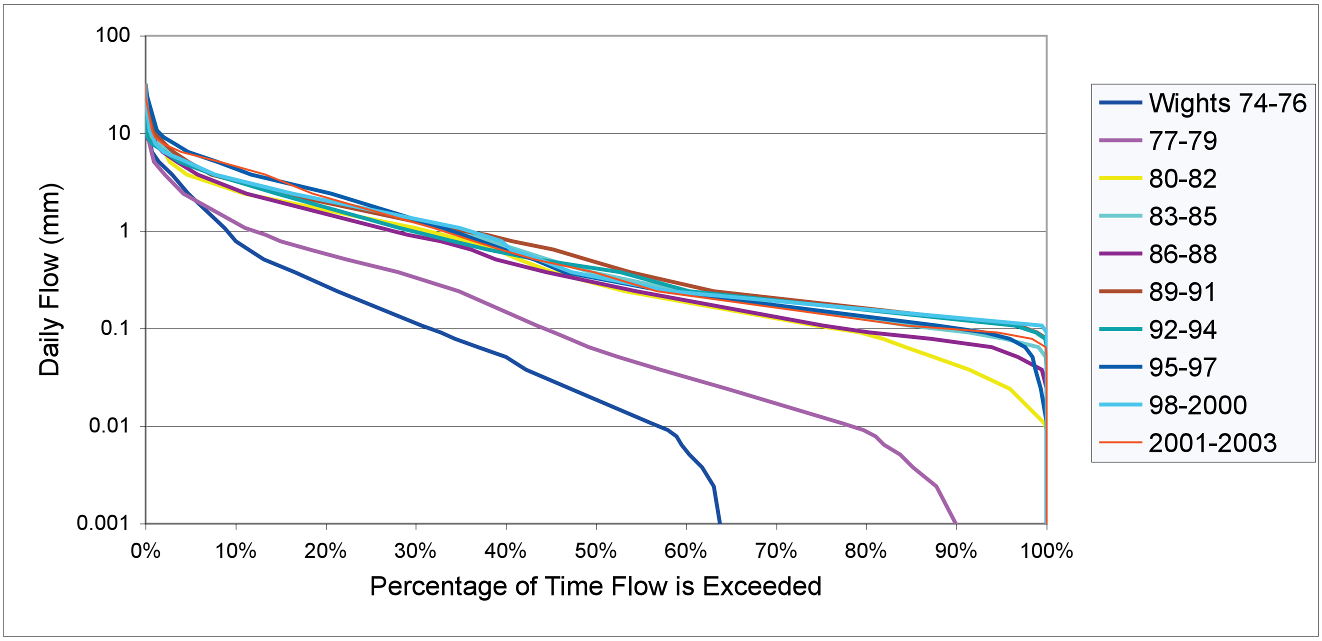

Figure 18. Flow Duration Curve for Wights (fully cleared) Catchment.

5.2.2 Climate Adjusted Percentiles of the FDC

The model was run for each decile of the treated (Lemon, Don and Wights) and control (Salmon and Ernie) catchments. Tables 3 and 4 show the statistical significance of each of the terms in the optimised models. The model has successfully separated the climate from the vegetation impacts only for combinations with a significant climate term in the optimisation fit. In model fits where the vegetation term is not significant, we conclude that the change in vegetation is having no impact on the percentile of the FDC and any change in the observed percentile is due entirely to the climatic influences.

Table 3. Significance of the Rainfall Term. *b* indicates that the rainfall term is significant at the 5% level. N/A indicates there are too few data points to undertake the analysis.

Percentile	Treated Catchments			Control Catchments	
	Wights	Lemon	Don	Salmon	Ernie
10	*b*	*b*	*b*	*b*	*b*
20	*b*	*b*	*b*	*b*	*b*
30	*b*	*b*	*b*	*b*	*N/A*
40	*b*	*b*	*b*	*b*	*N/A*
50	*b*	*b*	*N/A*	*b*	*N/A*
60	*b*	*b*	*N/A*	*N/A*	*N/A*
70	*b*	*b*	*N/A*	*N/A*	*N/A*
80	*b*	*b*	*N/A*	*N/A*	*N/A*
90	*b*	*b*	*N/A*	*N/A*	*N/A*
100	*b*	*b*	*N/A*	*N/A*	*N/A*

Table 4. Significance of the Vegetation Term. A_{sig} indicates that the vegetation term is significant at the 5% level. N/A indicates there are too few data points to undertake the analysis.

Percentile	Treated Catchments			Control Catchments	
	Wights	Lemon	Don	Salmon	Ernie
10	A_{sig}	A_{sig}	-	-	-
20	A_{sig}	A_{sig}	A_{sig}	-	-
30	A_{sig}	A_{sig}	-	-	*N/A*
40	A_{sig}	A_{sig}	-	-	*N/A*
50	A_{sig}	A_{sig}	*N/A*	-	*N/A*
60	A_{sig}	A_{sig}	*N/A*	*N/A*	*N/A*
70	A_{sig}	A_{sig}	*N/A*	*N/A*	*N/A*
80	A_{sig}	A_{sig}	*N/A*	*N/A*	*N/A*
90	A_{sig}	A_{sig}	*N/A*	*N/A*	*N/A*
100	A_{sig}	A_{sig}	*N/A*	*N/A*	*N/A*

While the significance of each of the terms in the overall model fit is important, the success of the methodology in separating the climatic variability from the vegetation impacts can only be assessed by examination of the model fit to the observed time series. This has been assessed using the Coefficient of Efficiency, E, (Nash and Sutcliffe, 1970; Chiew and McMahon, 1993; Legates and McCabe, 1999). E is given by:

$$E = 1 - \frac{\sum_{i=1}^{N}\left(O_i - P_i\right)^2}{\sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2} \qquad (10)$$

where:

O are observed data, P are predicted values, and $\bar{O}$ is the mean for the entire period. E is unity minus the ratio of the mean square error to the variance in the observed data, and ranges from minus infinity to 1.0. Higher values indicate greater agreement between observed and predicted data as per the coefficient of determination (r^2). E is used in preference to r^2 in evaluating hydrologic modelling because it is a measure of the deviance from the 1:1 line. As with the work of Lane *et al.,* 2003 it is considered that E of greater than 0.7 indicates a satisfactory model fit.

All flow percentiles in Lemon and Wights have E greater than 0.70. The results from Tables 3 to 5 indicate that the model provides a good fit to the observed time series of flow percentiles and separates the climatic and vegetation change impacts in Wights and Lemon catchments. The results in Don show unsatisfactory results at all percentiles, indicating that the model cannot fit the observed time series. This could be due to the very low-flow in the Don Catchment with a large number of zero flow percentiles for varying rainfalls.

The results of the statistical significance tests and the Coefficient of Efficiency for the control catchments indicate that while the sigmoidal term is not significant in these catchments, the formulation of the climate term is not appropriate to give a satisfactory model fit alone for most flow percentiles. The results for the Salmon catchment show that the climate term alone gives satisfactory model fits for the high flows (the

Table 5. Coefficient of Efficiency, E. N/A indicates that too few data points were available in the time series of percentile flows to fit the model.

Percentile	Treated Catchments			Control Catchments	
	Wights	**Lemon**	**Don**	**Salmon**	**Ernie**
10	0.83	0.90	0.49	0.77	-0.53
20	0.87	0.91	0.59	0.79	-0.20
30	0.86	0.88	0.56	0.66	*N/A*
40	0.79	0.79	0.34	0.50	*N/A*
50	0.69	0.76	*N/A*	0.28	*N/A*
60	0.75	0.91	*N/A*	*N/A*	*N/A*
70	0.87	0.92	*N/A*	*N/A*	*N/A*
80	0.85	0.92	*N/A*	*N/A*	*N/A*
90	0.85	0.91	*N/A*	*N/A*	*N/A*
100	0.76	0.91	*N/A*	*N/A*	*N/A*

10th and 20th percentiles) which are most likely driven by rainfall in the year of interest. However, the quality of the fit decreases as the percentiles increase (i.e. rainfall plays a larger role on the 10th percentile than the 30th percentile). The variability of the lower flows is likely to be driven by more seasonal rainfall patterns and soil water storage than directly by yearly total rainfall as appears be the case with the high flow percentiles. The results from Ernie indicate that the variability in all the flow percentiles cannot be explained by a climate term based on annual rainfall alone. The results in the Salmon catchment indicate that annual rainfall had a greater impact on high flows (10th percentile) compared to the low-flows (50th percentile). This was also found by Silberstein *et al.,* (2003).

Figures 19 to 21 show the observed and climate adjusted FDCs for the Wights, Lemon and Don catchments at various periods of time after treatment. The times taken for half the change in water yield to occur, $t_{\frac{1}{2}}$, after the clearing in the Wights and Lemon catchments are given in Table 6. The Wights Catchment, which underwent the largest change in vegetation, shows the most rapid change. It took less then five years for flow in Wights to go from ephemeral to perennial and after ten years it would appear that the catchment has reached a new equilibrium with no difference being seen in the climate adjusted flow duration curves for years 10 and 20. A similar conclusion can be drawn from the stream salinity. The estimates of $t_{\frac{1}{2}}$ in Wights show a median value of 3.7 years indicating that a new equilibrium has been reached in this catchment approximately seven years after treatment. Lemon catchment shows a more gradual change in the nature of the stream, with both the one and five year climate adjusted FDCs showing that the stream is ephemeral. The median $t_{\frac{1}{2}}$ in the Lemon catchment is 18 years indicating that a number of percentiles may not have reached a new equilibrium during the period of observed flow data. The Don Catchment, which had been cleared in strips, showed poor model fits and the results indicate that the vegetation term is not significant at two of the four percentiles investigated. However, the climate adjusted FDCs do show that immediately following clearing there is no change in the flow regime, with the climate adjusted FDCs for year 0 and year 5 being identical. No change is seen in the climate adjusted 10th and 20th percentiles of FDC for the Don catchment until after 15 years.

Table 6. $t_{\frac{1}{2}}$ Values for Wights and Lemon Catchments.

Wights	Lemon
3.71	15.50
3.34	15.39
2.24	15.92
2.49	16.90
3.22	17.30
3.56	20.62
4.06	19.48
4.20	19.87
4.17	19.95
4.58	23.83

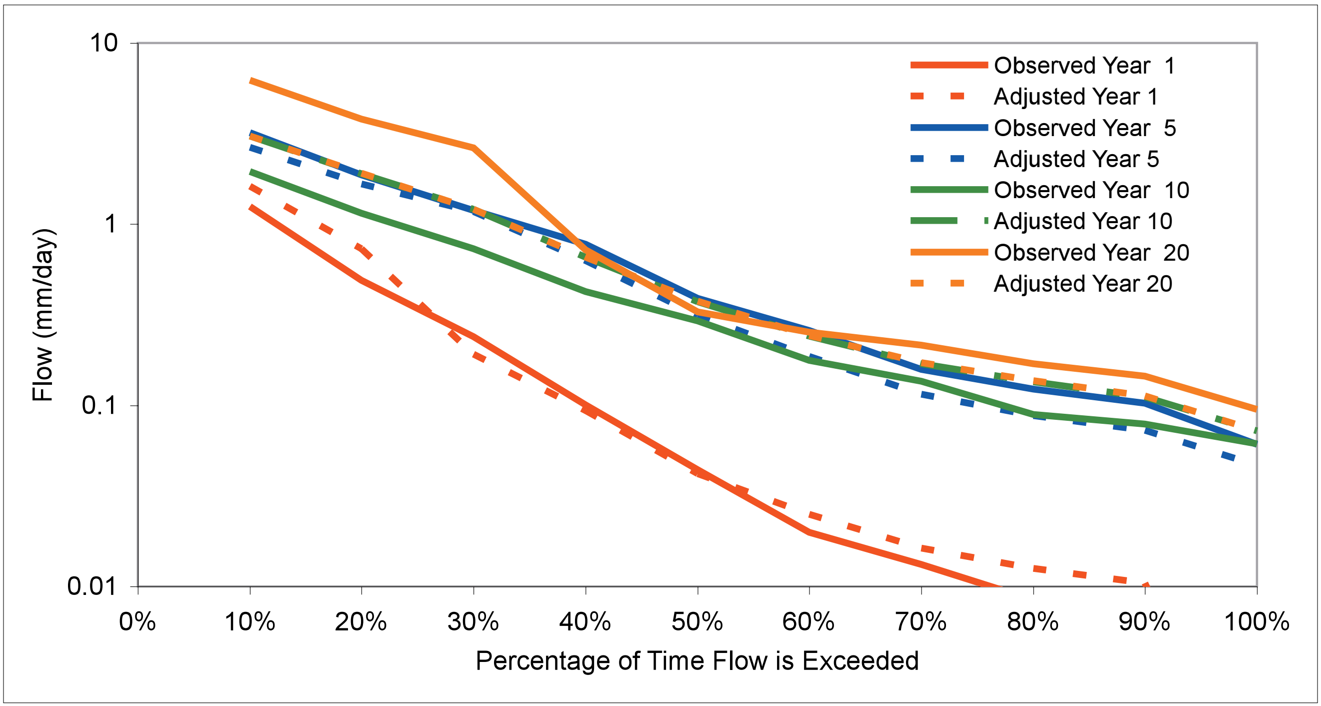

Figure 19. Observed and Climate Adjusted FDCs in Wights Catchment.

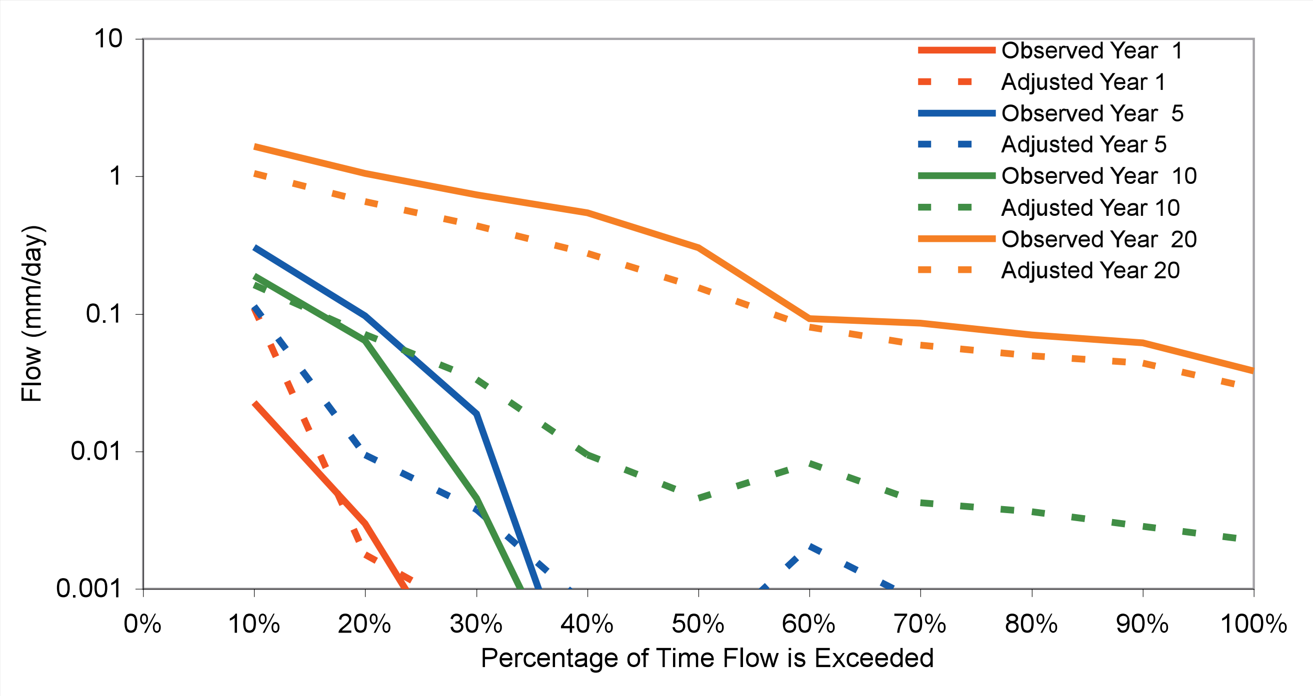

Figure 20. Observed and Climate Adjusted FDCs in Lemon Catchment.

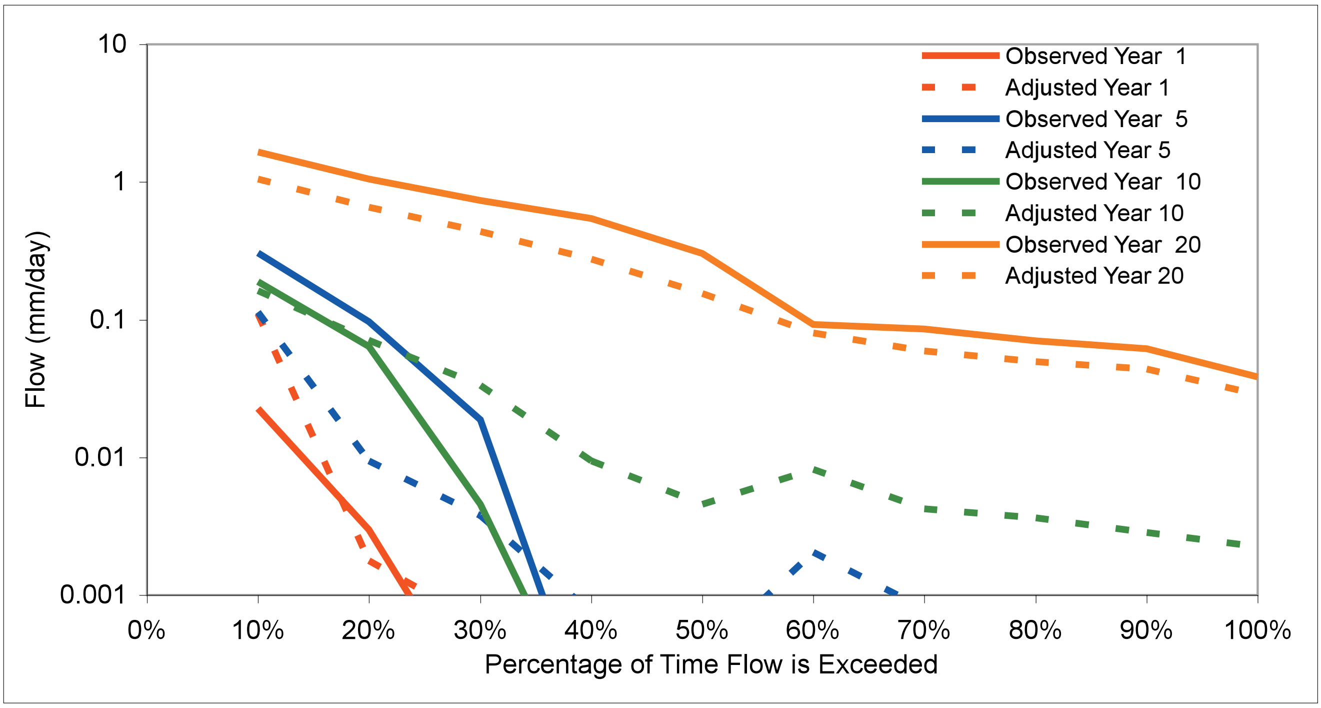

Figure 21. Observed and Climate Adjusted FDCs in Don Catchment.

5.3 Discussion

The methodology outlined by Lane *et al.,* 2003 for separating climatic and vegetation influences on the percentiles of the FDC has been tested in three deforested catchments and has proved to be appropriate in catchments undergoing a large percentage change in forest cover with rapid response times. However, the methodology does not appear to work in catchments where the observed response to vegetation change is small and, or, the time is greater than the observed period of record. As with the afforestation experiments of Lane *et al.,* 2003 problems were encountered in ensuring consistency between the percentiles of the climate adjusted FDCs. Consequently, some of the climate adjusted FDCs show flow magnitudes at the higher percentiles that exceed flows at the lower percentiles (e.g. in Lemon the 60th percentile flow may exceed the 50th percentile flow), which is not physically possible as the FDC is the cumulative distribution of flow. This arises due to the optimisation being undertaken on each time series of flow deciles independently of the other flow decides.

The analysis of Lane *et al.,* 2003, followed here, implicitly assumes that the climate dependence of individual percentile flows, Q%, and of N_{zero} is a linear function of annual total rainfall. Silberstein *et al.,* 2003 and Figure 12 show this to be erroneous. Clearly the number of days of zero flow has a more complicated relationship with climate than annual total rainfall. However, as seen in flow duration curves, the vegetation changes dominate the catchment response and the influence of climate may be neglected for these conditions.

The value of the analysis developed by Lane *et al.,* 2003 is that the adjusted FDCs can be analysed for the impact of vegetation changes. This is clearly demonstrated in Figure 19 for Wights Catchment. By Year 5 Wights had reached its new flow frequency distribution. This is also illustrated with the raw data plotted in Figure 16, where we have grouped data into three year periods to get a level of normalisation for climate, by reducing the impact of individual years. Figure 20 shows that this transition to a new state took all of the record, and some parts of the FDC probably have not yet reached their new state, as the analysis found $t_{\frac{1}{2}}$ to be over 20 years for some percentiles. Figures 19 and 20 show that both catchments had a very rapid response to clearing. The complete clearing of the lower half of Lemon has resulted in the catchment behaving somewhat as if it were simply a smaller catchment that had been completely cleared. The longer time (than Wights) to full expression is presumably related to the lower rainfall it receives and hence the longer time to have a permanent saturated area. The change in FDC in Don (Figures 14 and 21) is much more subtle. The adjusted FDCs (Figure 21) indicate that it took until about Year 10 before there was a change in FDC, and this was a relatively small modification. The discharge coefficient and the baseflow index have remained unchanged through the period of record, even though stream salinity has started to rise.

6. Determining a Generic Function for the Flow Duration Curve (FDC)

It was recognised by Lane *et al.,* that the model developed to remove the climate influences on individual percentiles of the FDC was not adequate for predicting the impact of vegetation change on the FDC. Therefore, this project has tried to develop a methodology that removes the climate influence on the entire FDC, in order to develop a model structure that can potentially be used for predicting the influence of vegetation on the FDC.

6.1 Methodology

For this phase we focussed on the control catchments that are still forested, Salmon and Ernie. We began by analysing the annual flow duration curves and sought parametric representations that could potentially be correlated with climate variables. It was clear that the shape of the flow duration curves was similar to the Fermi-Dirac distribution commonly used in physics, and which is given by:

$$F(x) = 1/(\exp(x/kT)+1) \qquad (11)$$

The function represents the distribution of the energy, x, of a fermionic system at a temperature, T. (Fermions are particles, such as electrons, that cannot exist in exactly the same place and time with the same energy state). For the flow duration curves, the function represents the distribution of the size of the flow, q.

$$F(q) = 1/(\exp(g(q))+1) \qquad (12)$$

where:

$g(q)$ is a polynomial or fractional power function of q. The initial choice of the polynomial was of cubic order, and the coefficients were chosen so as to give the best least squares fit to the data. Thus, four unknowns were used to fit to the distribution.

We have experimented with three forms:

i) $g(q) = (q+S)/T$ (13)

ii) $g(q) = (q^3+Aq^2+Bq+S)/T$ (14)

iii) $g(q) = (q^{1/b}+S)/T$ (15)

all of which describe a distribution with a median value of $-S$. The value of T effectively defines the slope of the curve (Figure 20).

We seek to characterise the climate dependence of the FDCs for the forested catchments, before then addressing the response of the cleared catchments. We normalised the FDCs by removing the zero values (this removed eight years form the Ernie record) and dividing by the maximum flow for the year, and then plotted each year as an individual FDC (Figure 23).

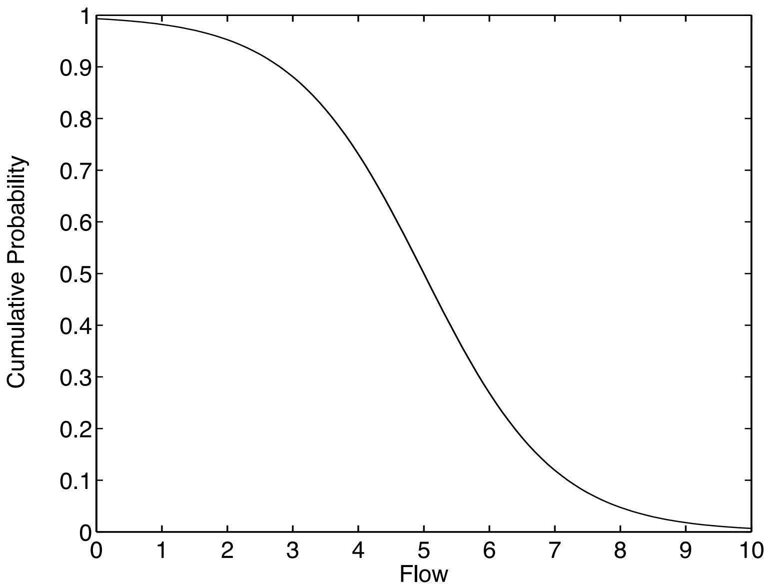

Figure 22. Generic Distribution Curve as Represented by Equations 13-15.

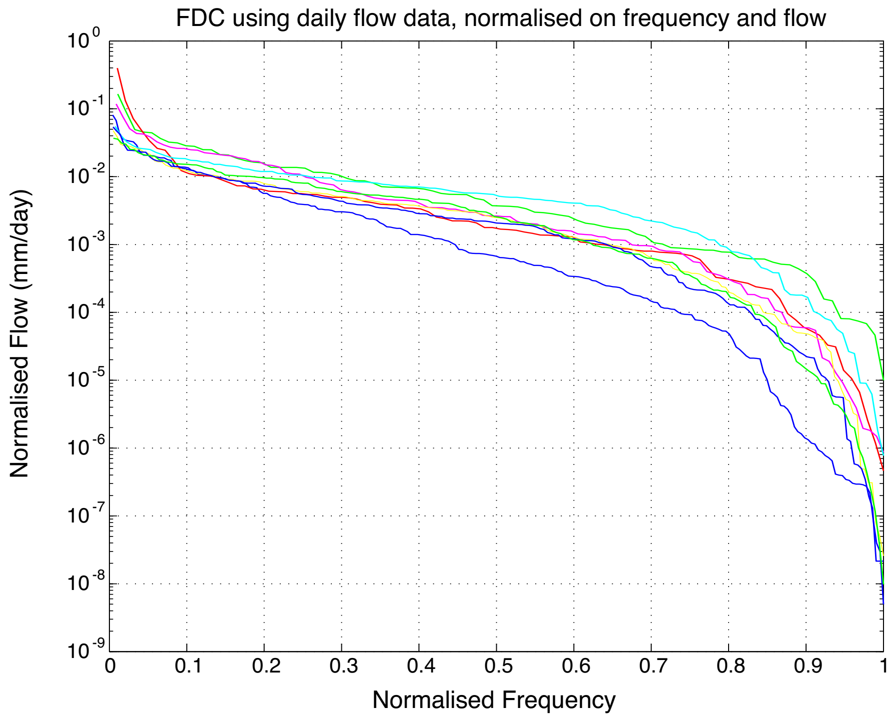

Figure 23. Annual Flow Duration Curves for Ernie Catchment, Normalised by Maximum Flow and with Zero Flow Days Removed.

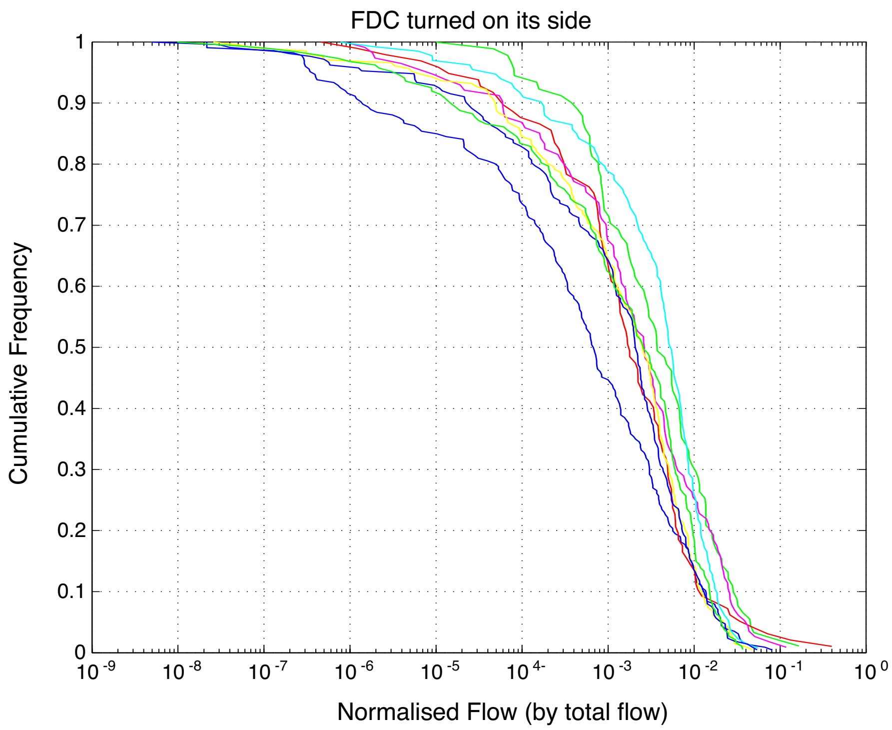

Figure 24. Annual Flow Duration Curves for Ernie Plotted with Orientation of Equations 13-15 and Figure 22.

6.2 Results

6.2.1 For Linear Function of *q*

The yearly flow frequency curves were represented by the expression from Equation 13, and the parameters fitted by optimisation to best represent the whole curves. It was apparent that the curves of best fit fell into three classes. The values for these parameters were determined by fitting the function *F(x)* to the graphs with a least squares method. This has been done for the catchments Don, Ernie, Lemon, Salmon and Wights but Figure 25 shows the results for Ernie only. It was found that even though the parameters had appeared to separate into five classes the curves were effectively only three classes.

Though this functional representation has similarity to the graphs, it underestimates the extreme ends of the FDCs, i.e. for low and high flows. Further, if this functional representation is to be useful it would also have to be linked with environmental parameters, such as the amount of rain which fell during some particular season, or similar. Some climate variables which have been examined for their correlation to these parameters have been:

1. The total amount of rain which has fallen in the water year (which begins on the 1st April),
2. The difference in mean rainfall between the wettest and driest halves of the water year, and
3. The mean rainfall in the wettest or driest half of the year.

None of these has shown a strong correlation. As an example, a plot of the parameter *S* against the median flow value, total rainfall for the water year, and the difference between the wettest and driest halves of the water year, respectively, for the five catchments can be seen in Figure 26. This procedure was also tried using the rain falling in wettest and driest three months as our climate indicator, but did not produce any more significant result.

There appears to a reasonable relation for the median value of the flow, but since that is what the parameter *S* represents this is not surprising. There appears not much in the second graph (*S* vs. total rainfall), or at least a minimal relationship. For the last graph (*S* vs. difference between wettest and driest six months), again there appears to be a relationship.

6.2.2 Cubic Function of *q*

Optimisation on the cubic expression, (Equation 14) produced better fits to the FDCs, as would be expected because of the extra degrees of freedom, but the curves were consistently too far along the probability axis. Figures 27 and 28 show the temporal sequence of the four parameter values for the two forested catchments (Ernie and Salmon, respectively). Other attempts at finding the environmental causes of certain behaviours of the catchments involved examining the length of flow and non-flow events, and the amount of rain that fell during these intervals. Although showing promise, these results are inconclusive.

Clearly from the plots, there is some internal correlation between the parameters, and so some redundancy there, but despite extensive testing, no definite correlations between these parameters and climate indicators have been found.

6.2.3 For Non-integer Exponent of *q*

Optimisation using Equation 15 produced the best representation of the FDCs of the three forms tested. Similar to the results of the previous section, no single function could be fit to the whole curve and so for this reason we broke the curve into high (top 25% of flows), medium (middle 50%), and low (bottom 25%) flow sections, with each being independently fitted with the three parameters (*b, S* and *T*). For practical purposes this may not be a major impediment as often different parts of the flow distribution are used independently, with the focus being on high flows for flood studies, low-flows for ecological studies and median flows for water resources. The coefficients showed similar trends to those in the previous section, and are not reproduced here. However, for all catchments the average value of the exponent $1/b$ was close to 0.5. This is similar to the finding of Wittenberg and Sivapalan (1999), who proposed the non-linear storage relation $S=Aq^b$ and also reported $b=1/2$ for a number of catchments.

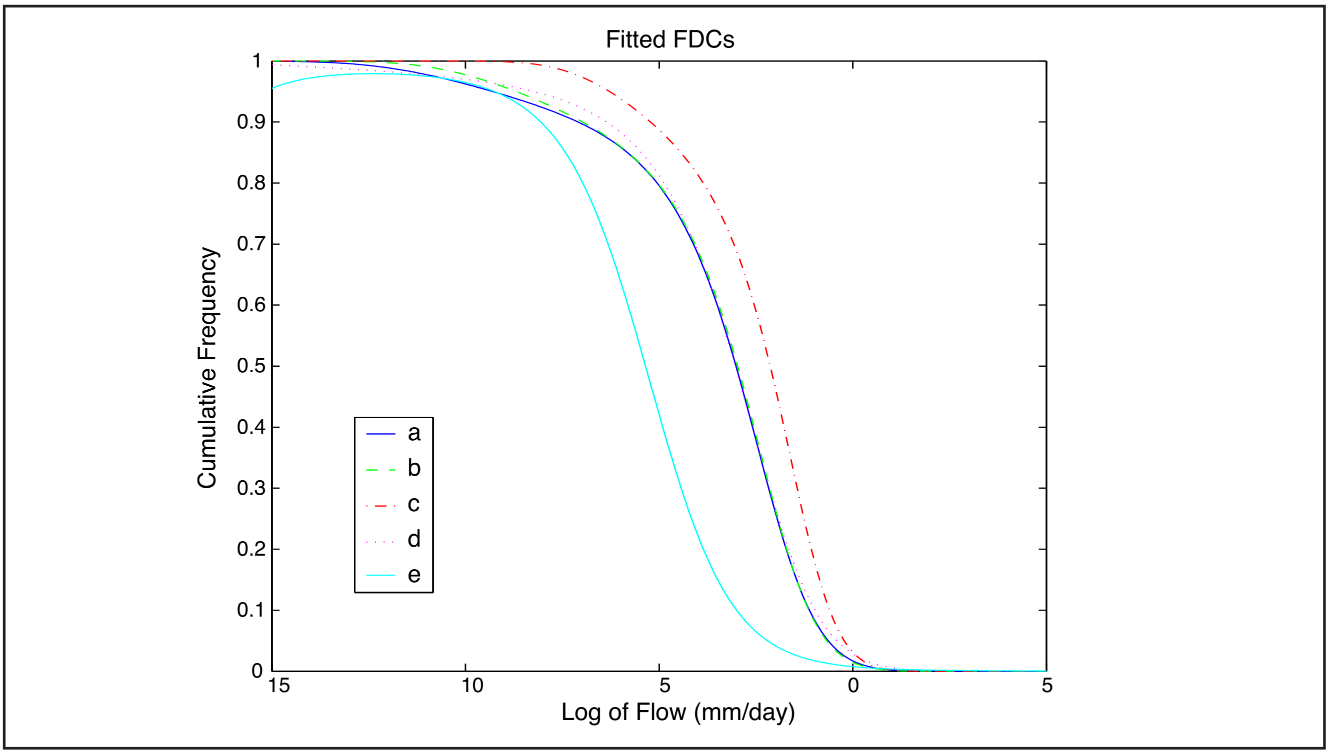

Figure 25. Generic FDCs Obtained using Equation 13. All FDCs were condensed to one of five cases, curve “a” applies to 1974,75,83,89,90, curve “b” applies to 1978,92,94,95,96, curve “c” applies to 1982,85,88,91, curve “d” applies to 1993, curve “e” applies to 1981.

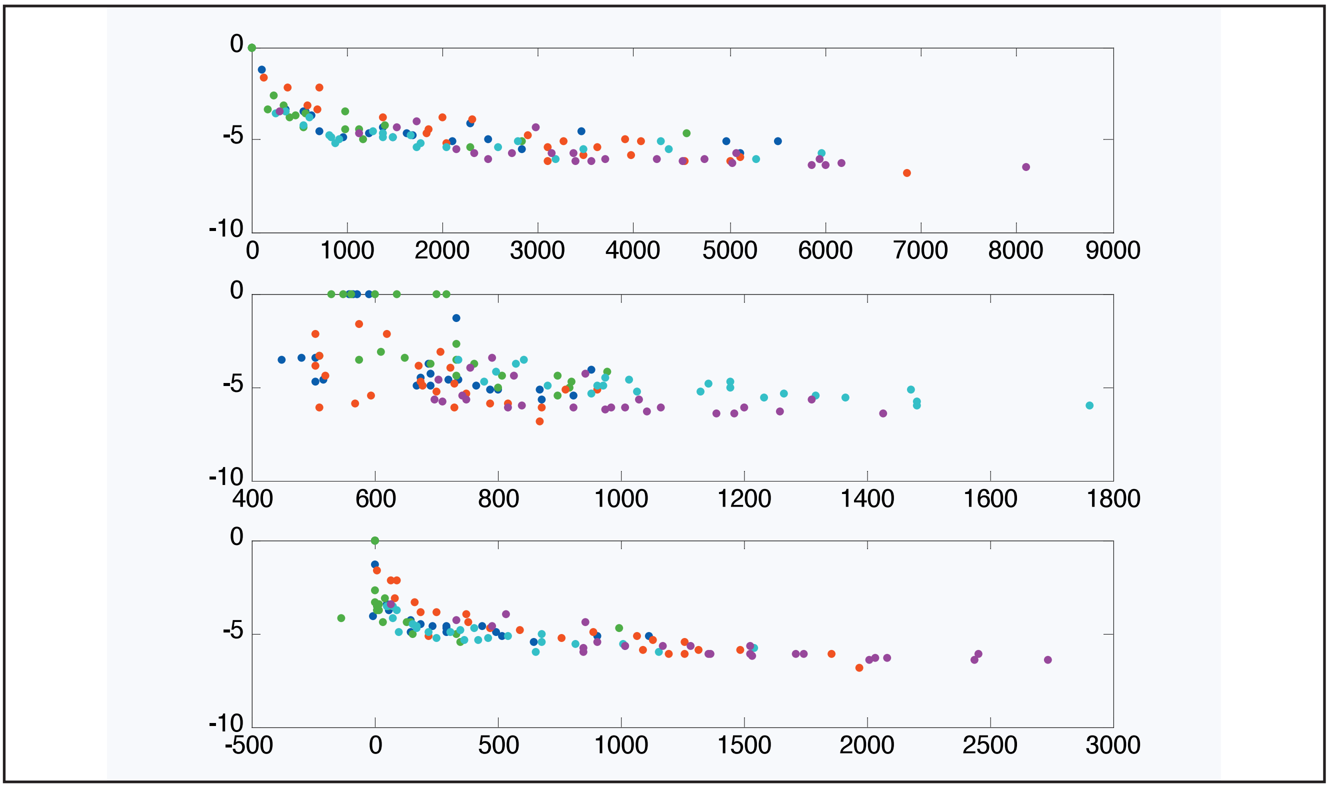

Figure 26. Optimised Value of Parameter S from Equation 11, plotted against *a*) median annual flow value, *b*) annual total rainfall, and c) rainfall in wettest half of year minus that in the driest half of year, for all five catchments.

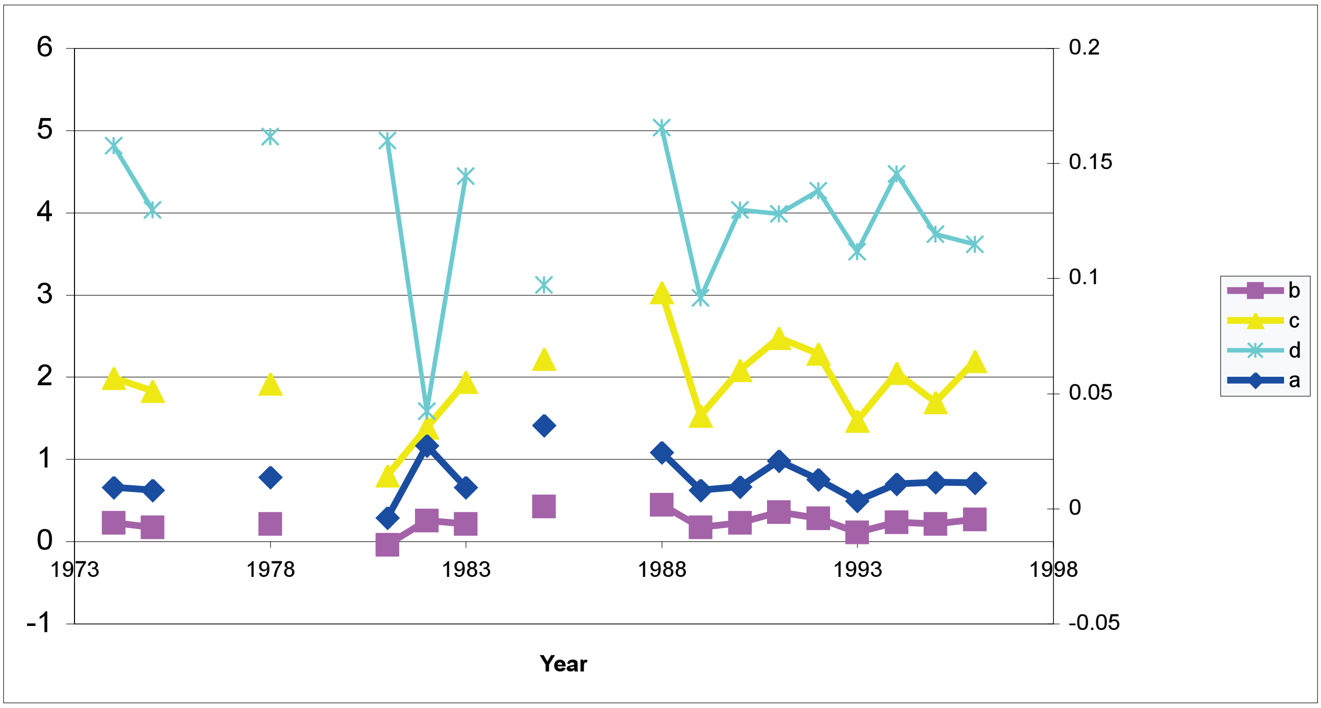

Figure 27. Time Sequence of Optimised Parameters for Equation 14 Fitting to FDC for Ernie. The trace for "a" uses the right-hand Y-axis.

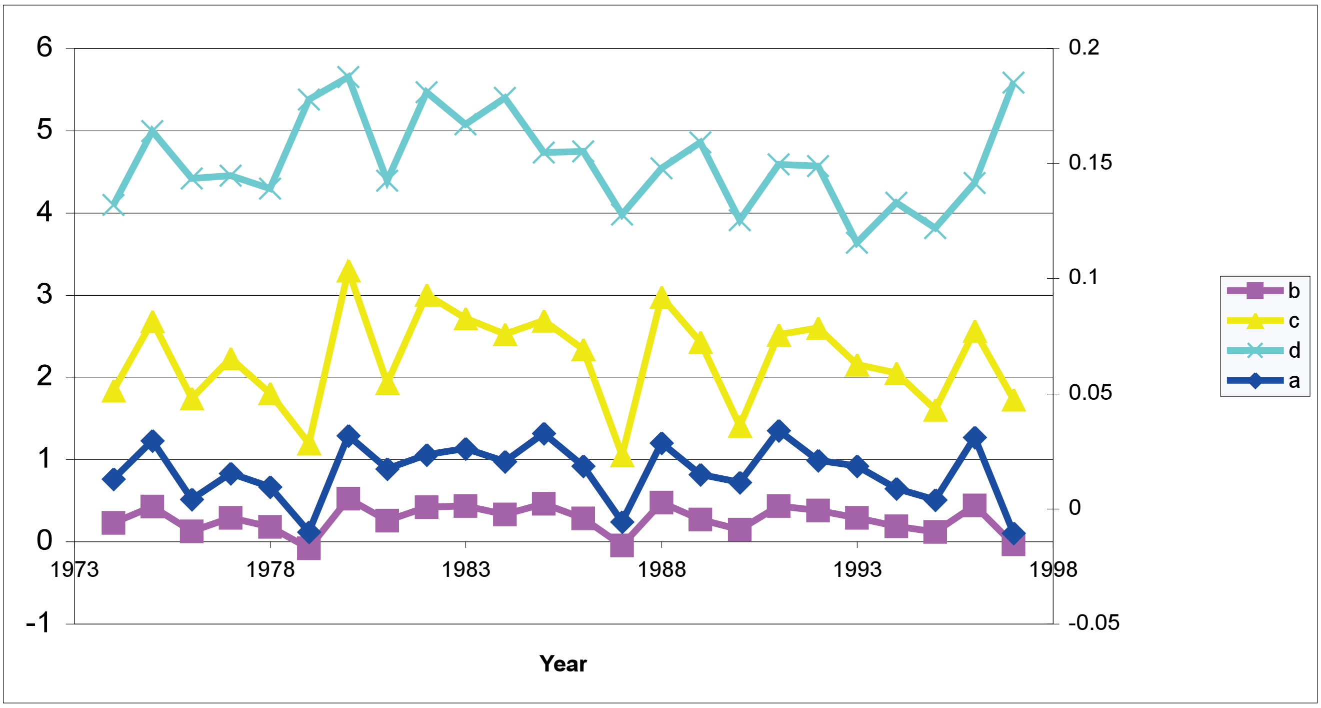

Figure 28. Time Sequence of Optimised Parameters for Equation 14 Fitting to FDC for Salmon. The trace for "a" uses the right-hand Y-axis.

6.3 Discussion

In Section 5 the focus on individual percentiles of the FDC led to a useful description of the dependence of these on climate, and a means of representing the change from one regime to another. The result, similar to that of Lane *et al.,* (2003), was a useful description of data, but it does not provide a method for predicting changes to the FDC in a new catchment. In this section we approached the problem from a higher perspective, to try to characterise the entire FDC with a single function that would allow development of a predictive model. Our aim has clearly not been entirely met as, although we have developed a set of models of the FDC, we have not managed to specify the dependence of the parameters of the model on independent catchment and climate characteristics.

The analysis described here required the removal of zero flow days and normalisation by the maximum flow in the recorded series. This facilitates normalisation of the curves and introduces these two parameters that need specification in order to apply the model to new catchments. By developing the normalised approach we have a way of moving towards a more generic model that would be predictive, however there is still a way to go.

Our exploration of fractional powers of flow in the FDC model produced more promising fits to the FDC, without being materially different in substance – that is they still had some parameters that changed through time and some that did not. It appears that a fractional power of flow, specifically $\frac{1}{2}$ is more likely to produce a good result and future work should focus on this.

7. Summary Discussion

In this project our approach can be condensed to three main steps:

- Analysis of the flow regime of well monitored small catchments, specifically, the discharge coefficient, base flow index, number of zero flow days and flow duration curves.
- Fitting a sigmoidal function to a time series of flow percentiles in order to remove the climate signal, and exploring the relationship between Q% and time since vegetation change.
- Fitting a sigmoidal function to the whole FDC, and attempting to relate the curve parameters to climate.

Annual average rainfall and proportion of catchment cleared both clearly have an influence on response time of catchments to clearing. Because we lack replicates of treatment and rainfall we could not separate the two, but we observed that the response of the high rainfall catchment (Wights) was very rapid, with discharge coefficient increasing immediately on clearing, baseflow index increasing perhaps four years later (Figure 8), and stream salinity increasing within a year of the treatment (Figure 7). It should also be noted that Wights is much smaller than Don and Lemon (about 1/3 the area) and this may also result in a quicker response. In the lower rainfall catchments (Lemon and Don) the response was slower. In Lemon and Don there was an immediate increase in discharge coefficient after clearing (Figure 4), probably due to lower interception loss (Ruprecht and Schofield, 1989). After about 4 years the baseflow index in Don and Lemon had risen above their forested control, Ernie, but it took 11 years before the baseflow index in Lemon started to rise dramatically above that of Don. This was about the time that stream salinity started to increase in Lemon, and when a permanent saturated area appeared at the bottom of the catchment. The baseflow index in Don has remained at the same level since the initial rise after clearing, however, stream salinity started to rise in about 2000. There has not yet been a detectable change to the streamflow statistics accompanying this. This is very interesting because it probably indicates salt is accumulating in the surface soil ahead of the rising watertable (indicated by the rising soil water storage in Figure 5). The salt accumulation occurs through evaporation of water driving capillary rise from the watertable. Since the relative water storage in Don has now reached a similar level to that in Lemon, it is to be expected that the stream statistics will change in the next few years. It would seem likely that Don will gradually progress towards a similar state to Lemon, with increasing salinity and increasing baseflow, eventually becoming perennial. However, it is possible that the distribution of trees around the catchment will help to maintain a deeper watertable across the catchment and limit the surface saturation. The result would be that the FDC will not undergo the same degree of change. We await further data to be sure. The lower watertable would also result in lesser salt discharge and hence stream salinity. It is likely that the salt reaching the streams is being purged from “preferential flow zones” with higher transmissivities than the bulk of the catchment. As a consequence the time scale for stream recovery may be significantly less than that for complete flushing of the salt storage.

Silberstein *et al.,* 2003 examined these catchments for a relationship between flow percentiles and water storage within the catchment and saturated area. They were seeking a correlation between annual peak flows and saturated area. They did not find such a correlation, but they did find a good correlation between saturated area and low frequency (high rate) flows, in particular 90th percentile flows had generally the best coefficient of determination. At lower flows there was little direct correlation with saturated area, which tends to indicate that climate is still the dominant influence. However, base flow has increased significantly since clearing and there has been a dramatic shift in the low-flow characteristics of these catchments. This is also demonstrated by the relationship between number of zero flow days and saturated area for Lemon and Wights catchments. We found that the number of zero flow days exhibits binary behaviour, with a sharp change between the forested intermittent state and perennial flow.

Lane *et al.,* 2003 made some progress towards developing a model for characterisation of zero flow days in afforested catchments, but they could not develop a predictive model. We have discussed one of the limitations of their model is the implicit assumption of a linear relationship between yearly rainfall total and number of zero flow days. Clearly the relationship is more complicated. Intermittency of flow is related to evaporative demand between storms and at the time of rain, the number of rain days, the rain intensity through storms, and total rain that falls per rain-day. We have shown that a sigmoidal relationship can be used to describe the dependence of number of zero flow days on annual rainfall, and this may be used to separate the climatic influence on a catchment, independently of treatment for land-use change. However, the analysis presented earlier on fitting a function to individual deciles showed that, especially for catchments subject to clearing, the vegetation effects dominate the response and the rainfall influence is hidden within the statistical variability from year to year. Hence, the shortcomings of the Lane *et al.* model are less significant for this application, but while the approach is useful for describing data, it does not give a predictive capability.

Our efforts to find a simple representation for the FDC have been only partially successful. We have demonstrated that a simple relationship can represent the FDC, and that the annual FDCs collapse to a few type curves. However, we have yet to demonstrate a clear correlation between the FDC curve parameters and climate attributes. This work needs to continue.

In Section 6 we attempted to develop this through analysis of the whole FDC as a single normalised function. Normalisation is important for any generic FDC model if it is to be generally applicable. It is the basis for transfer of a generic model from one site to another to ensure it may be used predictively. It is essential that the generic catchment characteristics are captured in such a way that implementation of a model in a particular catchment is possible without a great amount of subjective assessment, calibration or predetermination. The first step is to remove the climate signal, similar to Lane *et al*. but we have broadened the approach by normalising the FDCs and seeking a function that describes the whole distribution, rather than individual percentile flows. While demonstrating that some of the parameters of the FDC functions change in time and others do not, we have shown that it is possible to separate out the climatic and vegetation influences. We have not managed to determine specific connections between the parameters and climate statistics, with the exception of annual total rainfall. For this work to reach a practical use, we need to link to more sophisticated climate statistics to the FDC parameters (Best *et. al.,* 2005; Brown *et. al.,* in prep). We also need to be able to generalise the functions to include catchment characteristics. We have not had resources to complete physical analyses of the catchments. Our terrain analysis of the five research catchments, not discussed above, has shown that four of the five have very similar height-area distributions. This is expected to also have an impact on the FDC, but characterisation will be difficult. This should be attempted in the next phase of this work.

Cigizoglu and Bayazit (2000) used a slightly different approach, but with similar philosophy. They represented the FDC as a convolution of two functions, one of which was stochastic. They found, as we did, the FDC could be represented with two or three parameters. They also concluded that there is a great need for more data from a large number of catchments to understand the physiographic controls on FDCs.

8. Concluding Remarks - Future Work

This project aimed to develop a predictive framework for the flow duration curve of catchments subject to land-use change – specifically clearing of forest for pasture. While we have made some progress, we have clearly not completed the task and we have identified areas for the focus of future work. It is clear that the intermittency of flow is a strong component of the flow frequency distribution, and intermittent streams need different approaches to perennial streams. Our land-use change was the opposite of that studied by Lane *et al.,* 2003, who found afforested streams that had begun as perennial became ephemeral. In our case, two of the catchments that were forested, in different rainfall regimes, began as ephemeral streams, but rapidly became perennial streams after clearing.

The next stage in this work should be to complete these analyses and quantify some of the trends that are only qualitatively identified so far. As part of this process data from some reafforestation experiments in the Collie Basin should be examined, as they are subject to a similar climate as the catchments used in this report, and are significantly different from the catchments studied by Lane *et al.,* 2003. The aim is to complete the comparison of FDC for the forested catchments and determine climate characteristics that can be used to define the FDC parameters. The focus should then move to association of the FDC parameters with catchment characteristics and the development of saturation area. Some of this work is discussed by Silberstein *et al.,* 2003.

In developing a model for the flow duration curve of a catchment, the catchment must be treated as a single entity with some key characteristic attributes which define:

- Total available storage for water;
- Area-height-distance distribution - to enable a representation of saturated area as a function of watertable height, and flow distance/time to outlet;
- Specific storage for catchment - linking recharge rate to rises of watertable;
- Some representation of the proportion of catchment groundwater which flows “rapidly” - thereby how much of the recharge actually contributes to salt flushing within a management time frame.

There must also be some representation of the climatic influences on the FDC, so the normalisation process should take account of total rainfall, particularly in relation to potential evaporation and storage within the catchment. The seasonal rainfall distribution needs to be included.

In the context of increasing salinity of streams in agricultural areas, it will also be important to consider the total salt storage in relation to the total water storage within a catchment, the proportion of salt in solution, and the proportion of salt storage which is mobile – thereby defining how much salt will be flushed out by the more mobile groundwater. These particularly pertain to recovery times for streamflow from the catchment, and for long term salt export trends. It is envisaged that some relatively simple rules will emerge to relate the changes in recharge after clearing (or reafforestation) to a rise (or fall) in watertable, and consequent change in saturated area giving changes in runoff regime.

In this report we have used only daily and annual flow statistics, and this was judged by us appropriate for the size of catchments used in the study. However, with catchments of this size that respond within a day or two of rainfall, there are likely to be significant mechanistic insights to be gained by examining shorter timescale data. Both flow and stream water quality data should be examined (Kirchner *et al.,* 2004) as these may well reveal more subtle changes that the longer time frame data do not.

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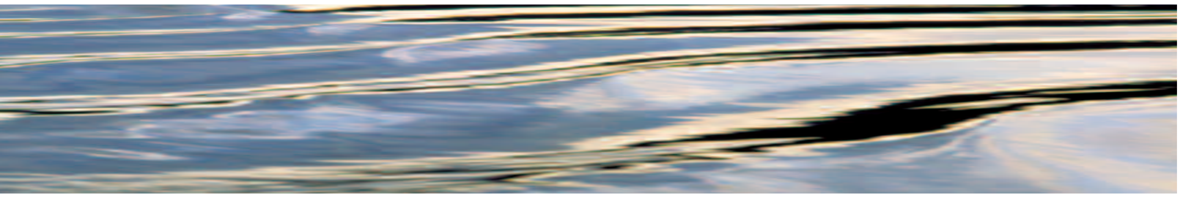

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