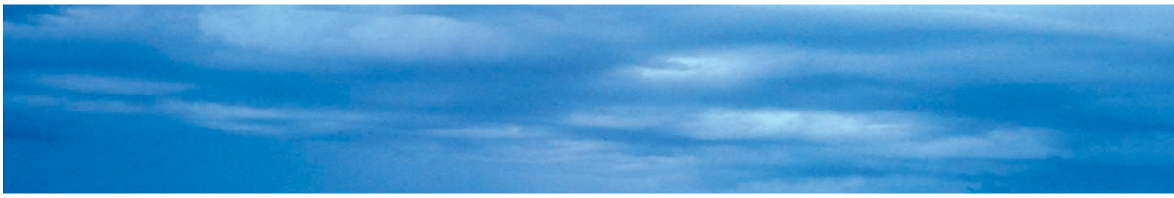
COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

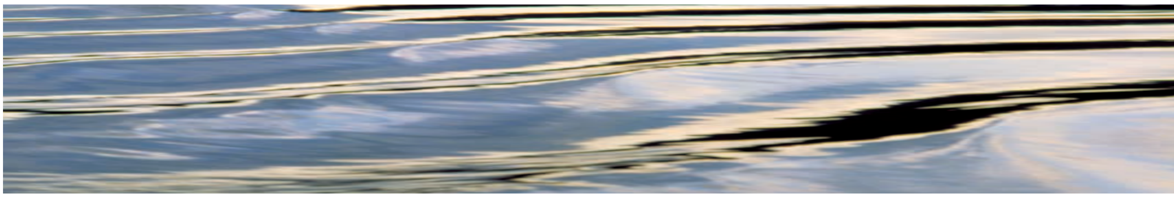
CHANGES IN FLOOD FLOWS, SATURATED AREA AND SALINITY ASSOCIATED WITH FOREST CLEARING FOR AGRICULTURE

TECHNICAL REPORT
Report 03/1

October 2003

Richard Silberstein / Anita Adhitya / Caesar Dabrowski





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CATCHMENT HYDROLOGY

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DRYLAND
SALINITY
Program
Know-how
to tackle salinity

Silberstein, R.P.

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Changes in Flood Flows, Saturated Area and Salinity Associated with Forest Clearing for Agriculture

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Preface

There is widespread awareness of the problems of land and stream salinity in the Australian community. As a consequence we are beginning to see the adoption of some strategies to either mitigate, or live with, the outcomes of salinisation. It has been speculated that salinisation will have a range of secondary impacts on our landscape. One of these impacts is an increase in flooding associated with reduced vegetation cover and increased areas of water logging. This report investigates these issues using data from experimental catchments in southern Western Australia.

This region has demonstrated some of the earliest salinity-related changes in Australia. It therefore is an important proving ground for our understanding of salinity in catchments and our management techniques. For this reason, this report will be valuable reading for specialists managing salinity through Australia.

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 sediment, and 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

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CRC for Catchment Hydrology

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Executive Summary

This report presents results of an investigation into the connection between stream flow and the rise of watertables following clearing, and their fall after reafforestation. The main focus is to identify as well as possible the relationship between high flows and saturated area. While there remains work to be done to completely fulfil the aims of the project, a number of key results can be reported.

Rainfall and streamflow data from seven 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 and reafforestation experiments in the Collie River basin in the early 1970's and (in the case of one) 1980's. A catchment pair was instrumented in the high rainfall zone (1120 mm/yr), three catchments in the intermediate rainfall zone (710 mm/yr) and two catchments with reafforestation experiments at 640 mm/yr. While the rise of groundwater after clearing is well established, what is not so well known is the proportion of clearing that would result in effective use of land while ensuring watertables do not rise to the ground surface. This work shows that clearing 50% of a catchment as one large block has significantly different effect than clearing in patches. While groundwater is still rising across the catchment that was cleared in patches, this is only occurring under the cleared areas and adjacent forest. It is not yet clear whether the groundwater will stabilise at a level deep enough to prevent major salinisation of the stream.

Following clearing, runoff coefficient has risen by a factor of 5 in the wetter catchments, about 10-20 in the intermediate catchments, and up to 100 times in the drier catchments, which have almost no runoff under natural conditions. Additionally, the runoff coefficient of Maxon Farm (Batalling Creek) has reduced after substantial reafforestation. The stream salinity has remained at a high level, but the stream salt load has followed the same trend as runoff coefficient, with the result that there is less salt reaching Wellington Dam from this part of the catchment. Flow frequency curves appear to be returning towards the forested conditions, but it is too early to be certain. Stream salinity has not yet shown any decrease, but total salt load has reduced along with total flow. At Maringee Farm which had only 10% of its catchment revegetated, there has been no noticeable change in flow regime or stream salinity.

The major impact of the risen watertables has been on low flow conditions, with these being dramatically increased in all catchments subjected to clearing. It is observed that the high flows are not increased as much as the low flows, but the median flows in cleared catchments are similar to 90th percentile flows in forested catchments at the same rainfall. This effect is stronger in the low rainfall catchments.

A clear relationship was found between saturated area in the intermediate rainfall catchment and 10th percentile exceedence flow (r^2 =0.73), but this was the only statistically clear result. There was no clear relationship between the increase in annual flood flow and saturated area in the cleared catchments. It is possible that this is partly due to the variability in climate masking the signal. Attempts to represent the flow exceedence curves in parametric form with climate derived parameters have so far been inconclusive. Only annual total rainfall has been established as a clear indicator of annual stream flow, and maximum storm rainfall with antecedent wetness the only clear indictor of stormflow.

Stream salinity in the high rainfall catchment appears to have stabilised. It is yet to do so in the lower rainfall catchments, and salinity has hardly risen after the patchwork clearing in Don catchment. Salinity in some groundwater bores is reducing – perhaps indicating flushing of parts of the regolith. Most bores show a fairly constant salinity through the 25 years of record. Estimates of salt flushing times vary with rainfall and degree of clearing, being 10-20 years for Wights (1120 mm), 20-100 years for Lemon (710 mm), to 100-1000 years for Don (710 mm, scattered clearing).

Future Work

The work completed to date has highlighted the need for further investigation in a number of areas. Clearly, the decision to cease gauging the clearing experiment catchments in 1997 and 1998 has had a major impact on our ability to make final determinations on a number of issues, most notably the flushing time for Wights catchment, the accession to a new steady state in Lemon, and significantly, the time of the watertable reaching the surface and the consequent rise in stream salinity in Don. **It is a very strong recommendation of this report that gauging be recommenced at Salmon and Lemon as soon as possible.**

The analysis presented above has shown some clear relationships between flow characteristics and saturated area, and rainfall. However, there is still considerable work to do to convert the initial statistical results in a physical model. Work is in progress to combine the saturated volume and area analysis with topographic distributions within the catchment to develop a model, that would be generic, and could be applied with a minimum of regolith data and a minimum of calibration. This is an ambitious undertaking, but one we feel is worth investing time and effort into.

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1. Introduction

Clearing of native vegetation for agriculture in south-west Western Australia has resulted in enormous environmental problems. The irony is stark in a region generally considered dry and lacking in water for much of the year, we have a problem caused by too much water accumulating in local areas. Prior to clearing for agriculture the deep rooted perennial native vegetation used virtually all the available rainfall, and maintained a very deep or non-existent watertable. What little groundwater flow there was, was very slow due to the low gradients and low transmissivities. As the vegetation used all the water, salt accumulated within the soil profile with a maximum in the zone where root activity was at its maximum. There are now tonnes of salt under most hectares of soil in the agricultural zone of Western Australia. Shallow rooted agricultural crops and pastures do not use all the rainfall, and so each winter a small amount of water (perhaps 5-100 mm depending on soil and climate) drains down through the soil until it reaches the now rising watertable. When the watertable rises the salt is dissolved. This groundwater flow carries huge quantities of salt to the surface, discharging to streams and concentrated by evaporation, causes large scale land and stream degradation (Schofield *et al*., 1988).

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 report “Dryland Salinity and its Impacts on Rural and Industries and the Environment” (PMSEIC, 1999) 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).

Salinisation is a naturally occurring process. Before European settlement, there were some naturally saline streams and many saline lakes in the drier regions of the State. In what has become the agricultural area, there was a balance between rainfall, water use by the native vegetation, and recharge to groundwater. As a result, salinity only occurred at particular locations in the landscape. Groundwater was generally below the root zone and rivers were able to carry any surface salt to the sea. However, clearing of the native vegetation since European settlement has tipped over this delicate balance and caused increased recharge, which led to rapid rise in groundwater tables and increased groundwater discharge to streams. In addition to the clearing, the increased regulation of river flows and the diversion of water for irrigation have significantly reduced natural dilution in streams. All these changes have contributed to dryland salinity. Understanding of the processes responsible and developing applicable knowledge is an important step toward sustainable management strategies.

There is also a major impact on stream flow as streams which were ephemeral under the native vegetation regime, have become permanent or at least flow for much longer periods. Groundwater contributed baseflow is now a significant part of the flow source for these streams and it is salty. As a result of the shallower saline watertables, evaporation at the soil surface brings salt to the surface through capillary rise, and accumulates in large white crusted salt scalds. When rain falls the surface accumulations of salt wash off and are rapidly transported to the stream. Additionally, the shallow watertable means that the infiltration capacity of catchments is reduced and the runoff/rainfall ratio increased. There is also the likelihood of increased “quickflow” contributing to increased flooding frequency and increased flooding height.

Preliminary analysis has identified that stream flow regimes will be impacted by rising watertables, as saturated areas increase and infiltration is reduced

(Bowman and Ruprecht, 2000). The result of this increases the likelihood of 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 has increased the total salt load of streams, the average stream salt concentrations, as well as the timing of salt input to streams, and its conjunction with flow events. Dryland salinity is a catchment scale problem developed over a period of decades. The consequence of this is that 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.

This project aims at developing a model which will predict the change in flow regime due to elevated watertables accompanying dryland salinity, and thence the likely impact proposed changes may have. This report catalogues results from analysis of streamflow and salinity trends in response to clearing and the accompanying rise of the watertable in five small catchments (0.8-3.4 km^2). We have been able to trace the increase in saturated area with the change in flow regime and particularly annual peak flows. 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. We relate the change in groundwater discharge and saturated area to changes in the streamflow regime, and to changes in flood flows.

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

- Using data from well monitored catchments, initially small ones, and test and generalise the relationships between land salinisation, groundwater discharge, and stream flow, including summer flood events. In particular, to examine the influence of the rise in watertables that has accompanied agricultural development on floods on an annual and longer recurrence period.
- Use a simple model relating groundwater level to saturation area to explore the observed relationships between groundwater tables and discharge on flooding and flow regime, namely how changing water tables and discharge will impact on saturation area, peak flow, base flow, and flood frequency.

In this report we analyse daily rainfall, runoff, salinity and groundwater level data from a number of small catchments, specifically instrumented to study the effect of clearing on stream salinity. The aim is to determine causal relationships in the data, thereby enabling the development of a new model that will be able to predict the future trends in stream flow regime and salinity. While flow mechanisms are broadly understood, quantification of flow through the different pathways remains problematic. In particular, we are some way from achieving a model that adequately represents flow on a wide range of catchments, without considerable calibration.

This paper reports the results of the data analysis, with model development to be reported in a later document. The work described here aims to assist this quest with some detailed analysis of data from amongst the best monitored catchments in Australia. Unfortunately, monitoring has ceased at several of the catchments used, and this has consequences for the ultimate interpretation of the data. The key questions addressed in this report are:

1. Is there a change in flood flow over time comparing the cleared and the still forested catchments? If so, is the relationship to saturated area clear.
2. What is the trend of salt export from the catchments? What is the time to salt exhaustion and stream quality recovery?

2. Literature Review

Recent work in the Cooperative Research Centre for Catchment Hydrology (CRCCH) by Zhang *et al.* (1999) has enabled the estimation of the impact of vegetation changes on long-term average water yield, based on factors that are easily measurable at the catchment scales. This uses a so-called ‘top-down’ approach that links the catchment response to our understanding of processes at finer scales. Models of this type are practical; much less data intensive than ‘bottom-up’ approaches, and in principle much easier to apply. This method has been applied to the Murrumbidgee catchment by Vertessy and Bessard (1999), enabling an investigation of the impact of wide scale afforestation in that catchment. However, their success in predicting catchment response across a range of catchment issues and types is unproven. This approach also gives a highly synoptic view of catchment behaviour. The model does not say anything about short term hydrology, such as seasonal runoff, inter-annual variability, and certainly not storm event runoff.

The recent adoption of a catchment categorisation approach to salinity control also enables further developments. There have been a number of intensively studied catchments in Australia, however because of the variation in function of these catchments with respect to salinity, it is not easy to interpolate understanding of processes and hence management between these intensively studied catchments. Under a RIRDC-funded project, hydrogeologists from around Australia agreed on a catchment categorisation that was relevant to salinity management (Coram, 1998). In the National Land and Water Resource Audit (NLWRA), a map at the national scale of the different catchment types has been produced by the Bureau of Rural Science (BRS). In the Catchment Categorisation Project, the development of groundwater models, information and management options relevant to each catchment type are being produced.

Clearing of native vegetation has led to changes in catchment water balance. Most catchments that have been cleared show rising groundwater tables as a result of increased recharge. In many cases the watertable is so close to the surface that there is an increase saturated areas and hence an increase in runoff generation and, potentially, flooding. Studies have shown that increased dryland salinity could also significantly increase flood risk and damage to farmland, roads, and buildings. A recent study showed that increased dryland salinity could significantly increase peak flows of flood events and flood risk (Bowman and Ruprecht, 2000). It identified some key factors that should be considered in estimating the effects of salinity on flooding. The study used the urban runoff model URBS to simulate flood flows. They simulated expanding saturation areas by varying the loss parameters in selected subcatchments in the model. Results from this study could be improved with better process understanding of the relationships between land salinisation, groundwater discharge, and runoff and catchment scale salinity information. It is important to quantify the impact of clearing and dryland salinity on flood regimes in order to develop management strategies. Improved understanding of relationships between elevated watertables and flooding will assist development of management strategies to minimise damage to key assets of infrastructure and agricultural production.

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, 1967; variable source area-overland flow – Dunne and Black, 1970) little work 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 stream flow, 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) streamflow increased by 30% within about 6 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 stream flow and rainfall had been reached within about 6 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 "returnflow" or exfiltration) and saturation excess overland flow in winter, and infiltration excess in summer. They did not elaborate on which of the pathways supplied the majority of salt reaching the stream.

3. Methodology

This work has focussed on analysis of storm hydrographs, groundwater trends, expanding saturated areas, and stream and groundwater salinity in a number of catchments in south-west Western Australia. All data has been supplied by the Western Australia Water and Rivers Commission for the Collie River basin research catchments, with the exception of catchment digital elevation models (Dept of Land Administration, under the LandMonitor Programme) and regolith descriptions (Jasmine Rutherford, personal communication). In each catchment piezometer data have been analysed to give estimates of the change in catchment groundwater storage and of saturated area through time. From daily rainfall, streamflow, and salinity data we have analysed for the rise in stream flow following the rise in groundwater after clearing.

Although we do not dwell on them in this report, flow frequency curves have been developed for each catchment, and using the control forested catchments, these have been analysed to attempt to parameterise the curves in terms of climatic drivers. A parametric expression is used to describe the flow frequency curves. This work is discussed in detail in a companion report (Silberstein *et al.*, in prep). Here we focus on the relationship between low frequency (high flow) events and catchment water storage and saturated area.

Finally a simple model is used to analyse stream flow after the catchments have reached a new hydrologic steady state, when the watertable has stopped rising and recharge equals groundwater discharge, and predict salt flushing times, and hence recovery of stream water quality.

3.1 Catchment Description

Analysis commenced on seven small catchments within the Collie River Basin, south-west of Perth. Five of the catchments were established in the early 1970's as experiments to study the impact of clearing on stream flow and salinity. They were set up as: a pair at high rainfall (1120mm) (Salmon and Wights) and a triple at intermediate rainfall (710mm) (Ernie, Don and Lemon). One of each group was retained as forest (Salmon and Ernie), and the others were cleared, at least partially (see Table 1 for details). The clearing took place in the summer of 1976/77. Two catchment experiments were set up to study the effect of reafforestation, one at Maxon Farm on Batalling Creek in 1974, with the planting occurring over 1985-7, and at Maringee Farm on Mairdebing Creek, which was planted, and gauging commenced, in 1981/2. Daily pan evaporation from Collie were taken from the Bureau of Meteorology Patched Point Dataset (http://www.bom/gov.au/silo) have been used to estimate evaporation across the catchments.

Table 1 gives the main details of the catchments, including catchments that have been analysed but have not yielded clear results. This lack of clear result is generally due to the catchment size, sporadic nature of the clearing history, and lesser amount of monitoring, particularly of groundwater level and salinity, and relatively short gauging history in comparison to the size of the catchments.

3.2 Saturated Area

Within each catchment, the saturated area through time is calculated by fitting a groundwater surface to piezometer hydrographs, and comparing this to a digital elevation model (DEM) of the catchment. Up to 70 piezometers were installed in each of the research catchments in 1974, and monitored for water level and salinity every few months ever since. The base of the deep bores was used as the estimate of the bedrock surface, even though in many cases the drilling did not strike actual basement. This is not a severe handicap because we are mainly interested in changes rather than absolute measures of water storage. The groundwater surface is used to determine an estimated total water storage in the catchment, based on the "saturated volume" between the watertable and the bedrock, and an estimate of specific yield for the regolith. Specific yield is used rather than total porosity because, firstly, we are assuming that the regolith is close to field capacity through most of its depth, and secondly, we are mainly interested in the changes in storage which produce changes in saturated area and ultimately streamflow. The estimate of specific yield will be

Table 1 Catchment details

Stream	**Station Name and Number**	**Catchment Area (km^2)**	**Area Cleared (%)**	**Mean Annual Rainfall (mm)**	**Period of Record**	**Salt Storage (kg/ha)**
Bingham River Tributary	Don 612007	3.50	40% (strip and parkland cleared, 1976/77)	710	1974-1997	590,000[a]
Bingham River Tributary	Ernie 612008	2.68	0	710	1974-1997	590,000[a]
Pollard Brook Tributary	Lemon 612009	3.44	50% (lower half cleared, 1976/77)	710	1974-1997	590,000[a]
Salmon Brook Tributary	Wights 612010	0.94	100% 1976/77	1120	1974-1997	127,000[a]
Salmon Brook	Salmon 612011	0.82	0%	1120	1974-1997	127,000[a]
Mairdebing Creek	Maringee Farm 612026	12.75	54%, reducing to 44% by replanting 1981/82	630	1982-1997	1,200,000[b]
Batalling Creek	Maxon Farm 612016	16.6	51% in 1977 30% after 1987	640	1982-1998	1,200,000[b]
Collie River	Mungalup Tower 612002	2545	24%	759		
Denmark River	Kompup 603003	239.8	34%	750	1974-2000	42200[c]
Yate Flat Creek	Woonanup 603190	57.02	60%	750		
Denmark River	Lindesay Gorge 603002	473	1%	860		
Denmark River	Lot 2135 Denmark 603014	572.7	2%	860		
Denmark River	Mt Lindesay 603136	532.3	2%	880		
Denmark River	Clear Hills 603173	229.4	15% (began in 1950s, cleared area peaked 1977)	750		
Wooroloo Brook	Karls Ranch 616001	536	40%	910		70896[d]
Brockman River	Tanamerah 616006	958.3	40%	910		87776[d]
Brockman River	Yalliawirra 616019	1514	30%	880		87776[d]
Lake Ace	Spencers Farm 615016	185	100%	330		
Lake Ace	Hatters Hill 615017	54	100%	320		
Lake King Creek	Gardner 615018	78.01	100%	340		

a Johnston, 1987
b Bari, 1982
c Johnston *et al.*, 1980
d Calculated using baseflow salinity as estimate of groundwater salinity, from data supplied by Water and Rivers Commission

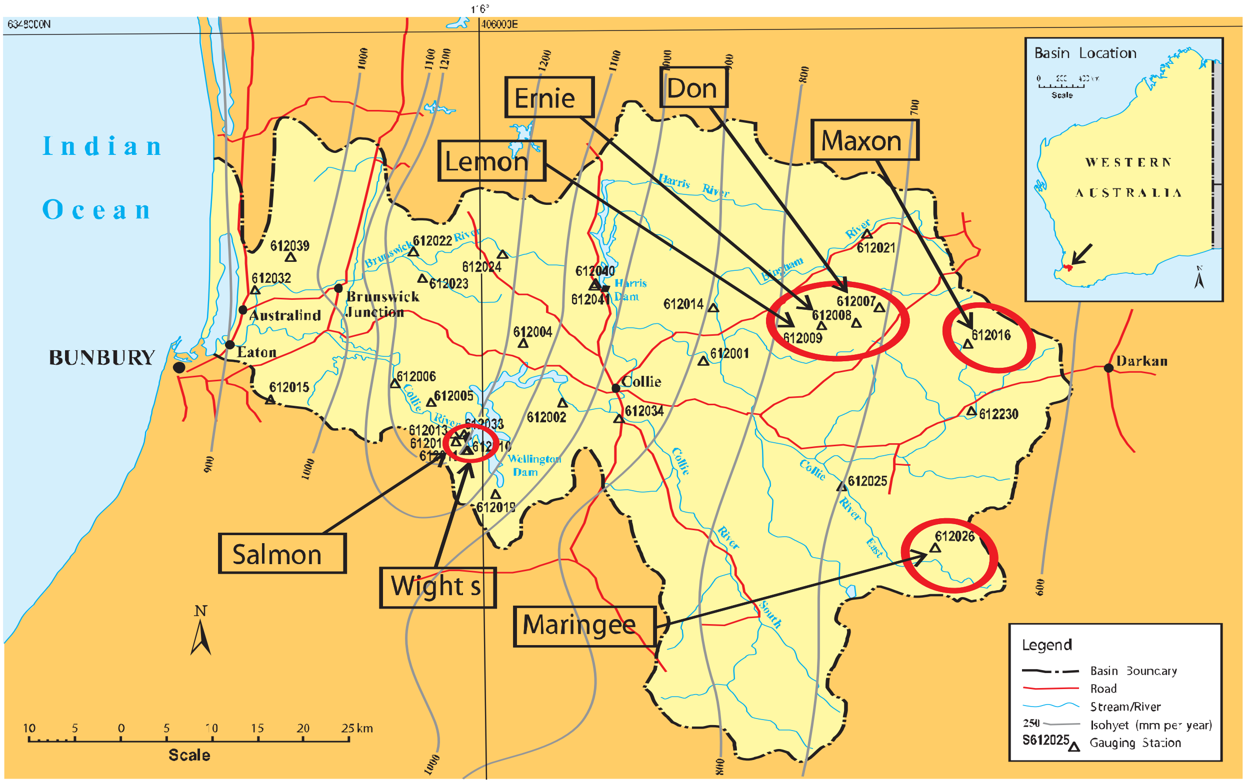

Figure 1 Location of Collie River basin in Western Australia, and the seven research catchments used in this study. (Figure compiled courtesy of Water and Rivers Commission).

Table 2 Catchment bore and regolith details.

Station Name and Number		No. of bores	Period of Record	Average Depth of Regolith (m)
Don	612007	95	1972-2001	31.2
Ernie	612008	38	1972-2001	Not determined
Lemon	612009	72	1972-2001	26.9
Wights	612010	43	1972-2001	32.1
Salmon	612011	39	1972-2001	Not determined
Maringee Farm	612026	89	1982-2001	Not determined
Maxon Farm	612016	40	1974-2001	Not determined

refined when drilling some new cores is completed. The number and period of record of bores in catchments analysed thus far are listed in Table 2. Also given in Table 2 are the average regolith depth determined between the fitted surfaces of the bedrock and the topographic surfaces of the catchments where sufficient data were available.

3.3 Streamflow Analysis

The streamflow data are analysed to determine annual flow frequencies. This has some inherent problem because the annual flow series are not always very long. In particular, the low rainfall control, Ernie, did not flow in 8 out of the 24 years of flow record, and

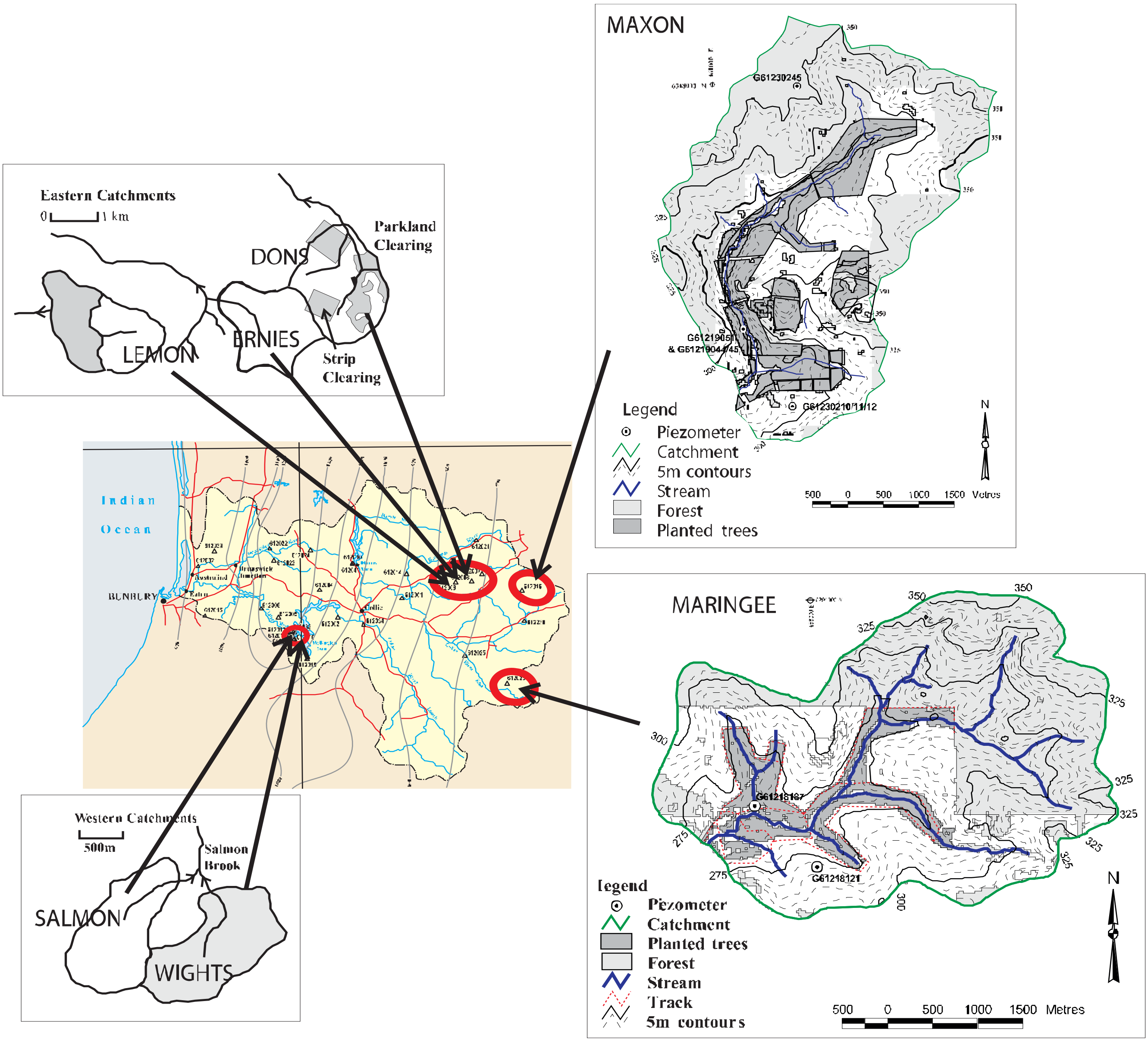

Figure 2 Layout of the clearing and reafforestation in Collie research catchments. Cleared areas are shown shaded, reafforestation is inside cleared areas at Maxon and Maringee farms.

(Figure compiled courtesy of Water and Rivers Commission.)

Lemon and Don did not flow during low rainfall years early in the period of record. However, despite these problems it is still possible to determine the flow statistics and present the trends over time. The flow data are analysed for each of the 100 percentile flows, and temporal trends shown and discussed in the next section. Annual flood flow is defined as the maximum daily flow rate occurring within each year, which is zero in years of no flow.

3.4 Catchment Salt Export and Stream Salinity Recovery

We use three methods to estimate a stream recovery time for the cleared catchments. Firstly, estimating the total water storage in the catchment, S_g, from bore levels and assuming all the baseflow (determined from hydrograph separation) equates to groundwater flow, *G*, we can calculate a groundwater "turnover time" (= S_g/G). This is analogous to the method used by Peck and Hurle (1973) to estimate equilibration times for several Western Australia catchments. Secondly, using salt concentration data from cores taken in drilled holes in each catchment, we can estimate a total salt storage within each catchment. Using the salinity of the groundwater, c_g, and of the stream, c_s, we can use an analogy of a dilution gauging technique to estimate groundwater export fluxes, ($G = Q\, c_g / c_s$ where Q is the streamflow, and we are neglecting any input of salt from rainfall and surface runoff) we can get another estimate of a salt "turnover time". The two estimates of turnover time would be the same if both the salt and water were uniformly mixed through the regolith and leaching happened uniformly across the catchment. However, because much of the salt is bound in unsaturated regolith, and because the parts of the regolith that are being actively leached through preferential flow pathways, the groundwater turnover time is likely to be less than the salt turnover time.

A third estimate of recovery time can be taken from the time trends in flow weighted salinity in the streams, although without assuming *a priori* a conceptual model of the catchment this cannot be used to forecast, and may need long periods of record to determine.

Hatton *et al.* (2002) used these three methods to estimate recovery times for a number of catchments in Western Australia, and compared the results with a simple storage and discharge model. The model chosen is effectively the simplest model available, namely a linear storage model, with outward flux directly proportional to the storage. The model gives a simple but robust estimate of the time to reach a target salt load and flow concentration in a given stream, based on known or estimated catchment storages. Gilfedder *et al.* (2001) used dimensional analysis to develop an alternative model of the groundwater balance of a catchment, and which includes a slightly more detailed representation of groundwater processes but not the salinity dynamics. In gaining the detail they introduce more catchment parameters that require estimation and complexity unwarranted in the current application. We are concerned with estimating the timescales for groundwater flux and salt export to streams, and particularly the recovery of stream salinity to some usable level, as salt loads reduce over time.

The model assumes the catchment is a bucket filled with soil. Water stored in the regolith matrix is assumed to be uniformly distributed throughout the profile, and salt is uniformly distributed throughout the water. Groundwater discharge occurs at a rate directly proportional to the water storage and salt export is assumed similarly to be proportional to total salt storage. This is a standard linear reservoir model. All fluxes are defined with respect to annual time units. Once the catchment has reached its new hydrological steady state, assuming stationary climate with no further increase in water storage possible, the result is that salinity of the stream is an exponentially decaying function of time:

$$c_s(t) = \{G_e\,[(c_{ge} - c_I)\exp[-(G_e/S_{ge})(t - t_e)] + c_I] + c_p R\}/(G_e + R) \tag{1}$$

where t is time and t_e is time of reaching the new hydrologic steady state, and flux terms are :

R = surface runoff

G_e = groundwater flow out of catchment at hydrologic steady state, at which it is assumed net infiltration equals groundwater discharge.

Storage terms are:

S_{ge} = total quantity of water storage in the catchment regolith at the new steady state – assumed to be saturated

Salt concentrations:

c_p = salt concentration in net precipitation

c_I = salt concentration in net infiltration, this is the concentration in precipitation increased by evaporation at the surface and from the canopy, and transpiration

c_{ge} = salt concentration in groundwater discharge, G_e

c_{se} = salt concentration in the stream

Now of interest here is the time, $\boldsymbol{t_+}$, for a salinised stream to drop to some designated concentration, $\boldsymbol{c_+}$.

This might be a potable limit, say 500 mg L^{-1}, or something suitable for stock or an industrial application. The above equation can be rearranged (and natural logarithm taken) to give:

$$(t_{+}- t_{e}) = (S_{ge}/G_{e})\log[(c_{ge} - c_{I})/[c_{+} - c_{I} + (c_{+} - c_{p})\ R/ G_{e}]] \qquad (2)$$

The results of these calculations for the cleared research catchments are given later in this report.

4. Results

The focus of this report is to identify the relationships between saturated area and high flow events. For this purpose we define "flood flows" as simply the highest daily flow (low exceedence probability) events recorded during the period of record. Saturated area develops because water storage increases over time when the recharge rate is greater than the discharge rate. By analysing both the increase in groundwater storage and the change in flow regime we expect to be able to elucidate the relationship between them. This is not a simple process because the regolith properties and topography both influence the area saturated for a given water storage.

4.1 Changes in Water Storage After Clearing

By determining watertable surfaces from the available bore data and projecting this onto available and estimated bedrock data, we have been able to estimate the progressive increase in water storage within the catchment regolith over the 24 year period of record. This is plotted (Figure 3) as "saturated volume" expressed as a proportion of total regolith volume between the soil surface and the estimated bedrock surface, hence "saturated volume fraction". This is effectively the average saturation in the catchment regolith. Williamson *et al.* (1987) found that moisture content in the unsaturated zone increased before there was any rise in the watertable, so strictly this extra moisture should be added. A number of differences between the catchments are evident from Figure 3, particularly that Wights started the period at about 40% saturated. This is consistent with the observation that the Wights catchment had a seep even before clearing. Converting the "saturated volume" calculation to actual water storage requires estimates of specific yield, distributed throughout the regolith. (Note comments on use of specific yield made earlier). A value of 5% is seen as reasonable for these regolith materials (Bettenay *et al.*, 1980). The total rise in water storage in each catchment from pre-clearing to 2001 is given in Table 3, as well as the recharge rate calculated from the period of most rapid rise. It is interesting that the saturated water storage has increased by similar amounts in each of the 3 cleared catchments over the period. The rate of rise of water storage (Figures 3 and 4) has been different through time, with saturation rising most rapidly after an initial slow period and slowing as the catchment approaches a maximum saturation level. Once the watertable reaches the surface, there is effectively no recharge over that area, as any rainfall would immediately runoff to the stream as saturation excess flow.

To estimate the rate of net recharge we only consider the period of more or less constant, and most rapid, rate of increase. This gives us values of net recharge in Table 3. Because only 50% of Lemon and 40% of Don catchments were cleared, and it is reasonable to assume recharge under the natural forest is negligible, the actual rate of recharge in the cleared area is

Table 3 Catchment water storage details.

Station Name and Number		Rise in Water Storage (mm)	Maximum Rate of Catchment Net Recharge (mm/yr)	Maximum Rate of Cleared Area Net Recharge (mm/yr)	Cleared Area Net Recharge as % of Rainfall
Don	612007	320	25	65	9.5
Ernie	612008	0	0	0	0
Lemon	612009	360	35	70	10.2
Wights	612010	400	49	49	4.9
Salmon	612011	0	0	0	0
Maringee Farm	612026	ND	ND	ND	ND
Maxon Farm	612016	ND	ND	ND	ND

ND = Not Determined

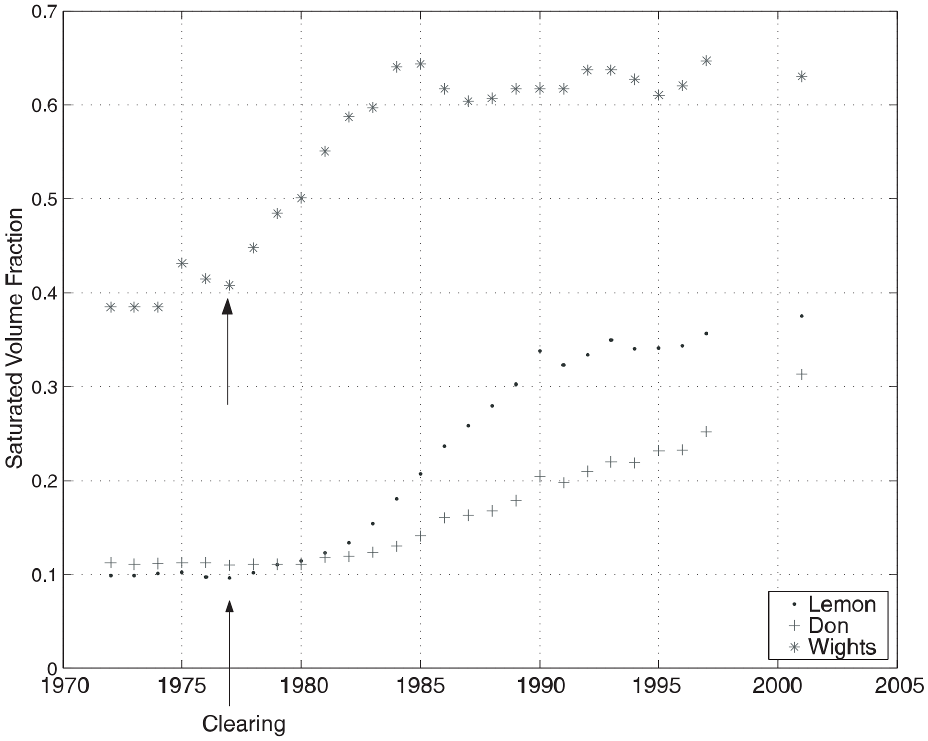

Figure 3 Estimated saturated volume as fraction of total regolith volume over time.

Figure 4 Estimated water storage per unit area in three catchments over time.

significantly higher than the catchment average. Given uncertainties in the data analysis, and regolith properties, the values for Don and Lemon are not considered significantly different.

At the time of writing, the time development of saturated area is only available for Lemon catchment (Figure 5), but will be developed for Wights in the near future. There is virtually no saturated area in Don, as the watertable has only recently reached the surface. The area of Lemon catchment is 3.44 km^2, so by 1996 9% of the catchment was permanently saturated.

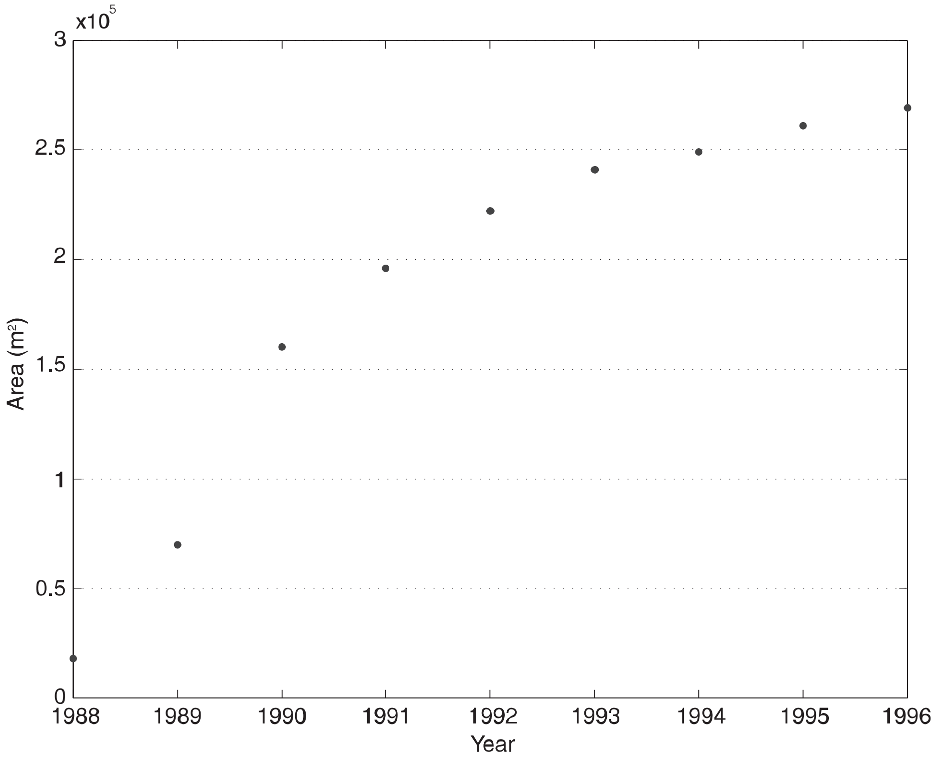

Figure 5 Permanently saturated surface area of Lemon catchment over time, after 1987 when the watertable first reached the surface.

4.2 Runoff Coefficient

The proportion of rainfall that becomes stream flow (runoff coefficient) has increased as a response to clearing, and continued to increase through time in the cleared catchments (Figures 6 and 7). While there is no trend in the flow to rain ratio over the period in the forested control catchments (Ernie, Salmon), Lemon shows a trend in increasing ratio for the whole period of time, and Wights increased very quickly, taking only 6 years to reach its new ratio of 0.4, over the forest value of 0.1. Although the runoff coefficient of Don is greater than Ernie, it increased in the first few years after clearing, it has not shown an increase after that. The reason may be that the strip and parkland clearing are maintaining a relatively deep watertable and the only effect has been due to less surface cover, less interception loss and a reduction in infiltration capacity in the cleared areas. However, Figures 3 and 4 show clearly that groundwater storage is increasing and the watertable is consequently approaching the surface. It is presumably only a matter of time before the water reaches the surface and there is further impact on flow regime and an accompanying increase in stream salinity. Since the fractional groundwater storage in Don reached a similar level to Lemon in 2001, it might be expected that an effect will show in the streamflow and stream quality. Latest measurements have indeed shown an increase in salinity. Unfortunately 2001 was a very dry year, and there was almost no streamflow, and not enough to detect changes in flow regime.

The cleared catchments (Don, Lemon and Wights) show an increase in runoff ratio from the first year after clearing, 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. Lemon stands out from 1987 onwards with a dramatic increase in runoff ratio – 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 runoff coefficient of the low rainfall control catchment, Ernie, has stayed at around 0.01 throughout the period of record. The runoff coefficient of Don rose to 0.04 after clearing and has stayed there since. The runoff coefficient of Salmon hovers 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.

Figure 8 shows the runoff coefficient for the reafforested catchments. While there is no real trend in the data from Maringee Farm, it appears that the planting is having an impact at Batalling Creek (Maxon Farm). This is also seen in the salt load data discussed later. The runoff coefficient seems to be reducing from the mid-1990's, but 1996 was a very high runoff year at all sites, and must be seen in that context. The comparison between Maringee and Batalling shows that prior to 1990, the two had very similar runoff coefficients, but from then on Maringee had significantly higher runoff than Batalling.

The runoff coefficient is clearly a function of saturated area. The relationship for Lemon is shown in Figure 9.

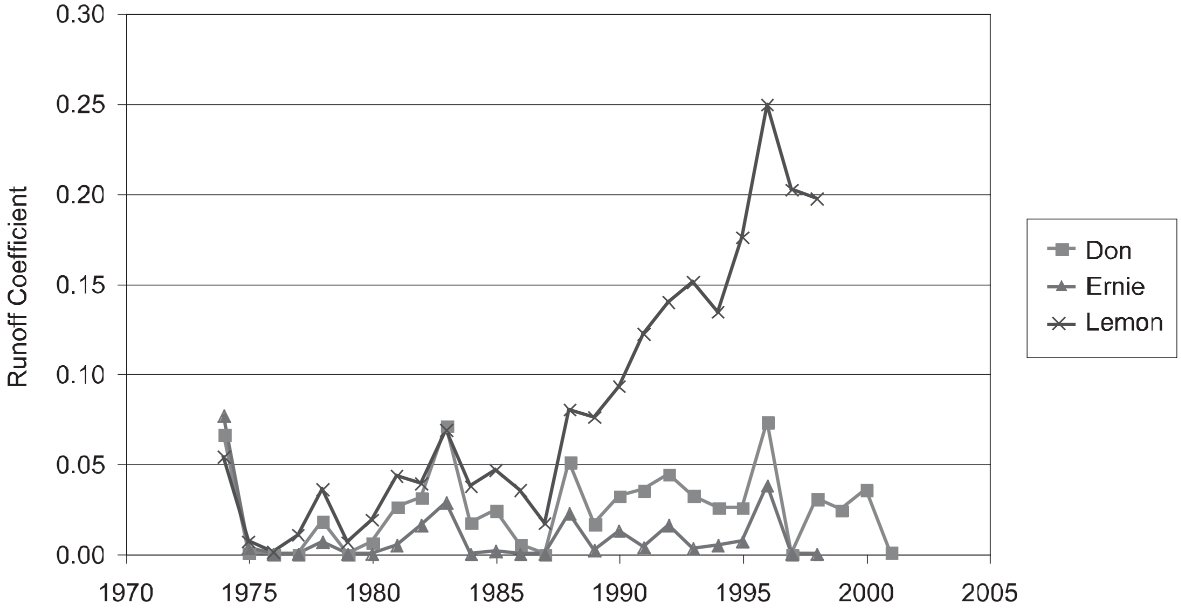

Figure 6 Runoff coefficient (ratio flow to rain) in Don, Ernie, Lemon catchments.

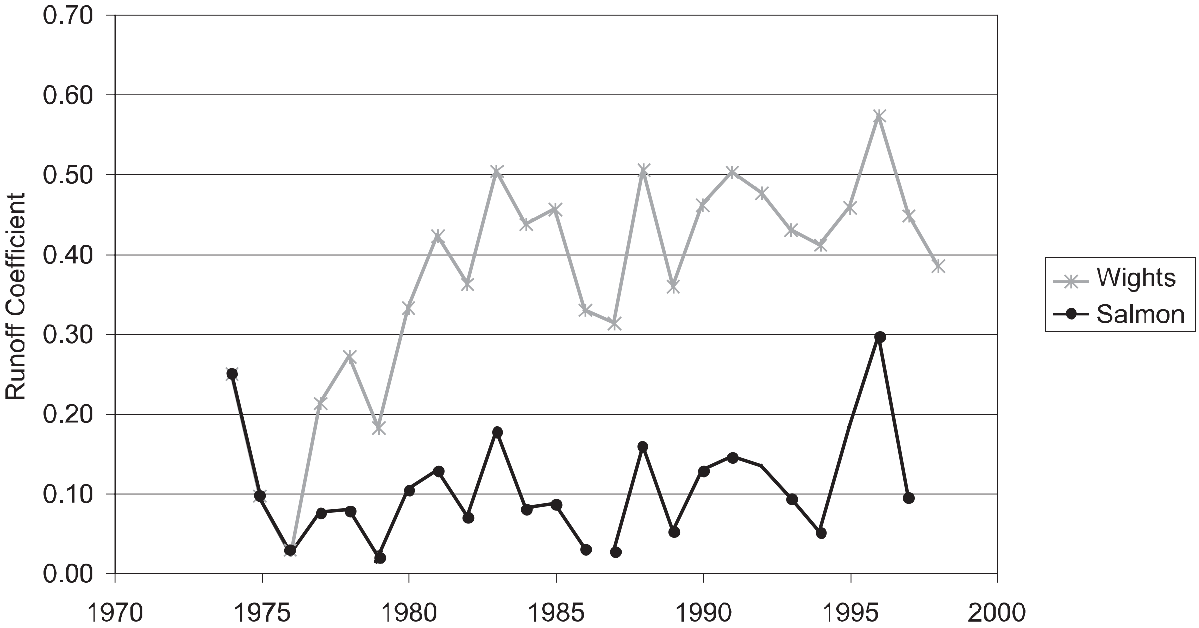

Figure 7 Ratio flow to rain in Salmon and Wights catchments.

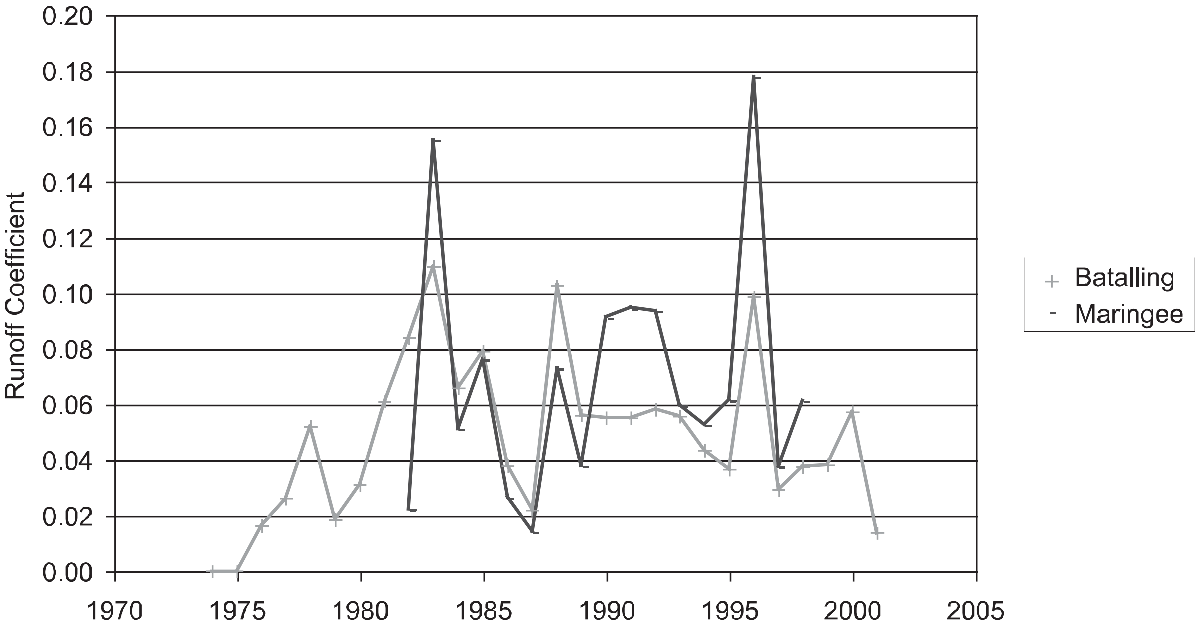

Figure 8 Runoff coefficient for Batalling Creek and Maringee Farm catchments.

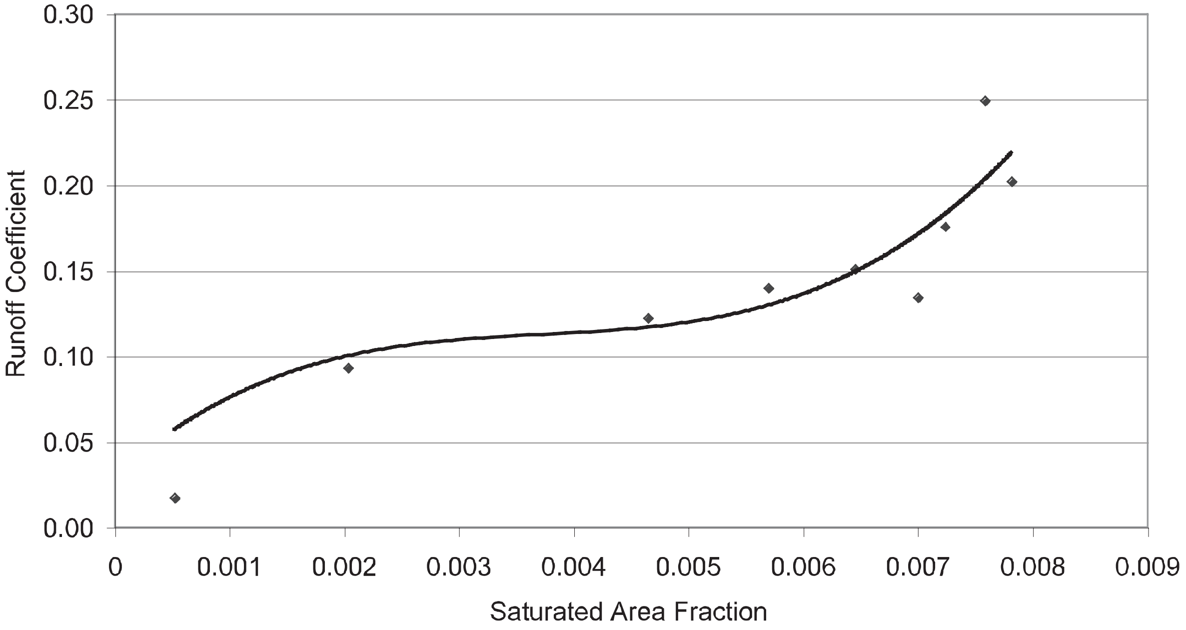

Figure 9 Runoff coefficient plotted against saturated area fraction in Lemon catchment.

The trendline shown has the equation $y = 1*10^6x^3 - 15000x^2 + 60x + 0.03$, with $r^2 = 0.84$. The best linear fit to these data is the line $y = 22.9x + 0.02$, with an $r^2=0.81$. Of course, both relationships tend to very large numbers in the limit as $x\rightarrow1$, and must be assigned an arbitrary domain of validity. The existence of such a relationship is obviously inherent in our understanding of runoff generation processes in catchments, and the fact that there is such a high statistical correlation is reassuring. However, the exact form of the relationship needs to be linked to physical structure within the catchment and the climate drivers to be generally useful.

4.3 Flow Quantiles

Figures 10-14 show a selection of flow quantiles for the five clearing experiment catchments. As is often observed, the major change to flow regime has been at the lower flows, rather than the peak floods. This puts the concerns about increases in non-extreme flows into some perspective. It means that perhaps the concern over increased flood damage may be unnecessary. However, the increased flow at lower levels, and the increased annual flood flow, means that while extreme events have possibly not been significantly affected, the more common, shorter recurrence interval events, have increased. For example, the median flow in Lemon catchment of the nine highest flow events in the last nine years is significantly higher than the equivalent in the first nine years (Figure 10). In comparison to Ernie catchment this is a significant difference. For example, what were once perhaps 90th percentile flows are now closer to median flows, whereas the median "flow" for Ernie is in fact no flow, as it flows less than half the time.

Figure 11 shows that while the 99th percentile flow in Lemon appears to have remained roughly stationary relative to Don and Ernie since about 1989, the lower percentile flows have continued to increase over the same period. Figure 12 shows that the increased in flow in Wights occurred much earlier than in Lemon. This is because the watertable was already intersecting the ground surface at the time of clearing, indicated by seepage present at the time. The watertable stabilised around 1984 and there has been very little increase in flow relative to Salmon since then (Figure 13). The 99th percentile flows for Salmon are equivalent to about 93rd percentile flows at Wights.

The relationship we seek is that between these flow percentiles and the development of water storage within the catchment and the associated saturated area. As shown in Figures 15 and 16 this is not so clear. Figure 15 shows the median (50th), 90th and 99th

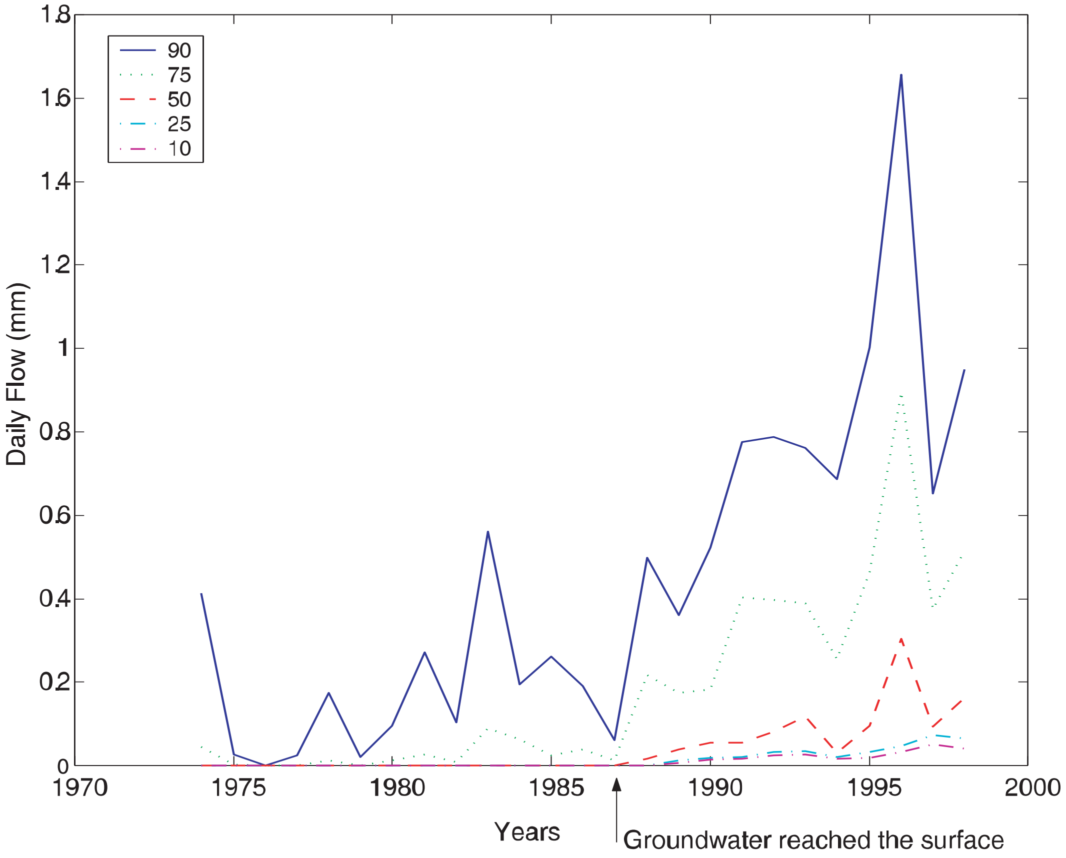

Figure 10 Time trend of selected daily percentile flows for Lemon catchment.

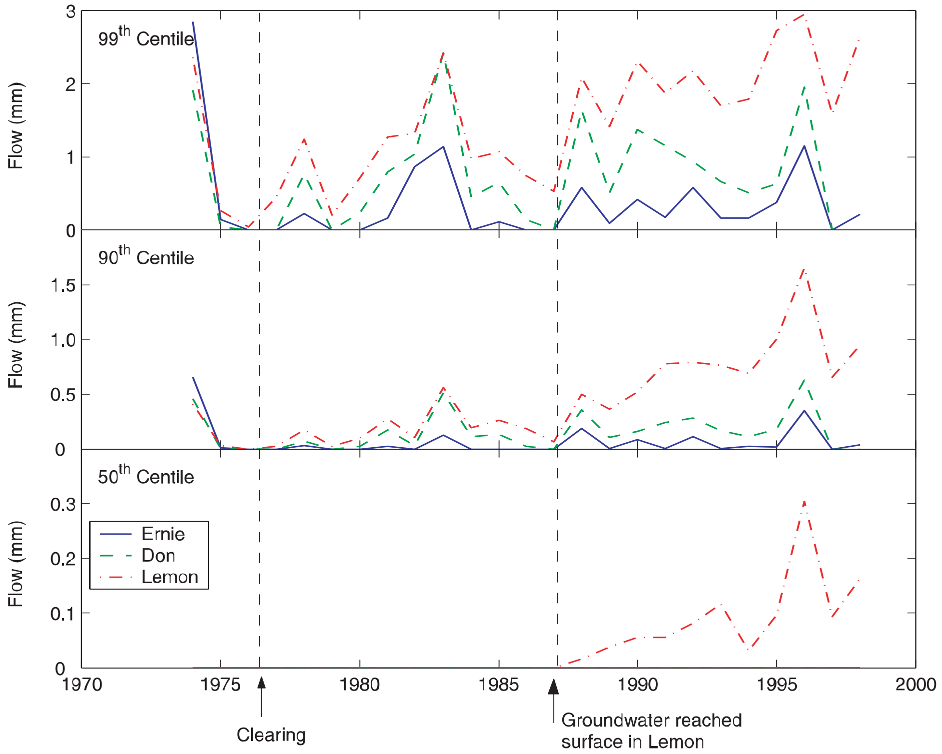

Figure 11 Time trend of 99th, 90th and 50th percentile daily flows for Don, Lemon and Ernie catchments.

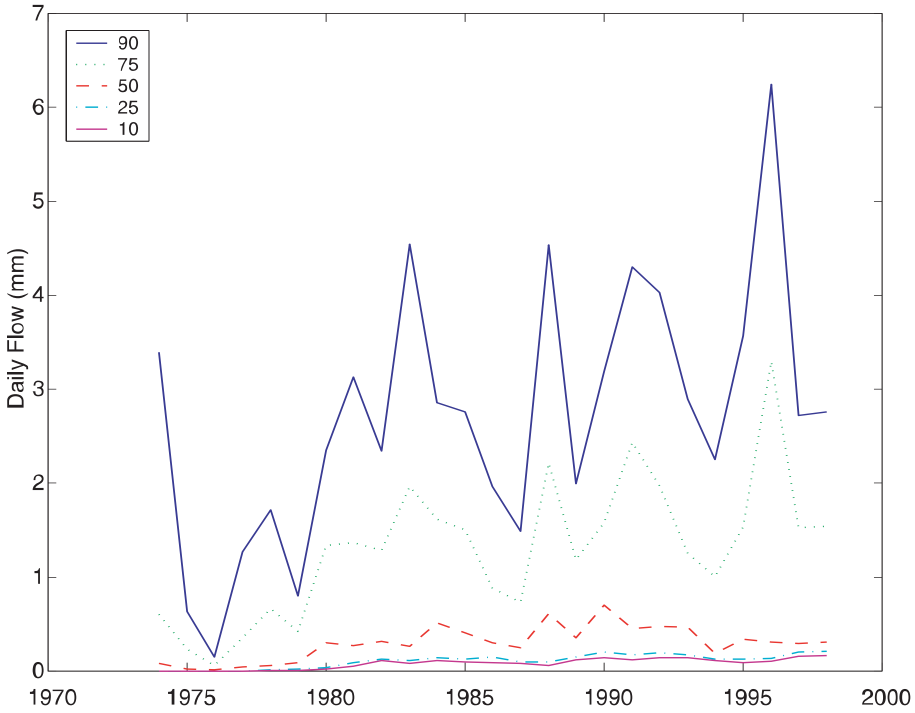

Figure 12 Time trend in selected daily percentile flows for Wights catchment.

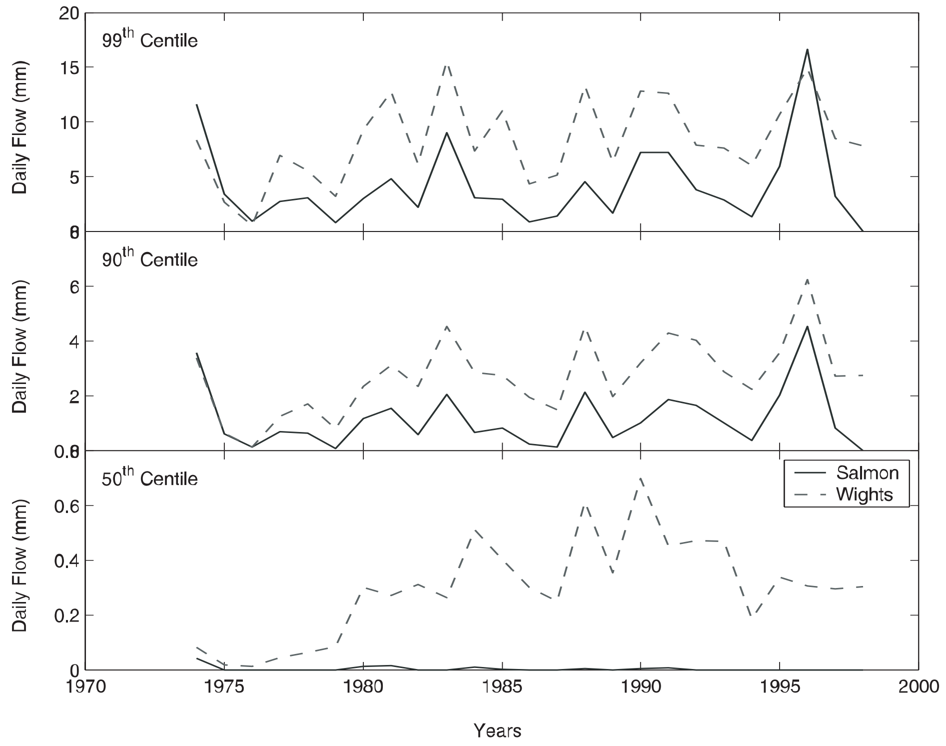

Figure 13 Time trend of 99th, 90th and 50th percentile daily flows for Salmon and Wights catchment

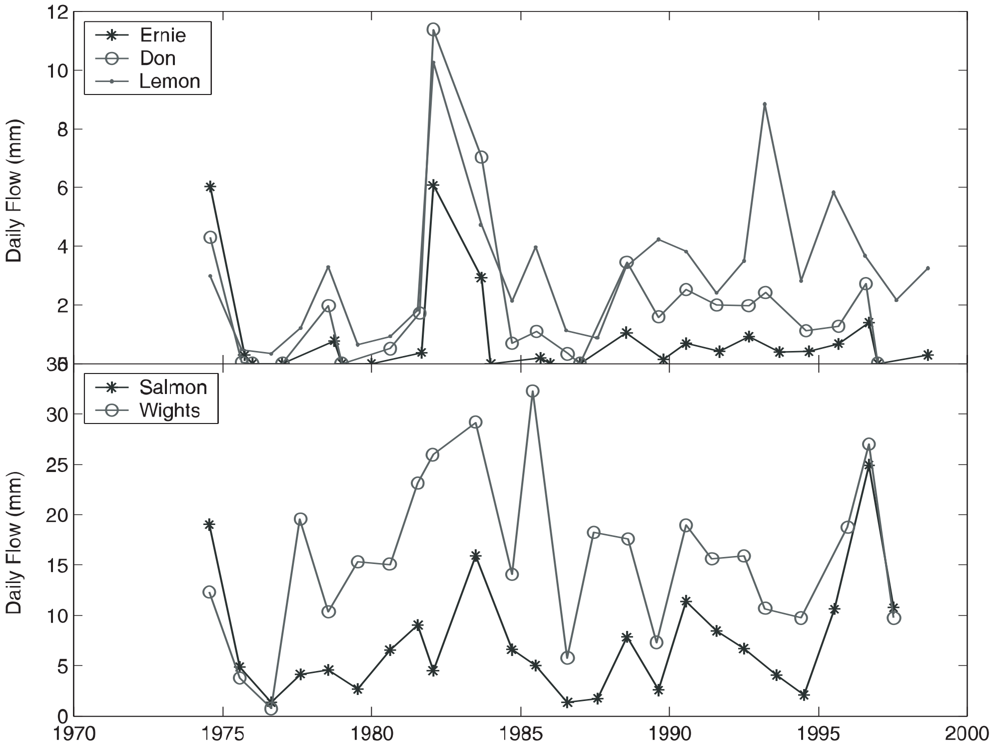

Figure 14 Annual daily flood flows for the five Collie research catchments.

percentile flows normalised by total yearly rainfall for Lemon catchment plotted against saturated volume, determined as described above. Contrary to that shown earlier for the whole season runoff coefficient (Figure 9), the relationship is not clear statistically.

The relationship is even worse when we do not normalise:

$Q_{99} = -0.000681 + 0.13364*\mathrm{Volume}$ $r^2 = 0.48$ (3a)

$Q_{90} = -0.000316 + 0.0481*\mathrm{Volume}$ $r^2 = 0.59$ (3b)

$Q_{50} = -7.854\mathrm{e}{-005} + 0.0067*\mathrm{Volume}$ $r^2 = 0.46$ (3c)

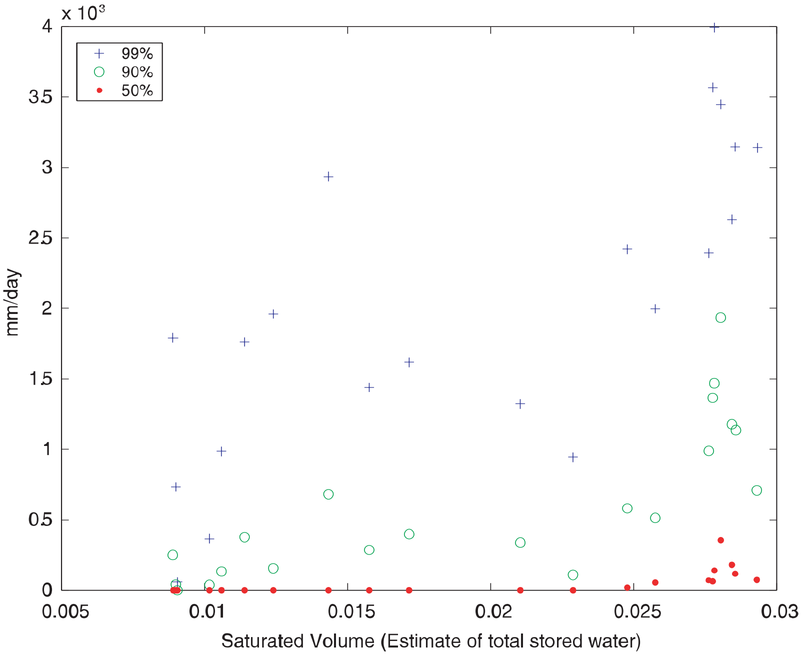

Figure 15 Runoff ratio for 50th, 90th, and 99th percentile flow plotted against saturated volume in Lemon catchment.

The relationship with saturated area is as follows:

$Q_{99} = 1.76*10^{-3} + 5.457*10^{-9}*\mathrm{Area}$ $r^2 = 0.58$ (4a)

$Q_{90} = 2.57*10^{-4} + 4.392*10^{-9}*\mathrm{Area}$ $r^2 = 0.73$ (4b)

$Q_{50} = -1.025*10^{-5} + 6.85*10^{-10}*\mathrm{Area}$ $r^2 = 0.38$ (4c)

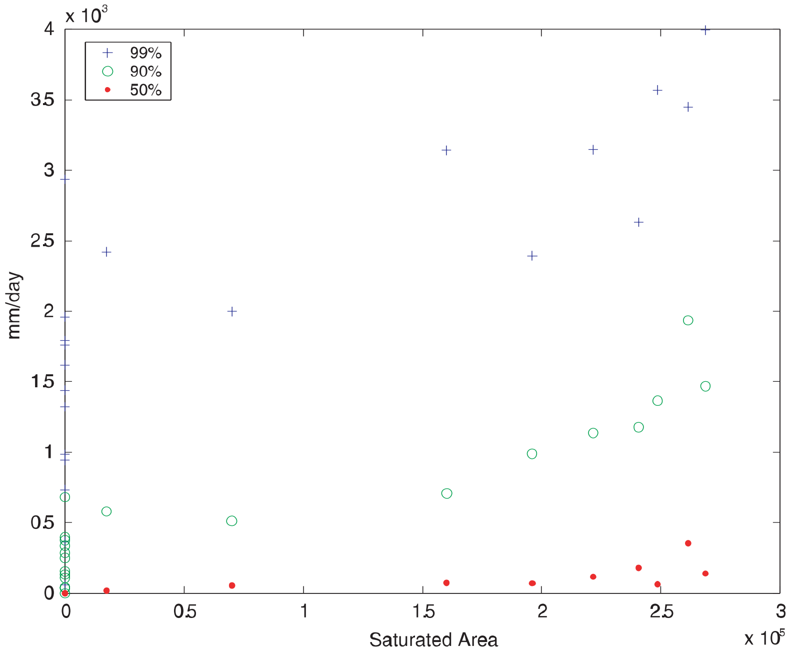

Figure 16 Runoff ratio for 50th, 90th, and 99th percentile flow plotted against saturated area in Lemon catchment.

4.4 Summary of the Effect of Clearing on Flow Frequency

Flow duration analysis is discussed in detail elsewhere (Silberstein *et al*., in prep), but a few main features are relevant to this discussion and are presented briefly below.

For all occurrence frequencies there is more flow in the cleared catchments and much fewer days without flow than in the catchments still forested over the same time period. These trends increase in time. There is much less variability in flow duration curves for Ernies than the other two catchments, although there are more zero-flow years (eight during the 14 year record).

The two cleared catchments both show a progression towards much longer periods of baseflow only, and as a consequence baseflow is a much greater component of total flow. 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 record. 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 it is anticipated that our modelling will eventually be able to predict this. The soil moisture storage in Don had just reached a similar level as in Lemon at the end of the record, and this has coincided with an increase in stream salinity (see Figure 20, although this is not discussed further here).

The Baseflow Index (proportion of total flow that is baseflow) has progressively increased in Lemon from a few years after the time of clearing, until perhaps the last two or three years of record when it appeared to flatten out. This is similar to the stream salinity trend which is discussed later.

4.5 Salinity in the Groundwater

The salinity in the deep bores in Lemon catchment is shown in Figure 18. All salinities in this paper are quoted as total dissolved salts, determined by electrical conductivity of water samples at 25°C and converted by calibration to mg L^{-1}. While most bores

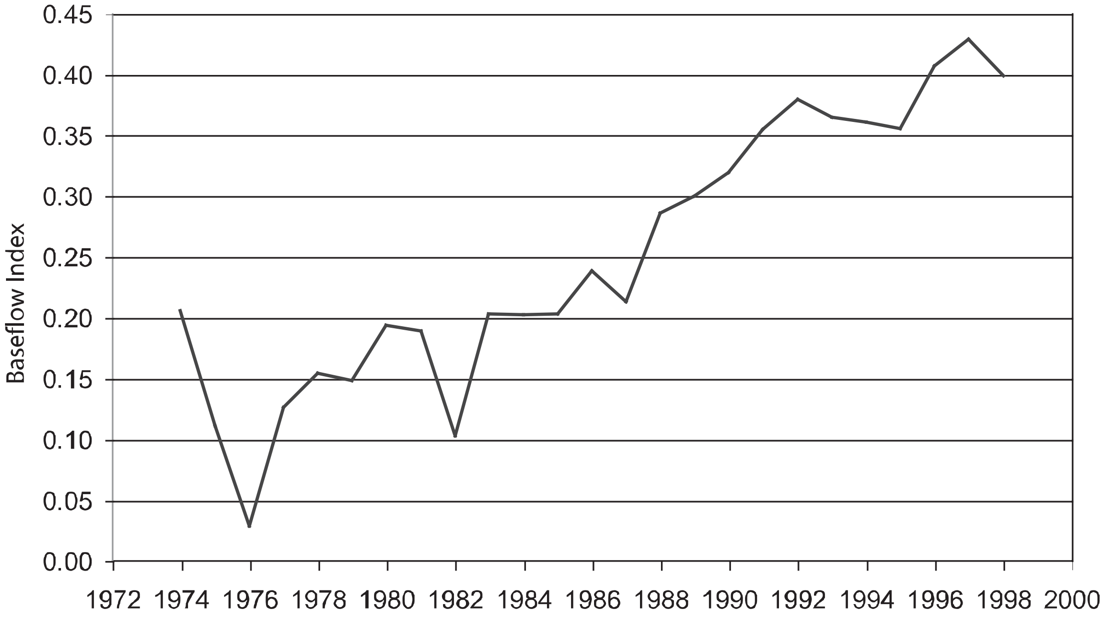

Figure 17 Annual average baseflow index at Lemon catchment. (Clearing occurred in 1977, watertable reached the surface in lower areas in 1988).

show little trend over the period, there are clearly a few that have decreasing salinity over time (bores 61218757, 61218740, 61218750, 61218751) in the Lemon catchment (1983-1997). It would appear that these few bores (on midslope positions in the catchment) are in zones of the catchment that are being preferentially leached. It is not yet clear how representative of the deep aquifer these bores are. We are soon to conduct some field measurements to estimate the salt mobility and the age of the groundwater in the bores to try to ascertain these effects.

Many of the shallow bores show an increase in salinity in time during the period 1988-1997 (Figure 19). This coincides with the watertable reaching the surface and the salinity of the shallow wells becoming similar to the deeper water.

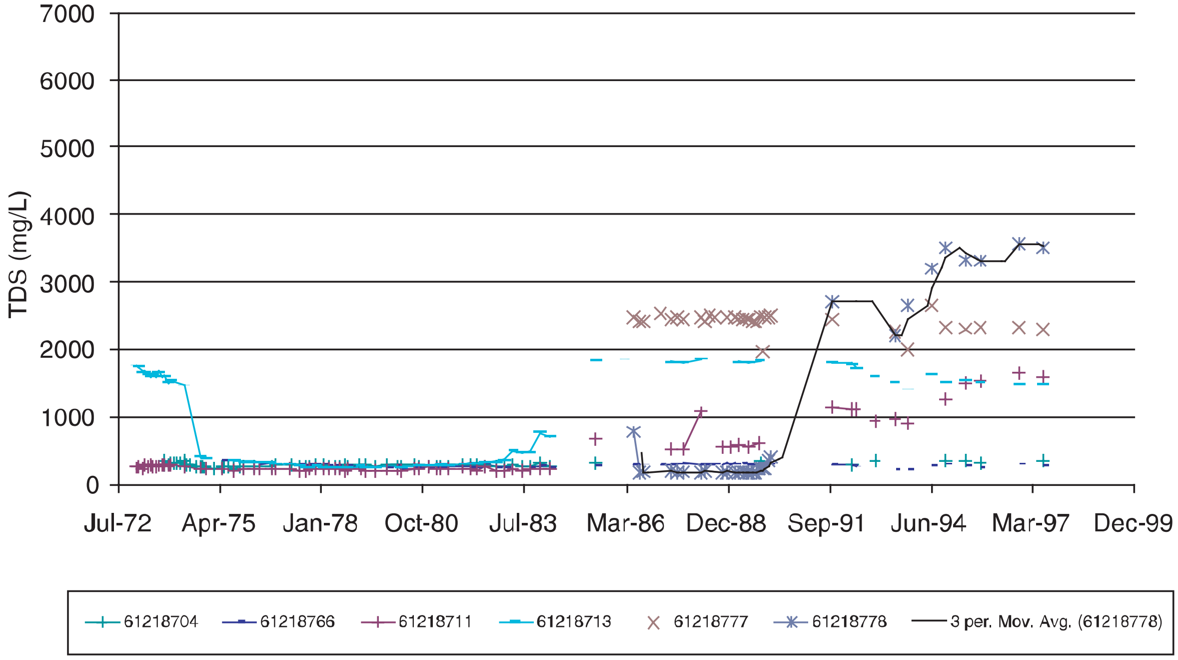

Figure 18 Instantaneous salinity (as total dissolved solids from electrical conductivity) over time in the deep bores in Lemon catchment.

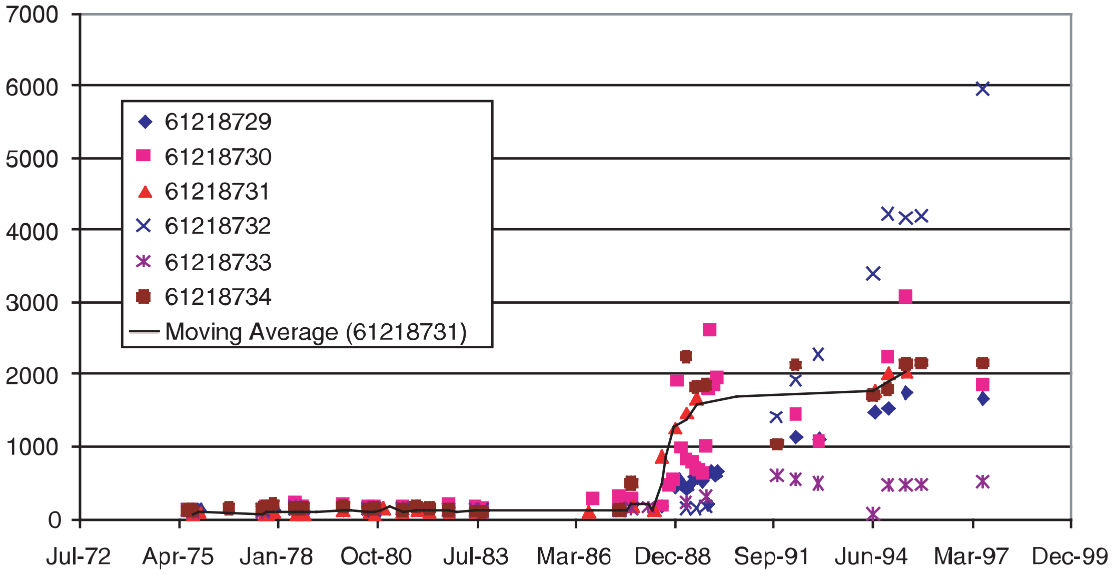

Figure 19 Instantaneous total dissolved solids over time in the shallow bores in Lemon catchment.

4.6 Salinity of the Streamflow

Annual flow weighted mean salt concentration is shown in three of the research catchments in Figure 20. The salinity of the forested controls has remained at around 100 mg/L throughout this period. The impact of rising watertables is clear in Lemon and Wights. Wights salinity increased within a few years after clearing, and has settled at around 500 mg/L. The trace for Lemon suggests that salinity was starting to level off in 1997 when gauging ceased.

The salinity of the Don stream has stayed low despite a rise in groundwater levels. However, Figure 20 shows that, coinciding with reaching a similar groundwater storage to that in Lemon (Figure 4), the salinity in the Don stream may have started to increase. It is too early to say whether this trend will continue.

independent of the long-term stream salinity and so flow regime will not be affected in the same way.

The catchment salt flushing rate is discussed in some detail by Hatton *et al.*, (2002), and suggests that the time to freshening of both Lemon and Wights streams is not excessively long (Table 4). The range of values given in Table 4 for flushing time reflect the different data and assumptions used by Hatton *et al.* (2002) to make these estimates. Salmon and Ernie catchments are still forested and are not expected to leach their salt, and in any case the streams are already less than 500 mgL^{-1} salinity. Maringee Farm and Batalling Creek are reafforestation catchments, expected to begin to bind their salt in situ.

Table 4 gives the amounts and proportion of total salt storage that has been flushed since gauging began in these catchments. The salt export methods calculated much longer flushing times than the groundwater balance methods (Table 4 and Figure 21). This is indicative of the heterogeneity of flow through the catchments. The variability from year to year (Figure 21) reflects the inherent variability in rainfall and recharge rate as well as the uncertainty in the measurements. Clearly the timescales for groundwater movement are significantly shorter than

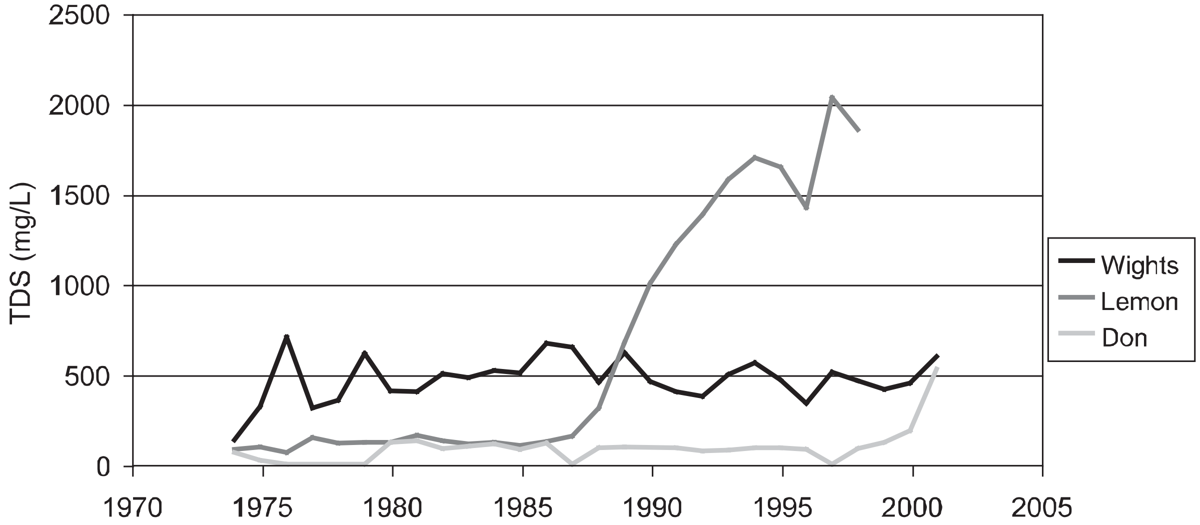

Figure 20 Annual flow weighted mean salinity in the streams in Lemon, Don and Wights catchments.

4.7 Catchment Equilibration Times

By taking data from cores drilled in 1973 we can estimate the total salt storage in the catchments at that time (Table 4). In combination with salt load in the stream, this gives an estimate of the flushing time for the catchment and hence a recovery time for the stream salinity. Of course, the elevated watertable is

Table 4 Salt flushed from Collie research catchments (from Hatton *et al*., 2002). The salt storage data are taken Table 1.

Station Name and Number	**Salt stored (t/ha)**	**Salt flushed 1974-97 (t/ha)**	**% flushed 1974-97**	**Time to reach 500mgL-1 (years)**	**Time to flush [Salt export method] (years)**	**Time to flush [Groundwater turnover] (years)**
Don 612007	590	0.39	0.1	100-1000	36,000	150-2600
Ernie 612008	590	0.16	0.03	Not applicable	Not applicable	Not applicable
Lemon 612009	590	17	2.9	20-200	800	30-270
Wights 612010	127	41	32.0	4-20	720	30-120
Salmon 612011	127	8.5	6.7	Not applicable	Not applicable	Not applicable
Maringee Farm 612026	1,200	32 (1982-97)	2.7	Not determined	570	600
Batalling Creek 612016	1,200	36	3.0	Not determined	800	600

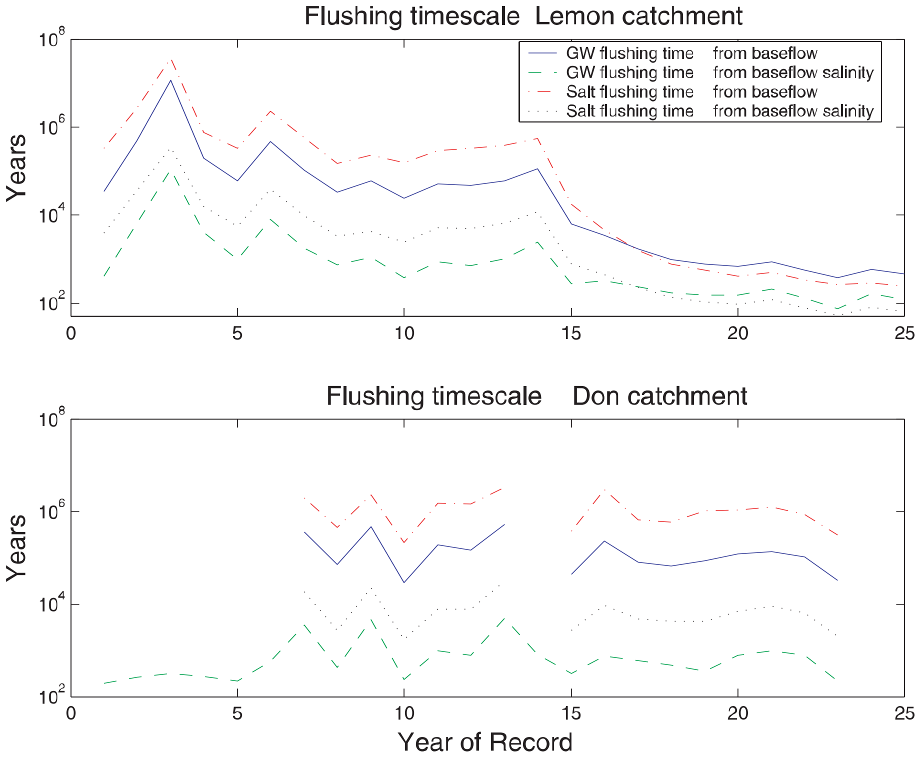

Figure 21 Calculated time scales for equilibration of the salt and water balance in Lemon and Dons catchments, using four different techniques.

those for flushing the salt storage, which we take to be indicative of preferential flow zones not carrying the bulk of the salt. This may be self-evident to some extent as salt could not accumulate in zones of rapid flow.

The evidence from the baseflow component of streamflow, the total water storage, salt storage, groundwater salinity and salt export rate, (Table 4) shows that the total groundwater turnover time is significantly less than the flushing time for all the salt stored in the catchments studied. However, it is also 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. It is expected that further analysis of these differing time scales, with groundwater flow rates and stream salinity time series will help quantify the proportion of the catchment regolith which is being flushed, and hence we should be able to refine the stream recovery estimates.

Estimates of change in water storage within the catchment (estimated from changes in watertable surface) may be used to understand changes in regolith properties through which the watertable is rising. Estimates of groundwater movement through the regolith, and accompanying salt flushing were made using baseflow separation, salt dilution and salinity of baseflow. These techniques gave us estimates of flushing times for the catchments.

The comparison of exceedence curves and percentile flows clearly shows the flow at all recurrence intervals has increased. However, increased flows have occurred more in the lower flows than high flows. This may be expected because conditions of high flow occur when the catchment has received a lot of rain, and hence much of the soil will be transiently saturated. Although this is likely to be enhanced with the elevated watertable, it is not as significant as a general increase in lower flow conditions. While the increased flow is visually related to increased saturated area, the functional relationship is not clear.

Detailed analysis in the context of trying to find climate drivers for the changes to flow regime and flood frequency is ongoing (Silberstein *et al.*, in prep.). This is, not surprisingly, difficult. Our focus has been on trying to identify these climate drivers, because we want to be able to eliminate them from the land-use signal in the cleared catchment. This is particularly critical in the lower rainfall catchments, because there were 8 years with no flow in Ernie. We have also found a high variability in annual pan evaporation, just to make matters worse.

5. Conclusions

Our work to date has produced a number of significant results, and at the same time opened some further avenues of enquiry.

1. **Scattered clearing protects catchments from salinisation.**

   A significant observation from this work is that the clearing regime undertaken in the Don catchment has resulted in very little increase in streamflow and salinity, especially when compared with that at Lemon that had a similar extent of clearing. While groundwater is still rising across the catchment, this is only occurring under the cleared areas and adjacent forest. What remains to be seen is whether the groundwater will stabilise at a level deep enough to prevent major salinisation of the stream. The indications are that stream salinity may have just begun to rise in Don. This occurs at a time when the relative water storage in the regolith has become comparable to that in Lemon. It is paramount that gauging be continued to enable the further monitoring of this situation. It would be a significant advance to know that 40% clearing would have resulted in a vastly different stream salinity situation than we have currently and may have great ramifications for areas that are still actively clearing.

2. **Runoff coefficient rises after clearing.**

   Runoff coefficient (ratio of runoff to rainfall) of the cleared catchments has clearly increased relative to their forested controls. Runoff coefficient has risen by a factor of 5 in the wetter catchments, about 10 in the intermediate catchments, and virtually infinitely in the drier catchments, which have almost no runoff under natural conditions. Additionally, the runoff coefficient of Maxon Farm (Batalling Creek) has reduced after substantial reafforestation. The stream salinity has remained at a high level, but the stream salt load has followed the same trend as runoff coefficient, with the result that there is less salt reaching Wellington Dam from this part of the catchment.

3. **There is greater impact on low flow than high flow after clearing.**

   The major impact of the risen watertables has been on low flow conditions, with these being dramatically increased in all catchments subject to clearing. This effect is proportionally much more significant in the drier catchments than the wet ones. This has implications for stream salinity, because the baseflow carries the salt. The Baseflow Index (BFI) (proportion of total flow that is base flow – or water of groundwater origin) increased in Wights from 0.37 to 0.45, but in Lemon from 0.15 to 0.45, and in Don from 0.1 to 0.3.

   It is observed that the high flows are not increased as much as the low flows, but the median flows in cleared catchments are similar to 10th percentile exceedence flows in forested catchments at the same rainfall. This trend is stronger in the low rainfall catchments.

4. **Reafforestation appears to reverse effects of clearing.**

   Data from Maxon Farm (Batalling Creek) show that BFI was increasing before replanting 40% of the cleared area in the late 1980s. Since about 1990, BFI has fallen from 0.3 to 0.28, and appears to be continuing. Flow frequency curves appear to be returning towards the forested conditions, but it is too early to be certain. Stream salinity has not yet shown any decrease, but total salt load has reduced along with total flow. At Maringee Farm which had only 10% of its catchment revegetated, there has been no noticeable change in flow regime or stream salinity.

5. **The link between saturated area and low probability flows is often not statistically strong.**

   A clear relationship was found between saturated area in the intermediate rainfall catchment and 10th percentile exceedence flow ($r2 = 0.73$), but this was the only statistically clear result. There was no clear relationship between the increase in annual peak flow and saturated area in the cleared catchments. It is possible that this is partly due to the variability in climate masking the signal. It should be noted, however, that this conclusion is for small catchments in the intermediate rainfall zone. The peak flows in large river systems are likely to be affected by other processes, notably the fact that water may flow a long way down stream from the area that received the rainfall. Since many of these large river systems have watertables near the surface, these stream that may have originally been "losing" streams, are no longer, and the river flow will travel further and faster than under natural conditions.

6. **Stream salinity in the high rainfall catchment appears to have stabilised.**

   The rise to peak salinity occurred within five to eight years after clearing in the high rainfall catchments, and appears to have stabilised or may be reducing. It is yet to do so in the lower rainfall catchments. Unfortunately, gauging ceased in Lemon around the time the salinity appeared to have peaked, so we do not yet know whether it has stabilised. Reopening the station for one or two years would probably confirm this. In the patchwork cleared catchment, Don, salinity has only just started to rise, in 2001. This is an important result as it demonstrates that a more refined approach to clearing would have delayed the onset of salinity by some 15 years. What is not yet clear is whether, now it has started to rise, salinity will reach the same level it has in the neighbouring Lemon catchment that had its lower half completely cleared. Data are required for probably another 15 years to answer that.

7. **Salinity in some groundwater bores is reducing.**

   While salinity in most shallow bores rose sharply as the watertable reached the surface, deep groundwater salinity appears generally to be stable. However, there are a few bores that show a decline in groundwater salinity. It is not yet apparent whether this is the result of leaching of salts from the profile as a result of the increased groundwater flux, or some other process.

8. **Estimates of salt flushing times vary with rainfall and degree of clearing.**

   Of critical interest to water managers is the time it will take for salts to naturally flush out of the system and the catchments become fresh again. Our relatively simple model estimates this time scale to be 10-20 years for Wights (rainfall 1120 mm), 20-100 years for Lemon (rainfall 700 mm), and 100-1000 years for Don (rainfall 700 mm, scattered clearing). This is important because it suggests that a few decades may be all that is required for streams to start to freshen and perhaps long-term strategies are not required - it would be enough to implement a medium-term strategy to deal with the stream salinity in the interim.

6. Future Work

The work completed to date has highlighted the need for further investigation in a number of areas. Clearly, the decision to cease gauging the Lemon catchment in 1997 has had a major impact on our ability to make final determinations on a number of issues, most notably the flushing time and the accession to a new steady state in Lemon. **It is a very strong recommendation of this report that gauging be recommenced at Lemon as soon as possible, and be maintained at Don to establish whether salinity will indeed rise to the same level as in Lemon**.

The analysis presented above has shown some clear relationships between flow characteristics and saturated area, and rainfall. However, there is still considerable work to do to convert the initial statistical results into a physical model. Work is in progress to combine the saturated volume and area analysis with topographic distributions within the catchment to develop a model, that would be generic, and could be applied with a minimum of regolith data and a minimum of calibration. This is an ambitious undertaking, but one we feel is worth investing time and effort into.

We are also moving our focus on to building the conceptual model, and testing it with hydrograph data. It has been a core part of this project to utilise readily available stream flow and salinity data, and to interpret these in novel ways using the concept that the salinity signal carries information about the regolith and flow pathways. Hourly data have been requested for these catchments, to provide more detail on a sub-storm timetable, but the analysis will be a large task.

Two parallel student projects are likely to greatly enhance the results generated to date. Firstly, the PhD project by Jasmine Rutherford (UWA) will provide independent geological and geophysical, and some detailed geochemistry to input to the model development. Secondly, the Masters project of Deepak Shakya (Edith Cowan University) will build on these results and apply the statistical relationships between flow characteristics and saturated area and topography in a GIS framework to explore flooding scenarios in two major catchments in south-west Western Australia.

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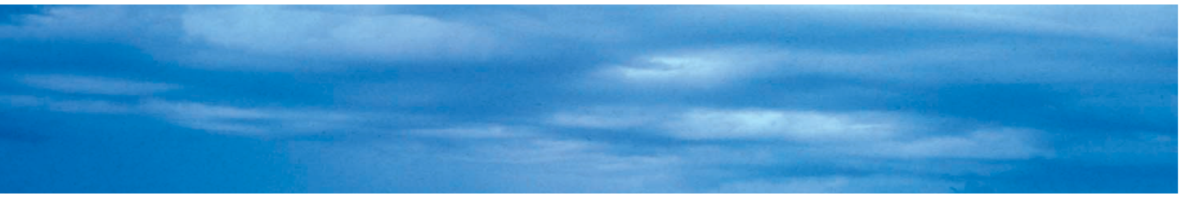

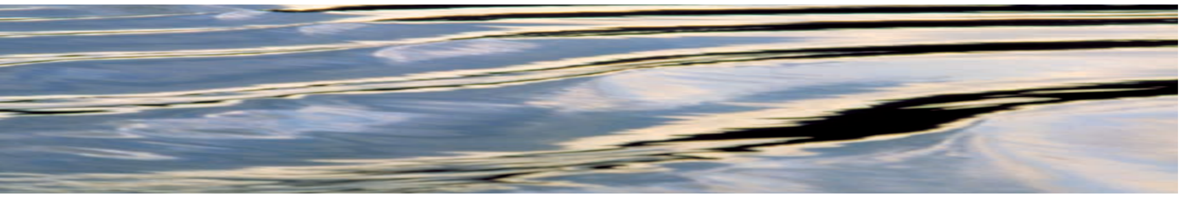

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