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THE IMPACT OF FOREST THINNING ON THE HYDROLOGY OF THREE SMALL CATCHMENTS IN THE SOUTH WEST OF WESTERN AUSTRALIA

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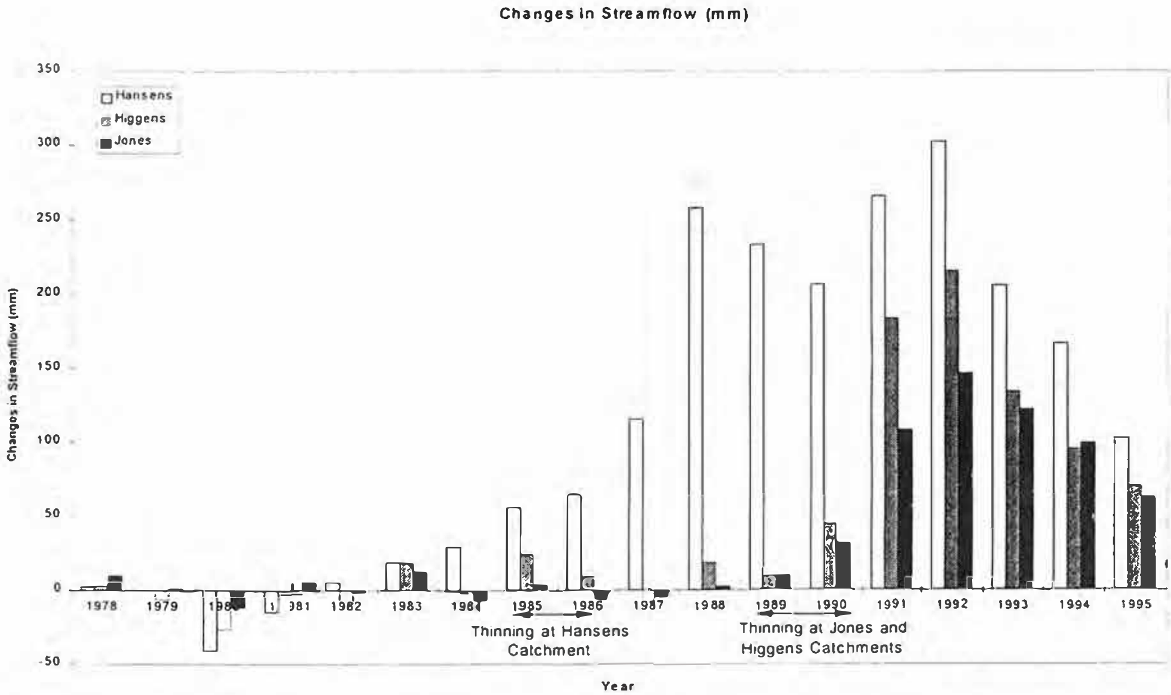

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THE IMPACT OF FOREST THINNING ON THE HYDROLOGY OF THREE SMALL CATCHMENTS IN THE SOUTH WEST OF WESTERN AUSTRALIA

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Water and Rivers Commission
Resource Investigation Division

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Summary

Currently, about 70% of Perth's water supply is from surface water catchments in the northern Jarrah forest. By 2021 the water supply requirement for Perth is expected to increase by 230 GL from 280 GL in 1995. A possible source of this increased water demand is to use of forest thinning to increase catchment water yields. Forest thinning reduces the interception and evaporative potential of the forest. The resulting change in the water balance increases streamflow but may also raise groundwater levels and increase stream salinity. The aim of the research presented in this report is to investigate and attempt to quantify the effect forest thinning on streamflow, groundwater, and stream and groundwater salinity for catchment's in the High Rainfall Zone (>1100 mm/yr) of the Northern Jarrah Forest.

The research focuses on four experimental catchments in the High Rainfall Zone of the northern Jarrah Forest, namely Lewis, Hansens, Higgens and Jones. The study period for the investigation is between 1978 and 1995. During this period, rainfall, streamflow, stream salinity have been collected for each catchment. Groundwater data has been collected since 1985 for Higgens and Jones and since 1988 for Lewis and Hansens. Measurements of vegetation cover have also been made for the catchments.

Hansens, Higgens, and Jones all had different thinning treatments, while Lewis was left as an untreated control catchment. Before thinning, all the catchments had similar forest densities with measured basal areas between 35-43 m^2/ha and measured Foliage Cover between 46-54%. Hansens catchment under went a uniform forest thinning treatment in 1985/86 where basal area was reduced to 7 m^2/ha. Since this time, the forest has regenerated and currently (1996) the basal area is 14 m^2/ha. Higgens catchment was thinned uniformly in 1988/89 and basal area was reduced to 15 m^2/ha. The forest has subsequently regenerated and the basal area is currently (1996) 18 m^2/ha. Jones was thinned in 1988/89, unlike Hansens and Higgens, was not thinned uniformly but instead it's treatment mimicked treatment expected in an operational thinning programme where thinning was concentrated in areas at least risk from die back. Since thinning there has been very little measured regrowth on Jones and basal area is currently about the same density its treatment density of 17 m^2/ha.

The aim of the report is to examine the effect of these different treatments upon groundwater levels, streamflow, and groundwater and stream salinity. The main conclusions are summarised below.

Groundwater Levels and Salinity

(i) After treatment groundwater levels have increased on all three catchments. The increase reached an maximum 3 to 4 years after treatment then decreased for the remainder of the study period. Hansens catchment had the most severe thinning treatment and the lowest increase in groundwater levels. It had an average increase between 1985 and 1990 of 2.28 m and 3.88 m in valley and upslope bores, respectively. In contrast, Jones had the least severe thinning treatment and the highest increase in groundwater levels. It had an average increase between 1988 and 1992 of 5.9 m and 7.3 m in valley and upslope bores, respectively. Higgens catchment had an increase between 1988 and 1993 of 3.6 m and 5.34 m in valley and upslope bores.

(ii) All catchments had low groundwater salinity concentrations (90 to 180 mg/L TSS). There was no evidence of an increase in salinity concentration during the study period.

Streamflow and Stream Salinity

(i) Most of the streamflow on all four catchments occurred during the winter period. The effect of the thinning treatments was to increase the duration of this period. After subsequent regrowth the streamflow at Higgens and Jones appears to be returning to its pre-treatment regime. Hansens, in contrast, shows no signs of returning to its pre-treatment seasonal regime.

(ii) During the pretreatment period, streamflow ranged from 0.1% to 5.4% of annual rainfall across the catchments. Hansens catchment had the highest annual streamflow, ranging from 26 mm to 114 mm with an average of 69 mm. The annual streamflow at Higgens catchment ranged from 6.6 mm to 39 mm and averaged 29 mm. Jones catchment had the lowest annual streamflow during the pretreatment period, ranging from nil to 35 mm. The mean annual streamflow was 12 mm with the mean runoff rate being 1.1%.

(iii) After thinning there was a large increase in streamflow on all catchments. Hansens recorded the largest increase, 300 mm, followed by Higgens, 220 mm, and Jones, 150 mm. The increases then reduced to 110, 65 and 55 mm, respectively, by the end of the study period. This reduction is higher than expected given the small amount of regrowth on the catchments. There is insufficient data to assess whether the catchments will return to their pre-treatment conditions if the they were allowed to fully regenerate.

(iv) There was a large increase in the flood magnitude for low ARI floods. For the 2 year average recurrence interval (ARI) for Hansens is 0.03 m3/s pre-treatment and 0.15 m^3/s post-treatment. At Higgens the increase is from 0.01 m^3/s to 0.04 m^3/s and at Jones the increase is from 0.007 m^3/s to 0.025 m^3/s. However, the data from Hansens and Jones suggest that the reduced variability of flood peaks will result in only small increases in the magnitudes of higher (eg 100 yr) ARI floods. More data is required to fully assess the effect of forest thinning on flood magnitude.

(v) Streamflow on all catchments is fresh (<500 mg/L TSS) for the entire study period. A typical result for catchments in the High Rainfall Zone. Lewis had annual mean salinities in the range 96 to 123 mg/L TSS and Hansens had salinities in the range 107 to 136 mg/L TSS. Higgens and Jones had salinities in the ranges 109 to 139 mg/L TSS and 111 to 149 mg/L TSS, respectively.

(vi) There is no evidence in an increase in stream salt concentrations. However, there is an increase in total salt load due to increased streamflow.

1. Introduction

The current water supply system for Perth provides 280 GL for a population of 1.2 million people. Currently, about 70% of the Perth's water supply is from surface water catchments in the Northern Jarrah Forest (Stokes *et al.*, 1995). These catchments typically produce low yields, averaging 7% of annual rainfall. These low yields are attributed to the large soil water storage available for evapotranspiration by vegetation (Ruprecht and Stoneman, 1993).

By 2021 the population is expected to increase to 2.0 million, and water supply will have to increase by 230 GL (Stokes *et al.*, 1995). A possible source for the increased water demand is the use of forest management to increase catchment water yields. A proposed method of increasing yield is to reduce the forest density and in doing so reduce interception and evaporative demand of the vegetation and thereby increase streamflow. The change in the water balance may also increase groundwater levels that may mobilise salt stored in the soil profile and increase stream salinity.

The Water Supply Strategy for Perth and Mandurah (Stokes *et al.*, 1995) currently identifies forest management option as a Category 2 source, a source that requires further research. This report forms part of the research requirement. It examines the effect of forest thinning on streamflow and salinity on three catchments in the High Rainfall Zone of the South-West of Western Australia. The report complements the reports by Bari and Boyd (1993) and Moulds *et al.* (1994) that also examine the effect of forest thinning on streamflow and stream salinity on other experimental catchments in the South-West of Western Australia.

Bari and Boyd (1993) examined the effect of forest thinning on three sets of catchments each set being in the High (> 1100 mm), Intermediate (900 to 1100 mm) and Low (< 900 mm) Rainfall Zones, respectively. They found that streamflow on each of the catchments increased after treatment but began to decline as the vegetation regenerated. They found that stream salinity increased in both the Intermediate and High Rainfall Zone catchments. However, the stream salinity for the High Rainfall Zone catchment was still well within the fresh salinity range (TSS<500 mg/L). They found no significant increase in salinity for the catchments in the Low Rainfall Zone. Moulds *et al.* (1994) examined the effects of forest thinning on the Yarragil Catchment in the Intermediate Rainfall Zone (900 to 100 mm/yr) of Western Australia. They found that forest thinning was able to significantly increase streamflow without significant increases in water salinity.

Other researchers report similar results with respect to yield changes. Bosch and Hewlett (1982) in a worldwide review found that increases in streamflow were approximately proportional to the reduction in basal area. Hornbeck *et al.*, (1993) reviewed the long term impacts of forest treatments on yields for catchments in the north eastern USA. They found that while there is a variety of responses in water yield to forest treatment there is a number of consistent themes: (i) there is a prompt initial increase in streamflow after thinning, (ii) the magnitude of the increase is approximately proportional to the percentage reduction in basal area, (iii) the increase can be sustained provided natural regrowth is controlled. Cornish (1993) examined the effects of logging and forest regeneration on water yields in a eucalypt forest catchment in New South Wales, Australia. He found that the magnitude of the initial increase in streamflow was proportional to the area logged. However, he also found that streamflow after subsequent forest regeneration may be lower than pre-thinning streamflow.

This report focus its attention on four experimental catchments with areas between 0.6 km^2 to 2.01 km^2 in the High Rainfall Zone of the South-West of Western Australia, namely Lewis, Hansens, Higgens and Jones. They are located approximately 100 km south of Perth (Figure 1). Hansens, Jones, and Higgens each had different thinning treatments and Lewis was left as an untreated control catchment. No previous report comparing the data of all four catchments has been published. However, Ruprecht *et al.* (1991) have made a preliminary analysis of the data collected for Lewis and Hansens.

The specific aims of the investigation are:

1. Determine changes in groundwater levels and salinity.
2. Determine changes in streamflow, stream salinity and salt load in relation to vegetation density.

The report is organised as follows. First, we describe the general catchment characteristics: instrumentation, rainfall, soils, geomorphology and a summary of the thinning treatments and vegetation history. The next section examines groundwater, streamflow and stream salinity data. This examination focuses on changes in the hydrological characteristics of the catchments over time in relation to forest cover and climate. The report finally provides a summary of results and recommendations for future work.

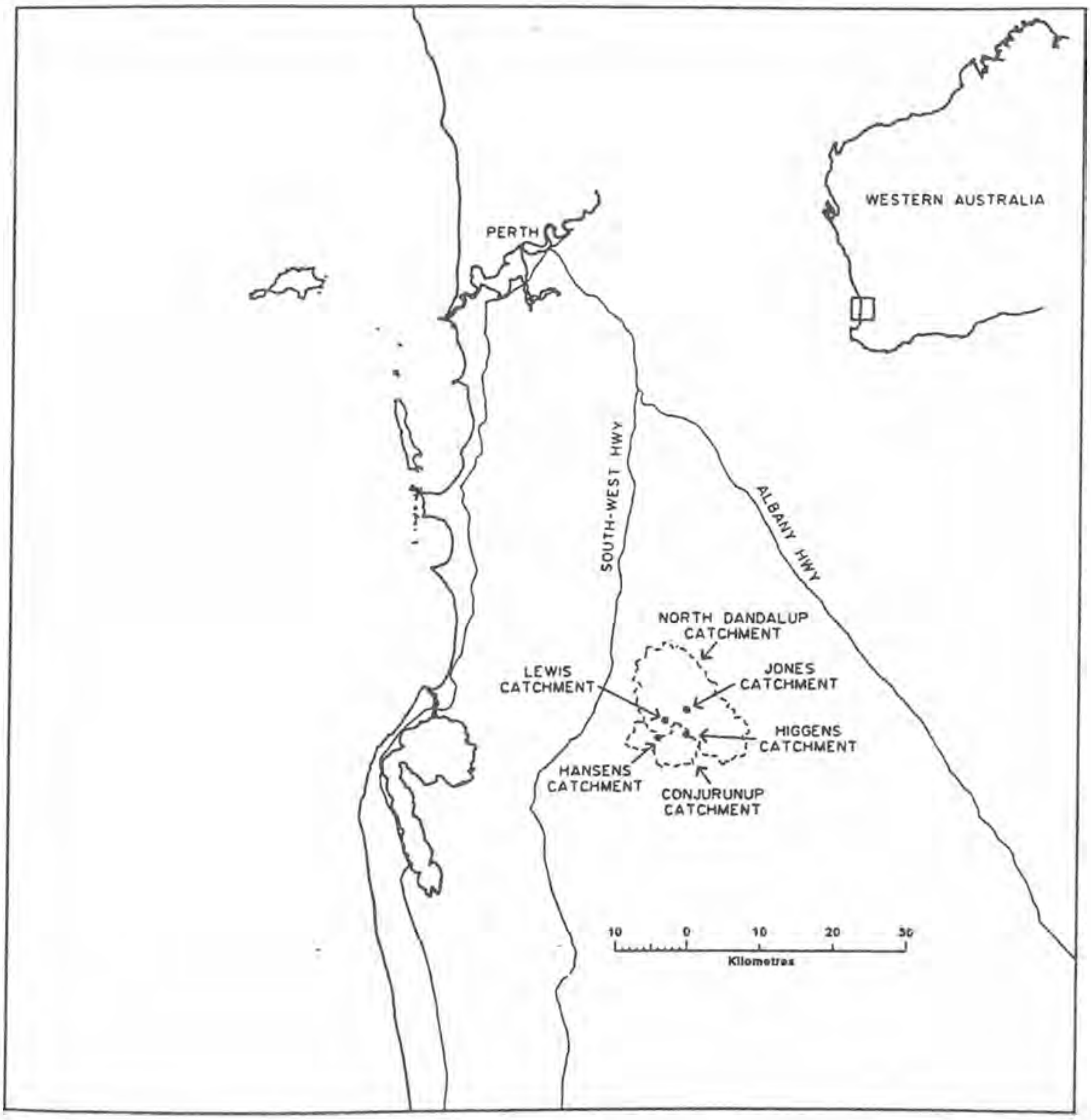


Figure 1: Location map of the experimental catchments

2. Catchment Descriptions

2.1 Precipitation and Climate

The four catchments are located in a region of Mediterranean climate with mild, wet winters and hot, dry summers. Figure 2 shows the annual rainfall from the nearby town of Dwellingup, indicating a long term (1934 to 1994) average rainfall of 1271 mm/yr with annual variation between 750 and 2000 mm/yr. The long term average rainfall for all four catchments, determined from the 1911 to 1979 isohyets, is 1300 mm/yr (Public Works Department, 1984). The long-term mean annual pan evaporation rate is 1600 mm/yr (Luke *et al.*, 1988).

Figure 3 shows the annual rainfall measured at each catchment during the study period (1978 to 1995). The figure indicates that the average rainfall over the study period is 1190 mm/yr that is 8% below the long term average of 1300 mm/yr. Appendix A explains the method used for filling gaps in the rainfall record.

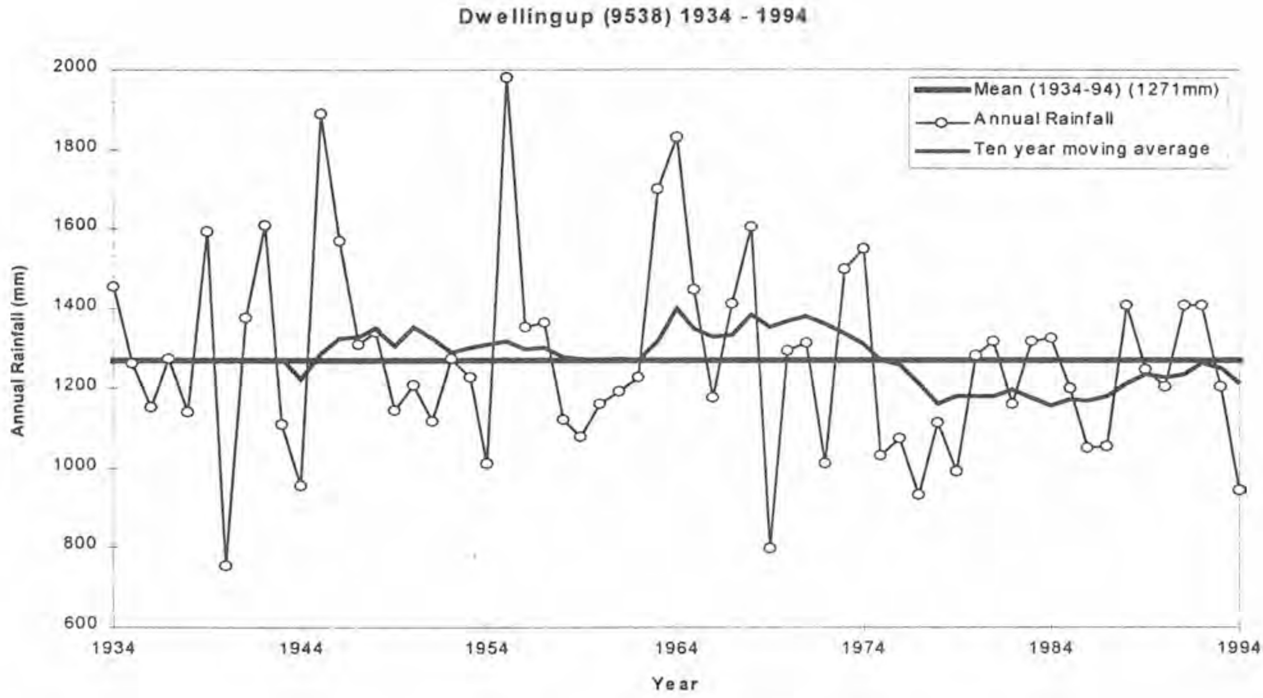


Figure 2: Annual rainfall at Dwellingup (1934-1994)

2.2 Instrumentation

Each catchment has a single pluviometer and permanent gauging station with V notch control structure that have been in operation since mid 1977. Stream salinity is measured with approximately weekly grab sampling. There is no continuous sampling on Hansens, Jones and Higgens, but continuous sampling has occurred on Lewis since 1992. The groundwater monitoring on Hansens and Jones is adequate with bores being monitored since 1985. However, the groundwater bore networks on Higgens and Lewis were only established in 1988. The catchment maps in Appendix B show the location of gauging stations, pluviometers and groundwater monitoring bores. Table 1 provides the catchment characteristics.

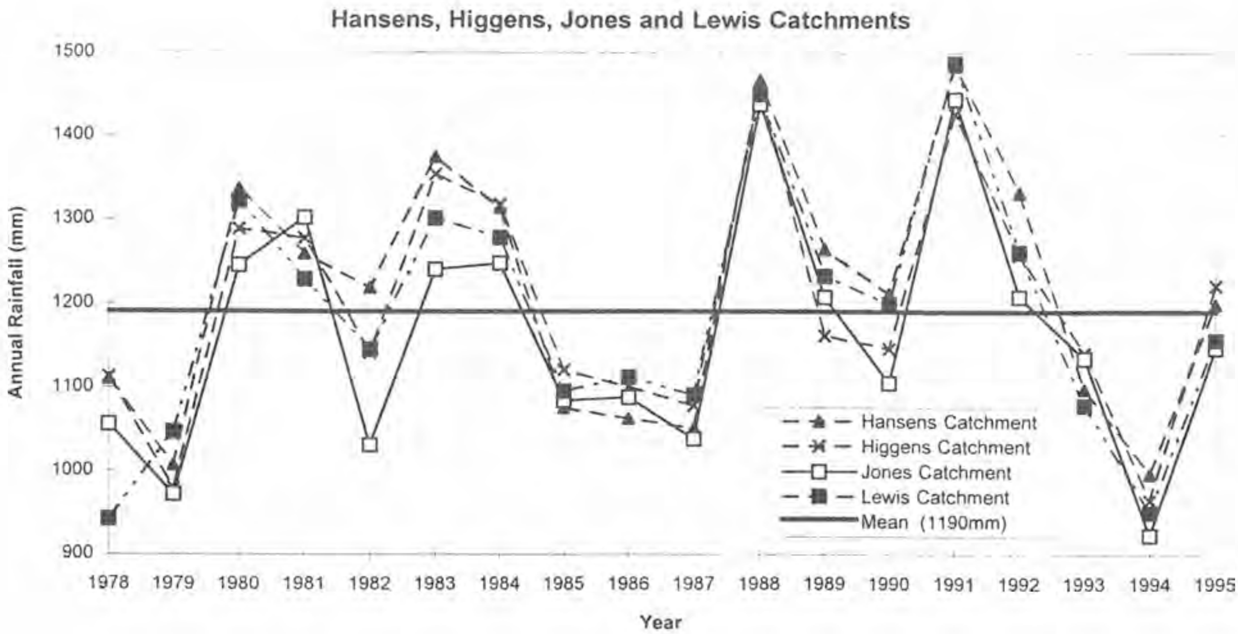


Figure 3: Annual rainfall at Lewis, Hansens, Higgens and Jones (1978-95)

Table 1: General catchment characteristics for Lewis, Hansens, Higgens, and Jones

Catchment	Catchment Area (km^2)	Annual Rainfall[1] (mm)	Annual Rainfall[2] (mm)	Annual streamflow[2] (mm)	Flow Weighted Mean stream salinity[2] (mg/L)
Lewis	2.01	1300	1188	183	111
Hansens	0.78	1300	1214	175	114
Higgens	0.60	1300	1197	74	126
Jones	0.69	1300	1162	28	134

Notes: 1. Long term average 1911 to 1979, Public Works Department (1984)
2: Average over monitored period (1978-1995)

2.3 Soils and Geomorphology

Public Works Department (1984) provide summary descriptions of the soil and geomorphological characteristics for all catchments based on 1:250,000 scale mapping. There are three landform map units associated with the catchments: Dwellingup Laterite Plateau, Yarragil Upland Valley, Murray Incised Valley. Dwellingup Laterite Plateau is characterised by duricrust (caprock), gravels and sands over mottled clay soils. Yarragil Upland Valley is characterised by sandy gravels on slopes, orange earths on swampy valley floors, and Murrary Incised Valley is characterised by moderate slopes, red and yellow earths and alluvium on valley floors. Table 2 presents the percentage of each landform for the catchments. McArthur (1980) and Ruprecht *et al.* (1991) describe detailed soil mapping for Hansens.

Table 2: Soils and landform for Lewis, Hansens, Higgens and Jones.

Map Unit	Lewis	Hansens	Jones	Higgens
Dwellingup Laterite Plateau	55%	50%	50%	55%
Murray Incised Valley	45%	50%	10%	0%
Yarragil Upland Valley	0%	0%	40%	45%

The summary descriptions (Table 2) are based on large scale mapping and further field work is required to properly describe the soils. During a field trip by M. Bari (WRC), B. Hawkins (WRC), P. Rakich (WRC) and J. Robinson (JDA) to the catchments on 25 October 1996 a number of features were identified which may effect runoff. On Higgens the area in the valley floor adjacent to the stream was swampy with some sands. There was a large area of exposed caprock near the upstream catchment divide where water from recent rainfall had ponded. These areas are probable sources of runoff generation. Hansens catchment was observed to have a saturated area in the valley floor, and runoff was observed from recent rainfall along roads and tracks in the catchment. Jones was swampy in the valley floor with tall undergrowth and runoff was observed along the tracks. Lewis was swampy in the valley bottom with tall undergrowth.

2.4 Catchment Treatment and Regeneration

All four catchments are Jarrah-Marri forests that, before the forest thinning programme, had regenerated from selective logging during the 1940s and 1950s. Dieback has severely affected Lewis and Hansens. They had, respectively, 26% and 27% affected areas, while Higgens and Jones had only 0% and 6% affected areas (Public Works Dept, 1984).

Before treatment, all catchments had similar levels of vegetation, with basal area estimates in 1981 of between 35-37 m^2/ha on Hansens, Higgens and Lewis and 43 m^2/ha on Jones (Table 3). They also had similar levels of Foliage cover in 1981, varying between 46% on Lewis and 54% on Jones (Table 3).

Table 3: Summary of Thinning History for Lewis, Hansens, Higgens and Jones

Catchment	Vegetation Cover	Pre-treatment	Treatment	Regrowth Period		
		1981	1985/86[2] 1988/89[3]	1989	1991	1996
Lewis	Foliage Cover (%)	46				
	Crown Cover (%)					
	Basal Area (m^2/ha)	36				
Hansens	Foliage Cover (%)	49				21
	Crown Cover (%)			14.4		26.0
	Basal Area (m^2/ha)	35.4	7	6.5	1	14.3
Higgens	Foliage Cover (%)	48.5				26.4
	Crown Cover (%)				29.1	38.5
	Basal Area (m^2/ha)	37.1	15		13.5	17.6
Jones	Foliage Cover (%)	54.4				31.0
	Crown Cover (%)				39.4	39.7
	Basal Area (m^2/ha)	43.3	17		17.0	17.4

Notes:

1. Table based on Ritson and Bari (1996)
2. Hansens was treated in 1985/86.
3. Higgens and Jones were treated in 1988/89.

Hansens and Higgens catchments had uniform thinning treatments. The treatments thinned vegetation at Hansens to a basal area of $7m^2$/ha in 1985/86 and thinned vegetation at Higgens to a basal area $15m^2$/ha in 1988/89 (Table 3). Jones catchment had a different thinning treatment. Its treatment mimicked expected treatments during an operational thinning programme with thinning concentrating on areas at least risk from dieback. After treatment, in 1988/89, Jones had a basal area of 17 m^2/ha (Table 3).

Lewis, the control catchment, did not undergo any thinning treatments and no further estimates of vegetation density were made since the initial estimate in 1981.

Basal area at Hansens, which was reduced from 35 m^2/ha to 7 m^2/ha in 1985/86, regenerated to 14 m^2/ha in 1996, while crown cover has regenerated from 14% to 26% (Table 3).

Higgens, reduced from 37 m^2/ha in 1981 to a basal area of 15 m^2/ha in 1988/89, regenerated to $18m^2$/ha in 1996. The crown cover regenerated from 29% to 38% (Table 3).

At Jones, only a slight increase in the basal area and crown cover was recorded in the five years since treatment in 1988/89 (Table 3). This could be due to losses from dieback, reducing gains in thinned areas. It could also be due to variability of the 24 point estimates used in calculating the basal area (Ritson and Bari, 1996). Currently the basal area and crown cover at Jones are respectively, 17 m^2/ha and 40%.

3. Groundwater

3.1 Monitoring Data

Groundwater monitoring bores for each catchment have been divided into two groups according to landscape position: upslope and valley. Valley bores being defined as bores located within 100 m of the stream channel.

Further to valley and deep bore groupings, two types of bores have been installed: shallow and deep. Deep bores are drilled deep into the soil profile to measure the permanent unconfined groundwater system. Shallow bores only penetrate a few metres below the natural surface and attempt to measure perched groundwater systems.

Our analysis focuses on "representative" bores for each catchment. The deep bores were selected based on location (one upslope and one valley) and on completeness of record. The selection of shallow bores was based upon whether they monitored perched rather than permanent groundwater. Appendix B shows the location of monitor bores for each catchment.

3.2 Seasonal Groundwater Variation

Figure 4 shows the seasonal groundwater level variation during 1992 for deep bores, upslope and valley. Bore G61418606 at Jones is a shallow bore but since it contained water all year it was considered deep (it was monitoring the permanent groundwater system).

The seasonal amplitude of the valley bores were 1.9 m, 1.9 m, 1.7 m and 2.6 m, respectively, for Hansens, Higgens, Jones and Lewis, while the seasonal amplitude of the upslope bores was 2.4 m, 3.1 m, 2.6 m and 4.1 m, respectively (Figure 4). Thus, all upslope bores tend to have a larger seasonal variation than valley bores.

Levels in valley bores at Hansens, Jones and Lewis all show multiple peaks during 1992, as does the upslope bore at Hansens. These peaks correspond to peak rainfall months of June and August in 1992 (Figure 4). These observations suggest a rapid response to rainfall inputs.

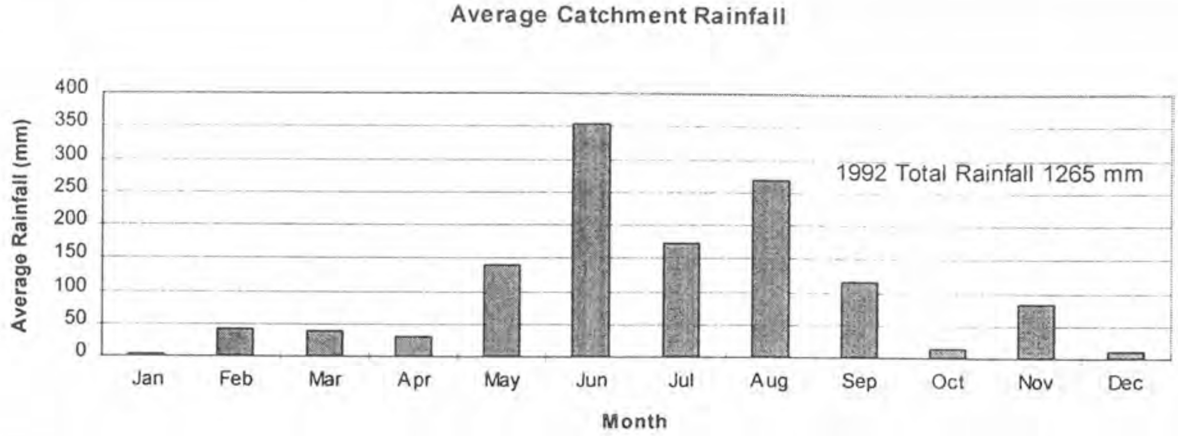
3.3 Annual Groundwater Variation

Annual minimum water table elevations were collated for each year for all four catchments (Table C2, Appendix C). For shallow bores the annual minimum groundwater levels were below the bottom of the bores. These bores have been placed to monitor the existence of ephemeral perched water and the duration of water in these bores is more important than water levels.

3.3.1 Lewis

Deep groundwater

There was very little change in groundwater levels in deep valley bore, Bore 3, on Lewis between 1989 and 1995 with the annual minima varying by about 1.0 m over this period. The upslope groundwater levels, in contrast, show a large variation with water levels rising by about 4.5 m in Bore 10 between 1988 and 1993 then falling by 3.5 m over the remainder of the study period (Figure 5). The other upslope bores on the catchment had similar patterns. The average rise in minimum groundwater levels between 1988 and 1993 was 3.7 m and the fall between 1993 and 1995 was 2.9 m (Table 4). The cross section through the catchment also illustrates these changes (Figure 6). Some of this variation may be attributed to the sequence of rainfall (Figure 5) which peaked in 1992 then decreased to the end of the study period. However, it is unclear why water levels in the valley bores did not increase over the same period. The increase could also be attributed to landuse change in the surrounding catchments such as bauxite mining.



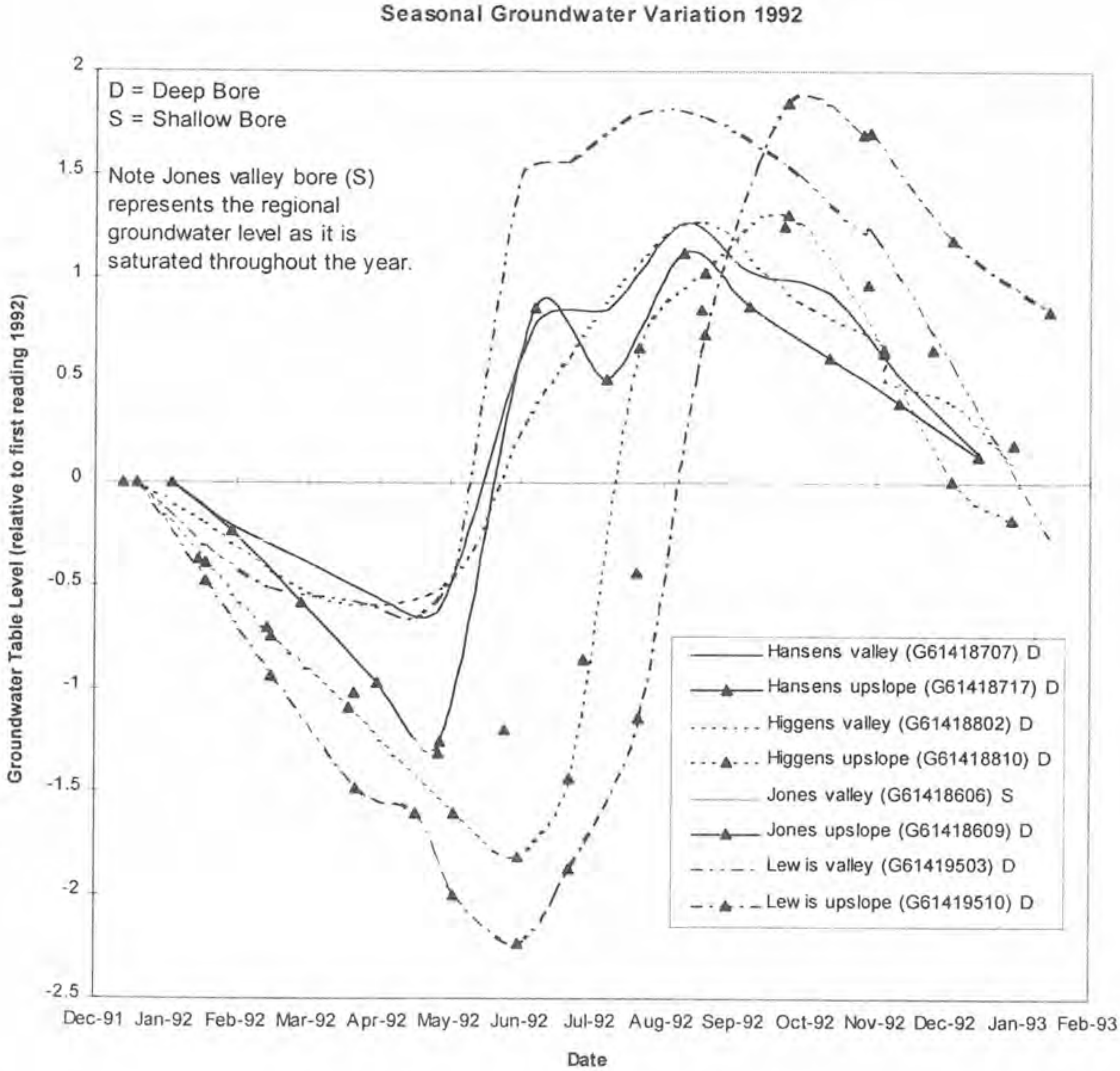


Figure 4: Seasonal variation in groundwater levels

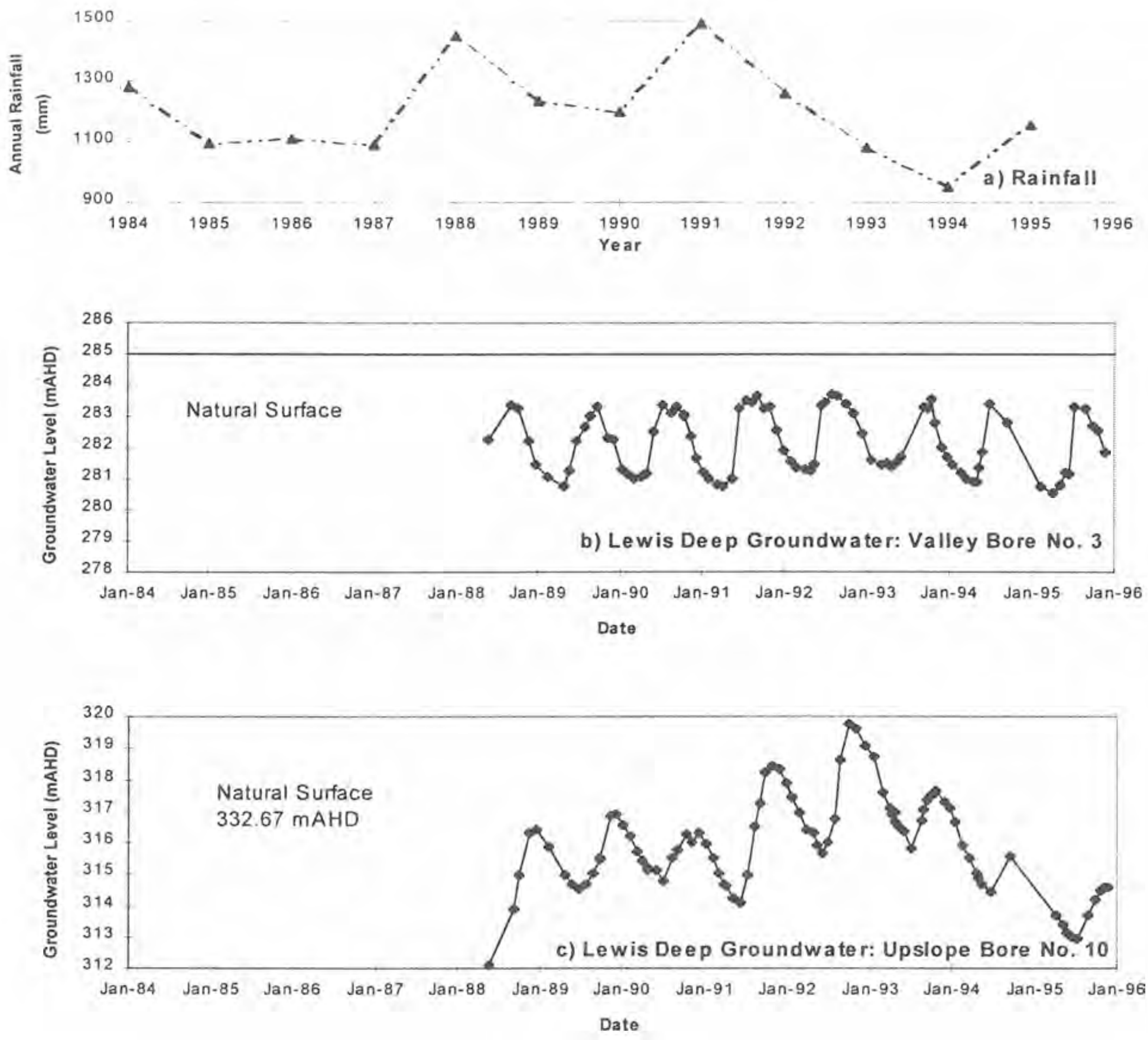


Figure 5: Annual rainfall and groundwater levels at Lewis.

Shallow groundwater

There was only one shallow bore (Bore 6) in the catchment. It appeared to monitor the permanent groundwater rather than a perched water table. Nearby deep bore data (Bore 5) showed similar observed water levels. There is, therefore, no evidence to confirm the existence of an ephemeral perched water table in this catchment.

3.3.2 Hansens

Deep Groundwater

Figure 7 shows the temporal changes in the regional groundwater level at Hansens. It indicates that both valley and upslope bores showed similar trends. They both rose after thinning, reaching a peak minima in 1989 and 1990 (3 years after treatment), after which there was no further increase in the annual minima, as foreseen by Ruprecht *et al.* (1991).

Table 4: Average changes in groundwater levels at Lewis, Hansens, Higgens, and Jones

Catchment	Increase in Groundwater Levels[2] (m)			Recovery in groundwater levels post-treatment[2] (m)		
	Valley Bores	Upslope Bores	Period[1]	Valley Bores	Upslope Bores	Period[3]
Lewis	0.59 (8)	3.7 (1)	1988-1993	-1.41 (8)	-2.9 (1)	1993-1995
Hansens	2.28 (5)	3.88 (6)	1985-1990	-0.84 (5)	-1.35 (6)	1990-1994
Higgens	3.6 (4)	5.34 (5)	1988-1992	-0.75 (4)	-1.02 (5)	1992-1994
Jones	5.96 (5)	7.3 (3)	1988-1993	-0.60 (5)	-1.00 (5)	1993-1994

Notes:

1. The period is from the first year of treatment, 1985 for Hansens and, 1988 for Higgens and Jones to the year of maximum groundwater level. At Lewis the period is from the first year of monitoring to the year of maximum groundwater level.
2. The increase and recovery of groundwater levels are based on the difference between the average of the annual minimum recorded level in each bore over the period. The number in brackets indicates the number of bores.
3. The recovery period corresponds to the years between the maximum groundwater level to the end of available record.

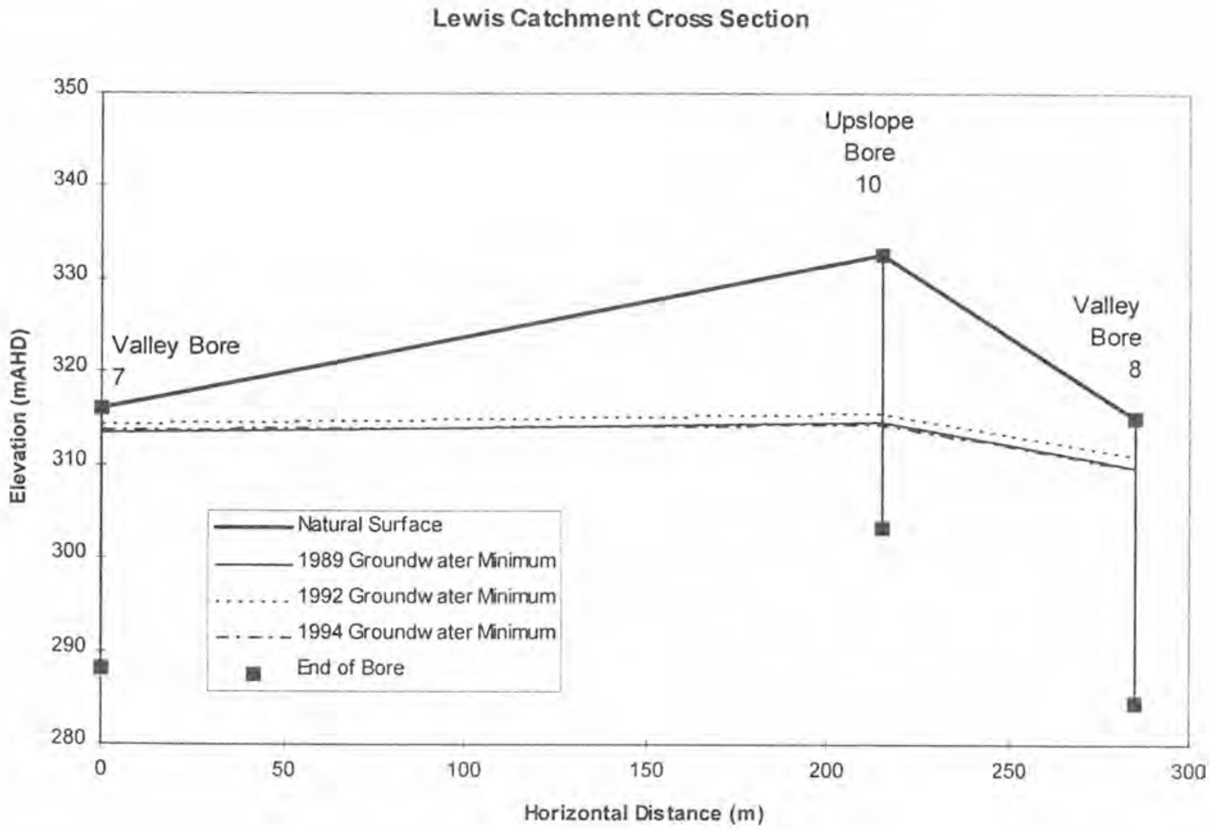


Figure 6: Groundwater level variation along cross section at Lewis

In the valley location, monitored by Bore 9, annual minimum levels rose by 3.0 m and then stabilised at about 2.5 m above pre-treatment levels after 1990 (Figure 7). Levels measured in this bore are above the natural surface for most of the year indicating that the swamp discharge area has increased past this point (Figure B2). The annual minima at Bore 22, upslope, rose by 5.0 m between 1985 and 1990 and then stabilised for the remainder of the study period to about 3.5 m above initial levels (Figure 7). These measurements show that the upslope bore tends to have a larger rise than the valley bore. Ruprecht *et al.* (1991) suggests that this was due to the proximity of the water table to the ground surface in valley locations.

The catchment groundwater pattern can be seen in a cross section of the catchment (Figure 8) where the groundwater rise peaks in 1989 and 1992 then falls until 1994. The average rise for all bores during the period 1985 to 1990 was 2.3 m in the valley bores and 3.88 m in the upslope bores (Table 4). The increase in water levels is attributed to increased rainfall in the period 1985 to 1990 and to the reduction in forest density following thinning in 1985/86. The subsequent fall in groundwater levels is attributed to low rainfall and forest regrowth during this period, where basal area increased to 14.3 m^2/ha in 1996 from the 7 m^2/ha when thinned in 1985/86.

Shallow groundwater

A shallow valley bore (Figure 7) shows the existence of perched water at Bore 6. This perched groundwater is situated above the regional groundwater table at the same location. Of the 13 shallow bores installed at Hansens only three monitored the existence of perched water. Two of these became saturated by the rise of the permanent groundwater table. Poor sampling frequency of shallow bores between 1989 and 1992 does not allow conclusions to be made at Hansens regarding the effect of thinning on the duration of perched water in the catchment.

3.3.3 Higgens

Deep groundwater

Groundwater levels followed the expected pattern following thinning and regeneration. Figure 9 shows that the groundwater elevation in Bore 1, a valley bore, reached its maximum level in 1992, three years after treatment. The groundwater rise was around 3.0 m, while at an upslope bore (Bore 9) the groundwater rise was 5.5 m. As with Hansens, the lower rise in the valley bore is attributed to the proximity to the water table to the ground surface. After 1992 maximum groundwater levels have slowly fallen.

The groundwater levels show that there is a reduction in the amplitude of seasonal variation of Bore 1 (Valley Bore) after the levels reached their peak in 1992 (Figure 9). The decrease in seasonal amplitude did not occur in the upslope bore therefore likely that the mechanism for the amplitude decrease is related to the landscape position. Possibly, the proximity of the water table to the ground surface, especially near the stream channels, is constraining the maximum water level and there by reducing the amount of seasonal variation.

The general trend of groundwater rise and fall is also seen in the cross section of the catchment (Figure 10). Groundwater levels increase after 1985 to a maximum in 1992 due to higher rainfall and reduced transpiration following forest thinning in 1988/89.

Shallow groundwater

There were no shallow bores at Higgens catchment.

3.3.4 Jones

Deep groundwater

At Jones water levels in Bore 3, valley, rose by around 4.5 m, while upslope, Bore 13, water levels rose by around 8.5 m (Figure 11). Over the period 1988 to 1993 the average rise in the five valley bores was 6 m and 7.3 m in three upslope bores (Table 4). These rises are similar pattern to those on Higgens and Jones with larger rises in the upslope than in the valley. However groundwater levels continued to increase until 1993, rather than 1992 as was the case on Hansens and Higgens. After 1993 there was a small fall in groundwater levels. Over the period 1993-1994 the

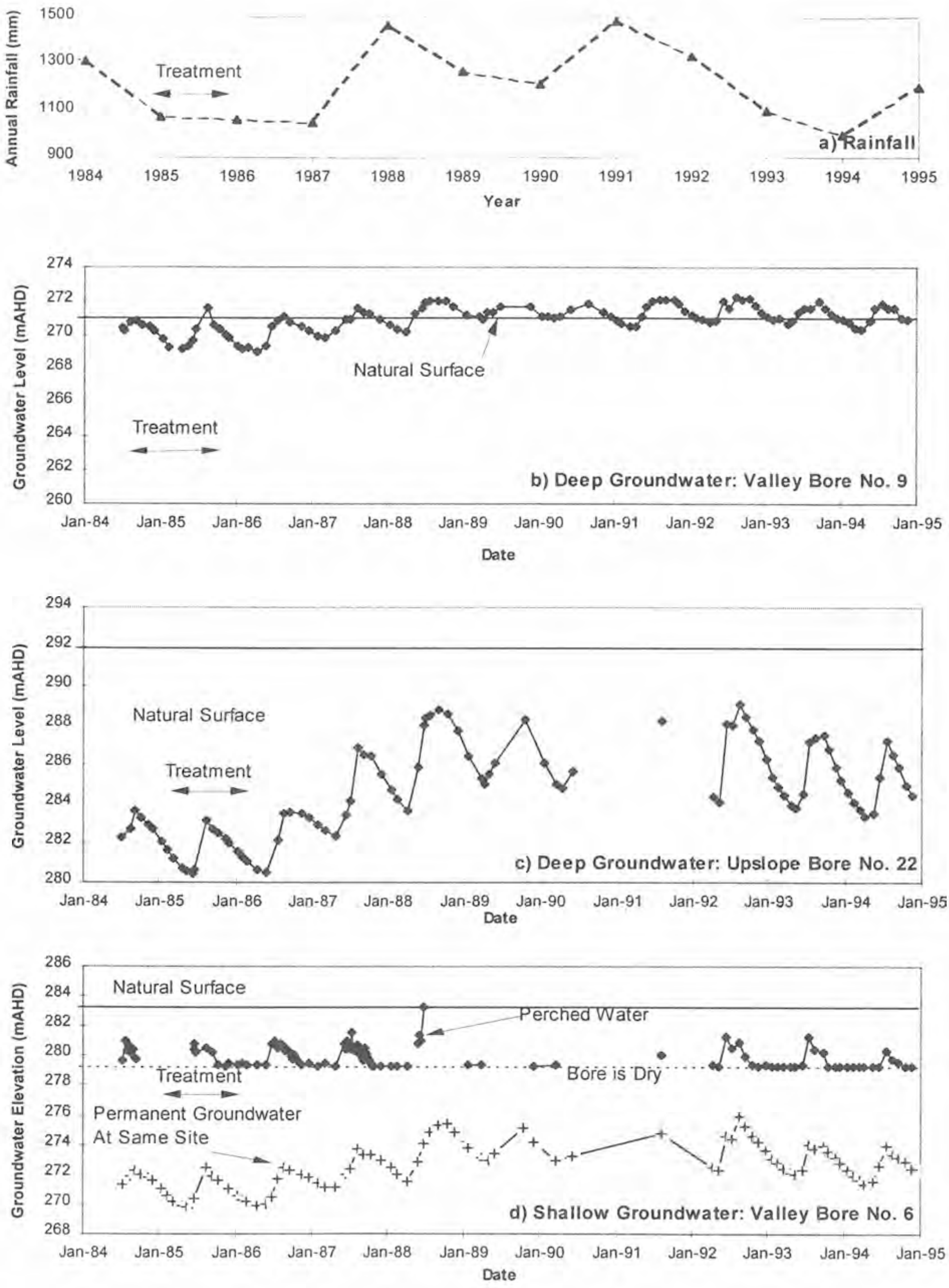


Figure 7: Annual Rainfall and Groundwater Levels at Hansens Catchment

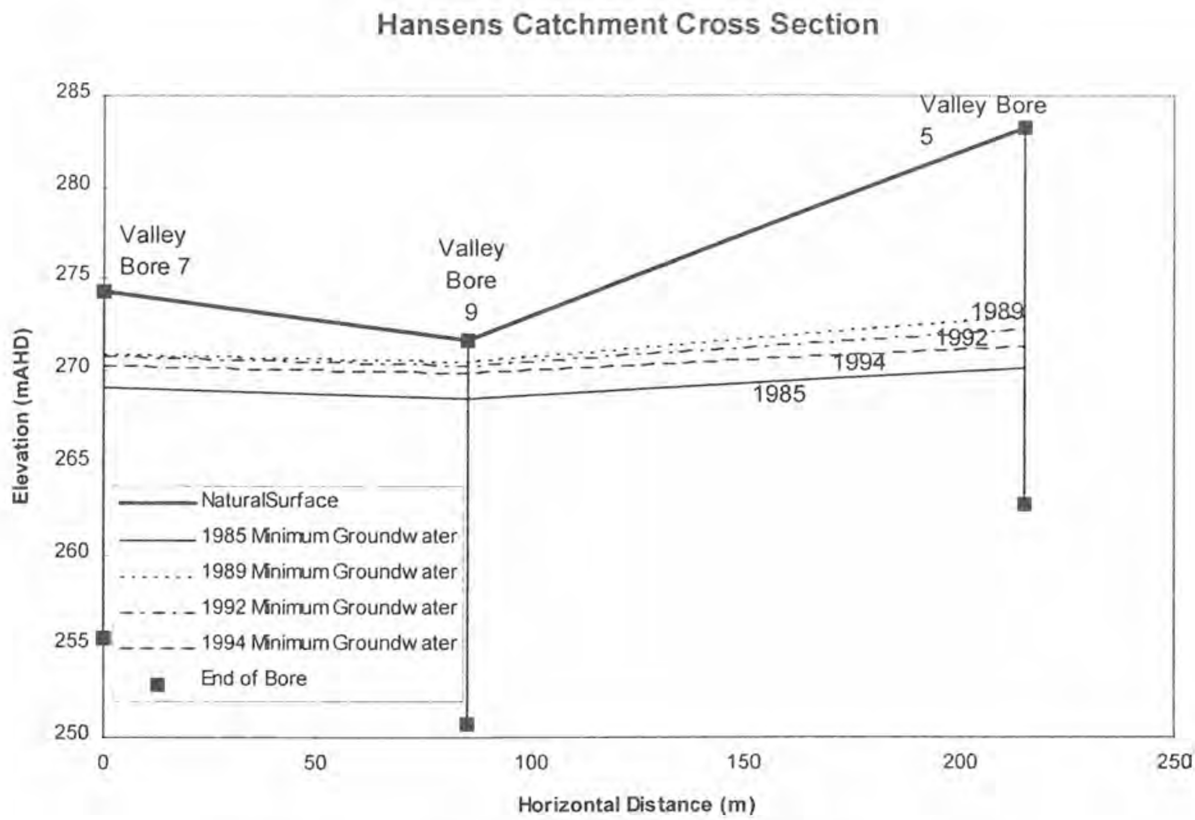


Figure 8: Groundwater level variation along the cross section at Hansens

average fall was 0.6 m in the Valley Bores and 1.0 m in the upslope bores (Table 4). The smaller recovery of groundwater levels on Jones is attributed to lower rates of forest regeneration with basal area and crown cover remaining approximately the same since thinning in 1998/89.

The valley bore, Bore 3, shows a reduction in seasonal amplitude after the peak in 1993 (Figure 11). This result is similar to that on Higgens that we suggest may be caused by the groundwater being closer to the ground surface in valley locations.

Figure 12 shows a catchment cross section with one stream situated near Bore 17 and another near Bores 3 and 5. This cross section shows the catchment groundwater rising after treatment (1989). 1994 levels are about the same as 1992 in the valley indicating that the catchment may have reached a new equilibrium. However, 1994 levels are lower in the upslope due to low rainfall (Figure 11). The fall is unlikely to be due to an increase in transpiration because the rate of regrowth at Jones has been very slow (Table 3).

Shallow Groundwater

Of nine shallow bores installed in the catchment only two monitored perched water, others either monitored the permanent groundwater or were dry. Valley bore 18 monitored the existence of perched water (Figure 11) for between three and four months duration before thinning. After thinning the period increased to between 5 and 6 months and became permanent in 1992.

3.4 Discussion

3.4.1 Deep groundwater

Deep groundwater levels on the treated catchments, Hansens, Higgens and Jones all increased following forest thinning. In contrast, the groundwater levels in

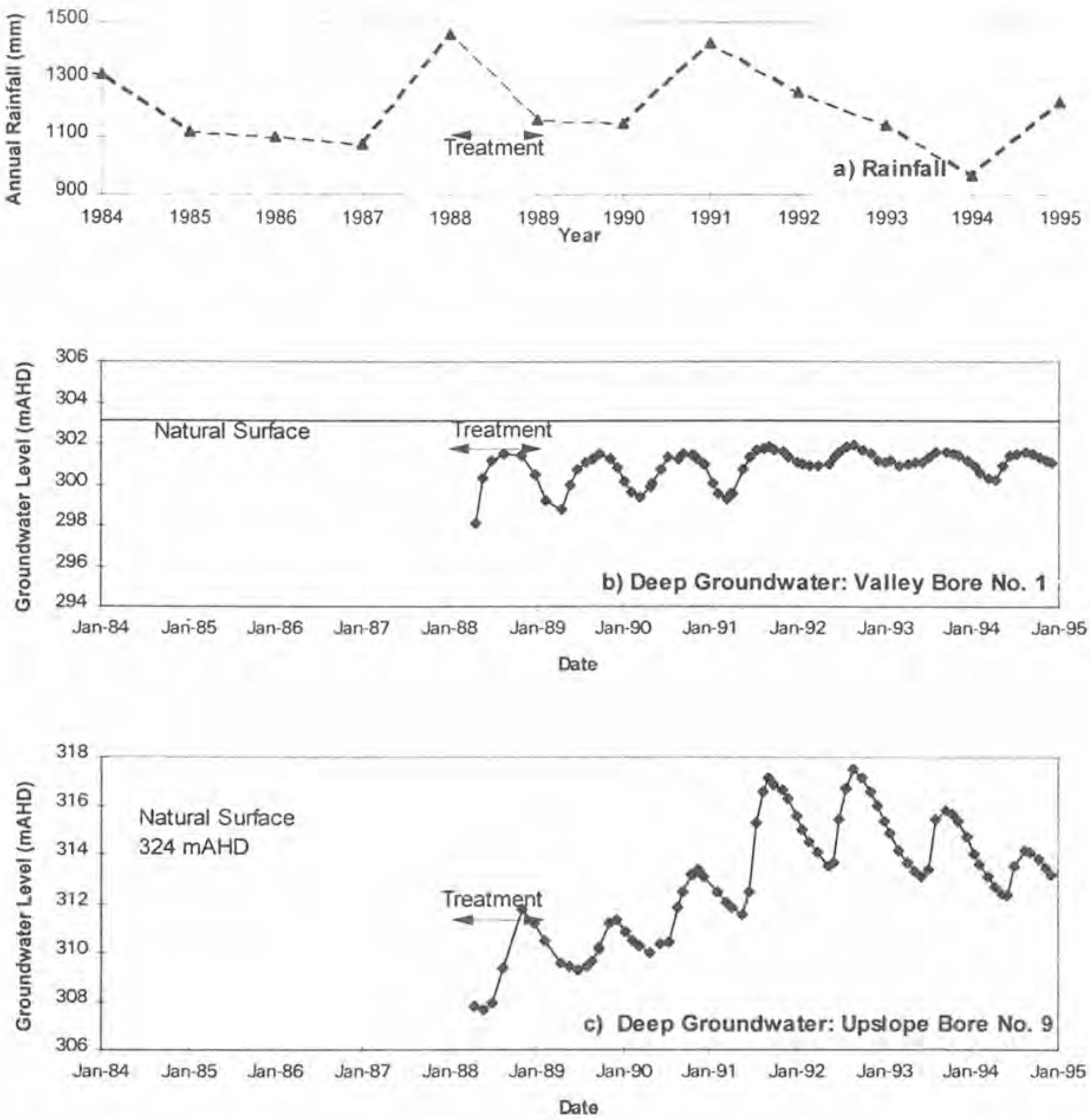


Figure 9: Annual Rainfall and Groundwater Levels at Higgens

the control catchment, Lewis, did not increase over the monitor period (1988-1996), although water levels in the upslope bore were highly variable. This result is similar to other studies (Bari and Boyd, 1993; and Moulds *et al.*, 1994).

The increase in water levels following forest thinning results from increased groundwater recharge caused by a reduction of transpiration and interception. The increase continues until a new balance between groundwater throughflow and recharge is established. On the three treated catchments the bore data suggested that it took 3 and 4 years after thinning to establish this new balance. This result is similar to Moulds *et al.* (1994) who found, for a catchment in intermediate rainfall zone, that it took 5 years to establish a new balance between rainfall and groundwater level.

The magnitude of groundwater rise could not be related to the severity of thinning. Hansens catchment was thinned the most but of the three treated catchments the average recorded groundwater rise was

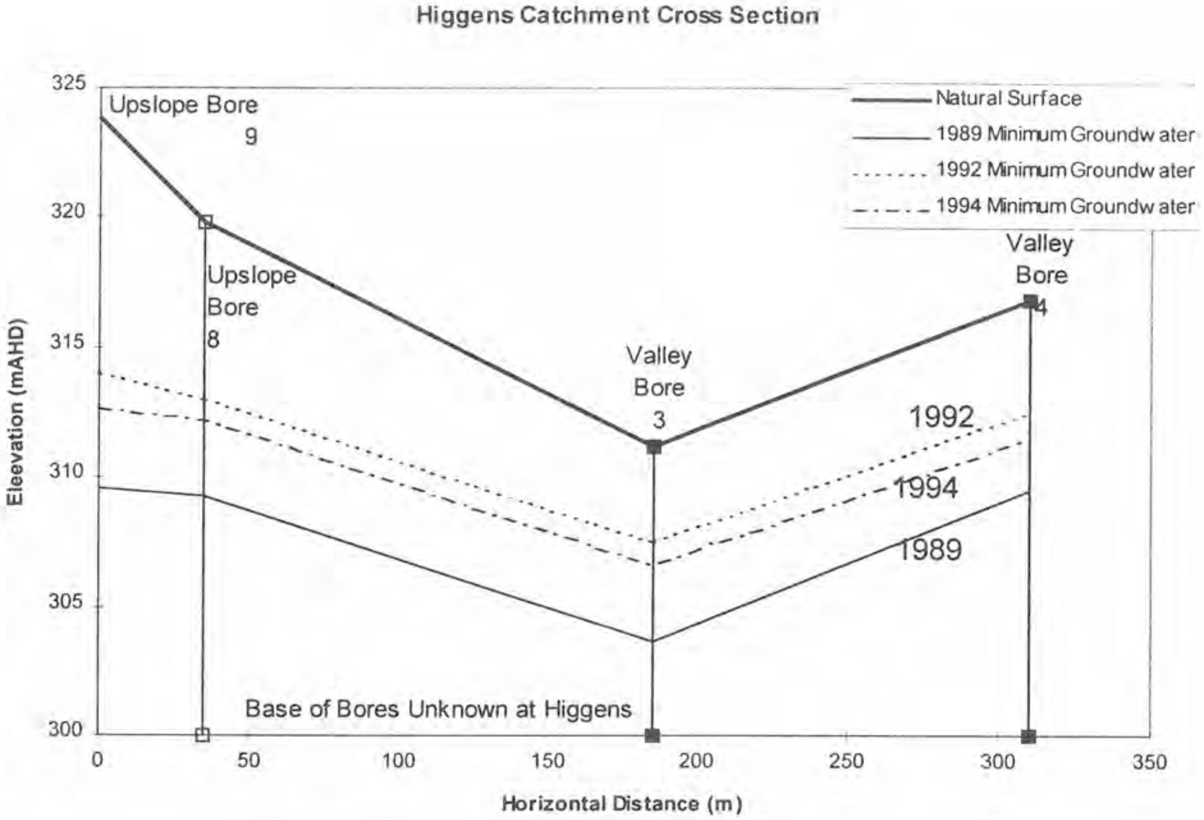


Figure 10: Groundwater level variation along cross-section at Higgens

the least, both in valley and upslope locations. Jones, which had the least thinning, had the largest rise. Therefore, it appears that local soil and geomorphic properties are more important in determining the magnitude of groundwater rise than the severity of thinning.

Groundwater rise in the valley areas was lower than in the hillslope areas. This was attributed to water table in the valley areas being closer to the ground surface.

3.4.2 Seasonal Variation

The rise in groundwater elevations in all the treated catchments has resulted in reduced seasonal variation in valley areas. To fully identify the mechanism for the decrease in seasonal variation requires further investigation. A possible explanation is that the proximity of the water table to the ground surface, especially near the stream channels, which may be constraining the maximum water levels and there by reducing the amount of seasonal variation.

3.4.3 Shallow Groundwater

Five bores at Jones and Hansens catchments monitored the presence of a shallow groundwater system, perched on caprock or clay. Permanent groundwater rose above the base elevation of four these bores. With infrequent sampling between 1989 and 1992, it is difficult to assess the effect of thinning on perched water systems in the catchments. Data at bore in Jones catchment suggests that the duration of the perched system has increased after thinning, due to increased recharge and reduced transpiration in the unsaturated zone.

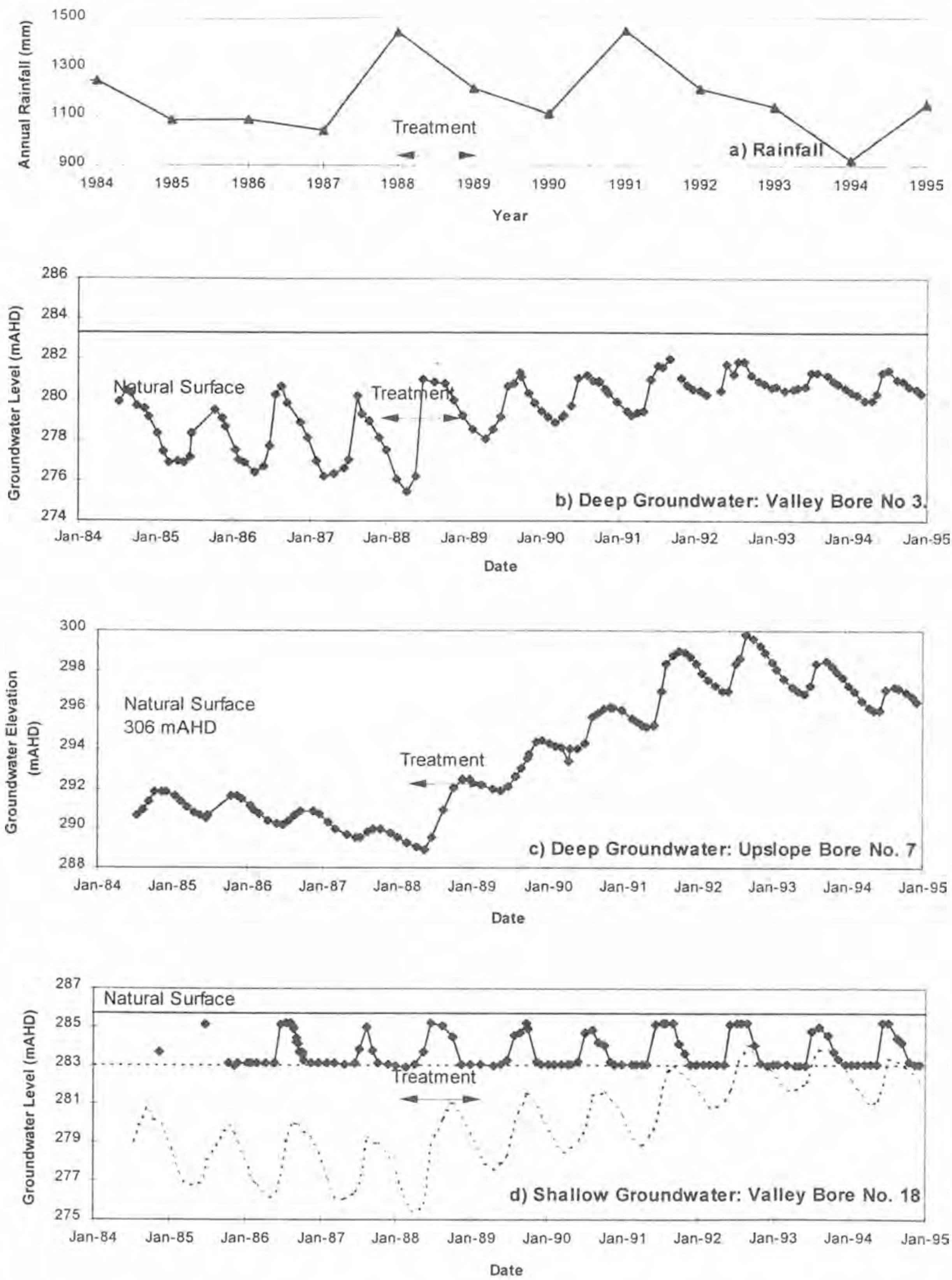


Figure 11: Annual rainfall and groundwater levels at Jones

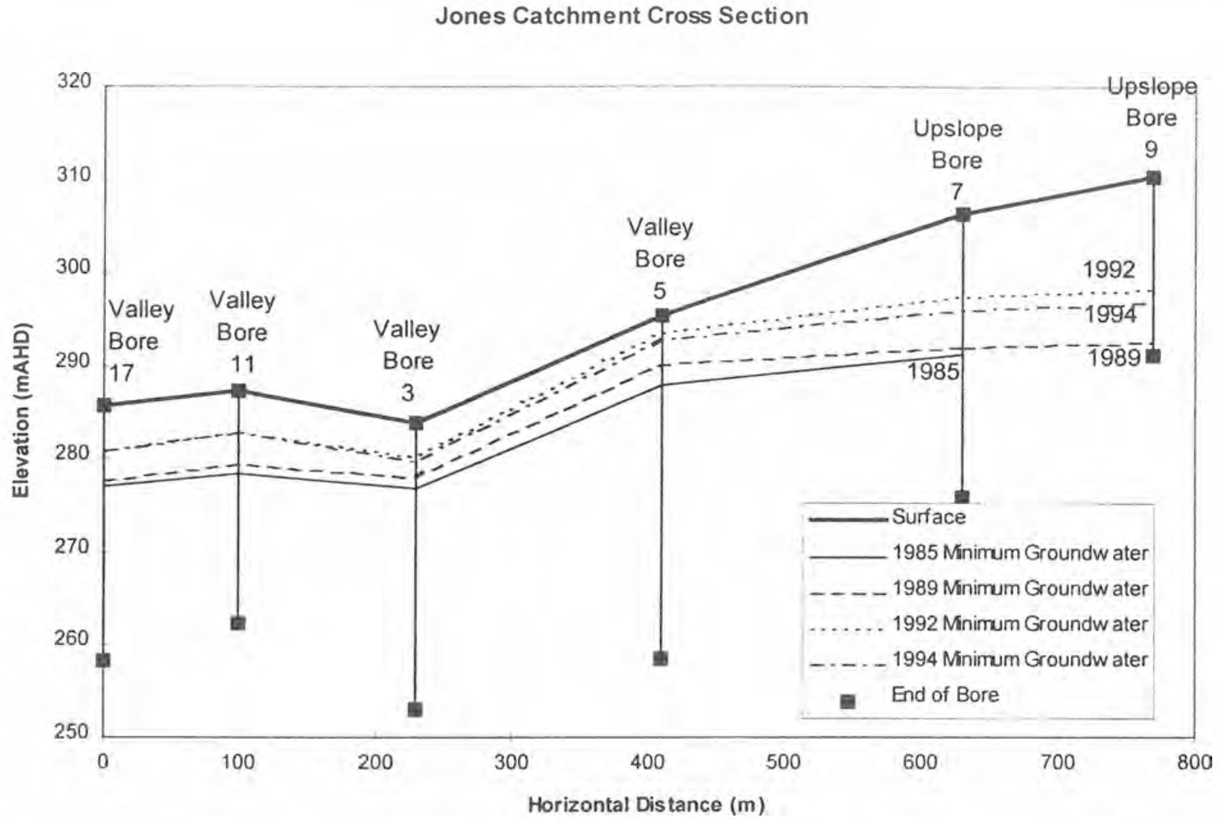


Figure 12: Groundwater level variation along cross-section at Jones

4. Streamflow

4.1 Streamflow Data

Streamflow records for the four catchments began in mid 1977 with the most recent records available being mid 1996. In this report records between 1978 and 1995 are analysed with incomplete years, 1977 and 1996, omitted from the analysis. During this period streamflow records are almost complete. Appendix A tabulates the number of days of missing record and describes the filling of these missing days.

Greenbase Consulting (1995) assessed the accuracy of streamflow records on Lewis and Hansens, and showed that the accuracy of the maximum (1978) and minimum annual streamflows (1992) for Lewis was $\pm$ 0.9% and $\pm$ 2.3%, and for Hansens was $\pm$ 0.2% and $\pm$ 1.2%, respectively. Less accurate measurement will apply to monthly and daily data. There is no assessment of the accuracy of the streamflows on Higgens and Jones.

4.2 Seasonal Streamflow Variation

Figure 13 shows daily streamflow for the four catchments during: (a) the first complete year (1978), (b) the year of maximum streamflow (1992), and (c) the most recent year (1995). The streamflow for each of these periods show a large seasonal variation with most streamflow occurring during the winter period (May and October) and, except for Hansens catchment, little streamflow during the summer.

1978 (pre-treatment) streamflow on Lewis and Hansens began in May and ended in October, with a small amount of baseflow that persisted until the end of the year. Higgens and Jones streamflow began two months later in July and ended in October. There was virtually no baseflow after October (Figure 13a).

For all catchments, 1992 (post-treatment) had the highest recorded streamflow and rainfall. The winter streamflow began in June and persisted until the end of the year. Lewis, Higgens and Jones catchments had very similar streamflow hydrographs. Hansens catchment, had much larger baseflow that persisted for the entire year (Figure 13b). These results are consistent with the level of forest thinning on the catchments. Higgens and Jones had similar thinned densities, with treatment basal areas of, respectively, 15 m^2/ha and 17 m^2/ha (Table 3). Hansens had the most sever treatment where thinning reduced basal area to 7 m^2/ha.

The temporal variation in streamflow during 1995 was quite similar on Lewis, Higgens and Jones. Winter streamflow began in June and ended in October, and baseflow persisted until the end of the year. As in 1992, Hansens had a higher and more persistent baseflow (Figure 13c).

4.3 Control Catchment Streamflow

In the study period annual streamflow at the Lewis control catchment varied between 28 mm (1979) and 199 mm (1992) (Figure 14a, Table 6). The runoff rate (streamflow/ rainfall) varied between 2.7% (1979) and 15.7% (1992) with the four highest rates occurring in the five most recent years of record (1991 to 1995). After removing climatic effects, the difference in runoff rates between the periods 1978-90 and 1991-95 was 4.5% $\pm$ 2.7% (95% confidence intervals). This was done by developing a regression relationship between runoff coefficient and annual rainfall, and then examining the statistics of the residuals. Appendix D provides more details. These results suggest that Lewis is unstable with runoff rates increasing in the study period's last five years.

The reason for the increase in runoff rates is unclear and requires further investigation. However, there are two probable causes. First, a reduction in vegetation density within the catchment due to die back, although there is no vegetation mapping to verify this hypothesis, the only vegetation study being made in 1981. Second, bauxite mining on the adjacent catchments has resulted in increased recharge and generally higher groundwater tables. We consider that the sequence of low rainfall years between 1975 and 1980 (Figure 2) can not account for the recent increase

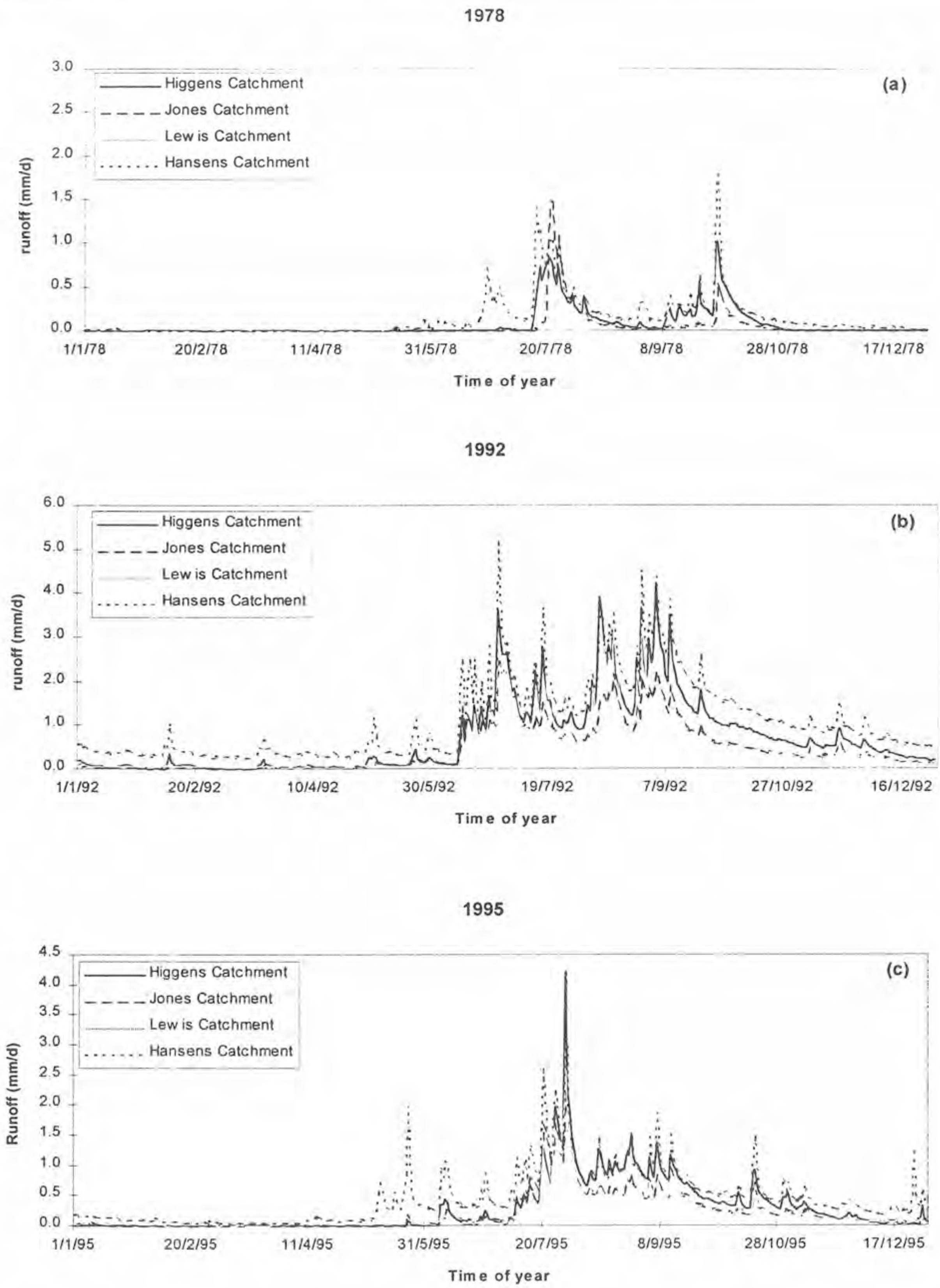


Figure 13: Daily streamflow for the years 1978, 1992 and 1995 for Lewis, Hansens, Higgens and Jones

in streamflow because there is no evidence for instability in the control between 1978 and 1990.

4.4 Annual Streamflow

4.4.1 Pre-treatment Streamflows

Hansens Catchment

Hansens' pre-treatment period was 1978 to 1985, during which streamflow varied between 26 mm and 114 mm with an average of 69 mm. The runoff rate had a mean of 5.4% and varied between 2.6% and 8.6% (Table 7). There appears to be a general increase in runoff over the pre-treatment period with the lowest runoff coefficients occurring in the first four years of record (1978-1981) (Table 7). Ruprecht *et al.* (1991) attributed this increase to a sequence of low rainfall years prior to 1980 (Figure 2). However, the average increase in the runoff rate of 0.44% per year over the pre-treatment period is not statistically significant (Appendix E).

Higgens Catchment

Higgens' pre-treatment period was 1978 to 1989. The streamflow varied between 6.6 mm and 39 mm and the runoff rate varied between 0.1% and 1.4% (Table 8, Figure 14 and Figure 15). There was a small increase in the runoff rate during the pre-treatment period, 0.16% per year, however the increase is not statistically significant (Appendix E). The mean streamflow and runoff coefficient for Higgens was 29 mm and 2.4%, respectively, which is more than half Hansens' pre-treatment runoff rates. The coefficients of variation, CVs, for the runoff rate and the runoff coefficient were, respectively, 0.67 and 0.62, which is much higher than the values of 0.49 and 0.42 calculated for Hansens.

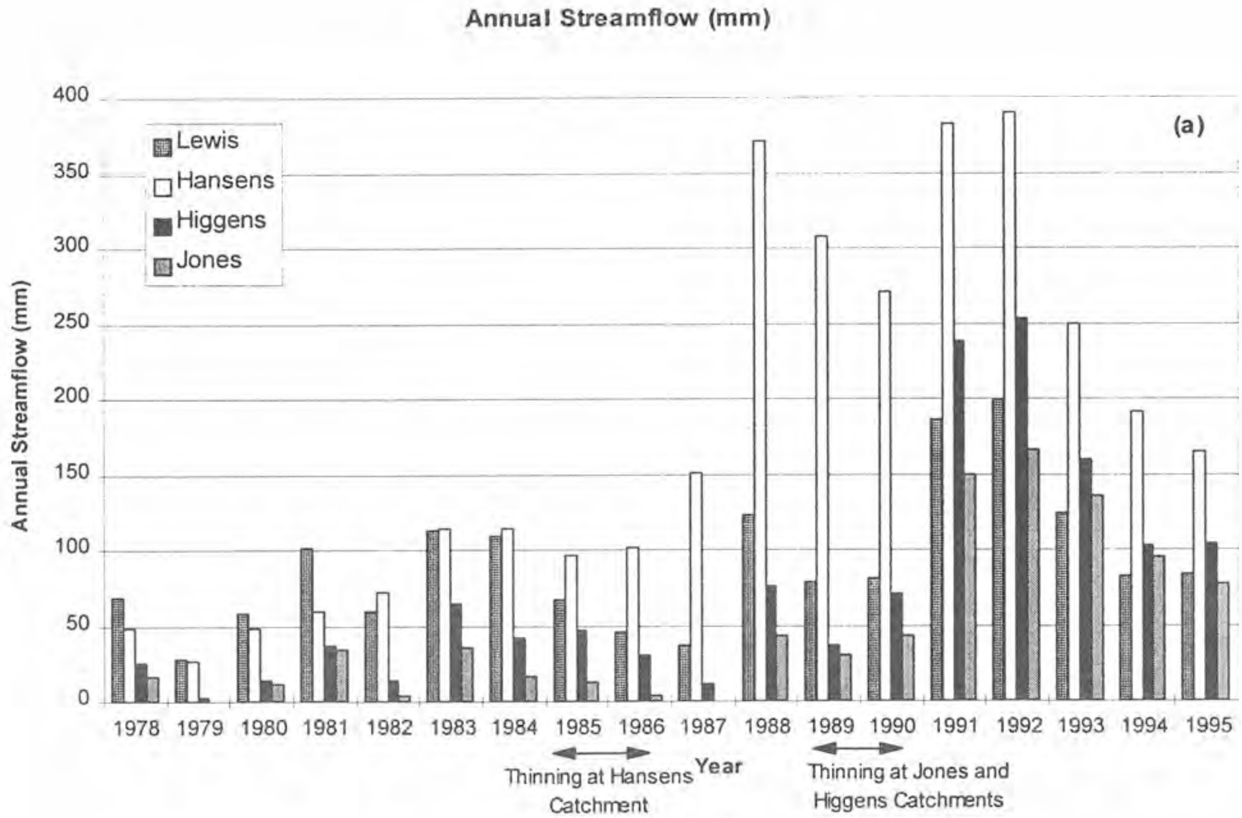


Figure 14: Annual streamflow (mm) for Lewis, Hansens, Higgens and Jones.

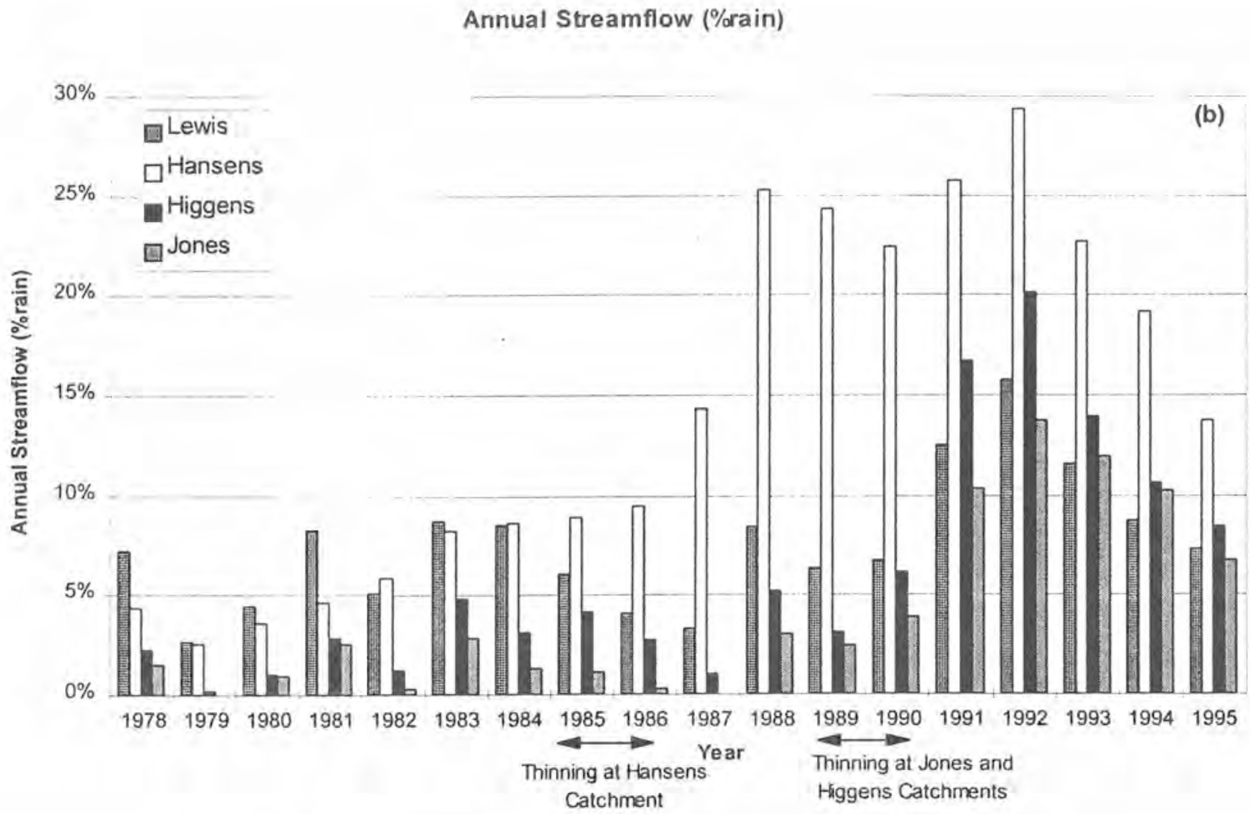


Figure 15: Annual streamflow (%rain) for Lewis, Hansens, Higgens and Jones

Jones Catchment

Jones had the same pre-treatment period as Higgens, 1978 to 1989. The annual streamflow on Jones had a range of 0 to 35 mm or 0 to 2.8% of rainfall (Table 9). There was no evidence of an increase in runoff during the pre-treatment period (Appendix E). The mean streamflow was 13 mm with the mean runoff rate being 1.1% (Table 5). These runoff rates are approximately half of those at Higgens and a quarter of Hansens'. The coefficient of variation of 1.1 for both annual streamflow and the runoff rate is also much higher than either Higgens or Hansens catchments.

4.4.2 Post-Treatment Annual Streamflow

Hansens Catchment

Post-treatment (1986-1995) streamflow varied between 101 mm and 390 mm, and annual runoff rates varied between 9.5% and 20.6%. The streamflow and runoff rate were, respectively, 257 mm and 20.6%, both of which are much greater than the pre-treatment means of 68 mm and 5.4%. These increases are possibly due to the thinning treatment on the catchment, but they could also be due to changes in climate.

To examine the effect of thinning on Hansens independently of any climatic changes Ruprecht *et al.* (1991) used a paired catchment approach with Lewis as a control. However, we can not adopt this approach because Lewis is unstable during part of the post treatment period (1991-1995) (Section 4.3). Instead, we use the pre-treatment period to establish rainfall runoff relationships that we can compare to runoff recorded post-treatment.

Appendix E shows pre-treatment relationships between rainfall and streamflow developed for Hansens (both %rain and mm). These regressions use data from the period 1978 to 1984 with 1985 being omitted because of a 1984 spring burn on Hansens catchment (Ruprecht *et al.*, 1991). We use these two relationships to estimate streamflow for the post-treatment period as if no treatment had taken place. The difference between this predicted streamflow and the measured streamflow provides an indication of the change in streamflow attributable to the thinning treatment and any subsequent regeneration.

For comparison to the methodology adopted above, Appendix F provides the analysis using the paired catchment approach with Lewis as a control. It shows similar increases to those shown in Figure 16 and Figure 17, however, the increases after 1991 are generally lower, corresponding to the period of instability at Lewis.

The increase in streamflow, suggest that it took until 1988 (2 years) to establish a new equilibrium between rainfall and streamflow. In the period 1988 to 1994 the average increase in streamflow was about 17% of rainfall or 220 mm with a maximum increase of 23% or 300 mm in 1992 (Figure 16 and Figure 17). After 1992 the increase streamflow declines to the end of the study period, 1995. In 1995 the increase in streamflow is 9% of rainfall or 100 mm, or about half of the initial increase. We may be able to attribute this decline in streamflow to forest regrowth following treatment. The basal area more than doubled from 6.5 m^2/ha in 1989 to 14.3 m^2/ha in 1996.

Higgens Catchment

In the post-treatment period (1989-1995) Higgens streamflow varied between 36 mm and 253 mm, and the runoff rates varied between 3.1% and 20.1%. The mean streamflow was 11.3% of rainfall or 137 mm, which compares to pre-treatment means of 2.4% of rainfall and 28.7 mm (Table 5). Thus, the streamflow post-treatment is considerably higher than pre-treatment. Figure 16 and Figure 17 show the estimated increase in streamflow. It shows that since treatment in 1989/90 the increase in streamflow reached a maximum in 1992 and then declined to the end of the study period. We may be able to attribute the decrease in the period 1992 and 1995 to regrowth. In 1991 Higgens had a crown cover of 29.1% and basal area of 13.5 m^2/ha, which then increased to 38.% and 17.6 m^2/ha in 1996.

Table 5: Summary of streamflow statistics for Lewis, Hansens, Higgens, Jones.

		Annual Runoff (mm)					Annual Runoff (%Rain)				
		Lewis[5]		Hansens	Higgens	Jones	Lewis		Hansens	Higgens	Jones
All years[1]	min	28		26.3	2.3	0.0	2.7		2.6	0.2	0.0
	max	199		390.2	252.8	166.3	15.8		29.3	20.1	13.8
	mean	91		175.3	73.6	48.5	7.5		14.1	6.0	4.1
	CV[4]	0.51		0.70	1.00	1.10	0.44		0.64	0.96	1.10
Pre-treatment[2]	min	28	28	26.3	2.3	0.0	2.7	2.7	2.6	0.2	0.0
	max	113	113	113.9	65.1	35.3	8.7	8.7	8.6	4.8	2.8
	mean	77	69	68.6	28.7	13.4	6.4	5.8	5.4	2.4	1.1
	CV[4]	0.41	0.44	0.49	0.67	0.95	0.37	0.38	0.42	0.62	0.90
Post-treatment[3]	min	36	76	101.3	36.3	29.9	3.3	6.4	9.5	3.1	2.5
	max	199	199	390.2	252.8	166.3	15.8	15.8	29.3	20.1	13.8
	mean	103	118	257.8	137.5	99.3	8.4	9.7	20.6	11.3	8.5
	CV[4]	0.53	0.39	0.40	0.60	0.53	0.46	0.37	0.30	0.53	0.50

Notes:

1. The period of record for all year is 1978-1995
2. The pre-treatment periods are taken to be 1978-1984 for Hansens, 1978-1987 for Higgens and 1978-1987 for Jones.
3. The post-treatment periods are taken to be 1986-1995 for Hansens, 1989-1995 for Higgens and 1989-1995 for Jones
4. CV is the coefficient of variation (i.e standard deviation divided by the mean)
5. Lewis is the control catchment and has had no forest treatments. The pre and post-treatment statistics correspond to the treatment periods on Hansens (left column) and Higgens and Jones (right column)

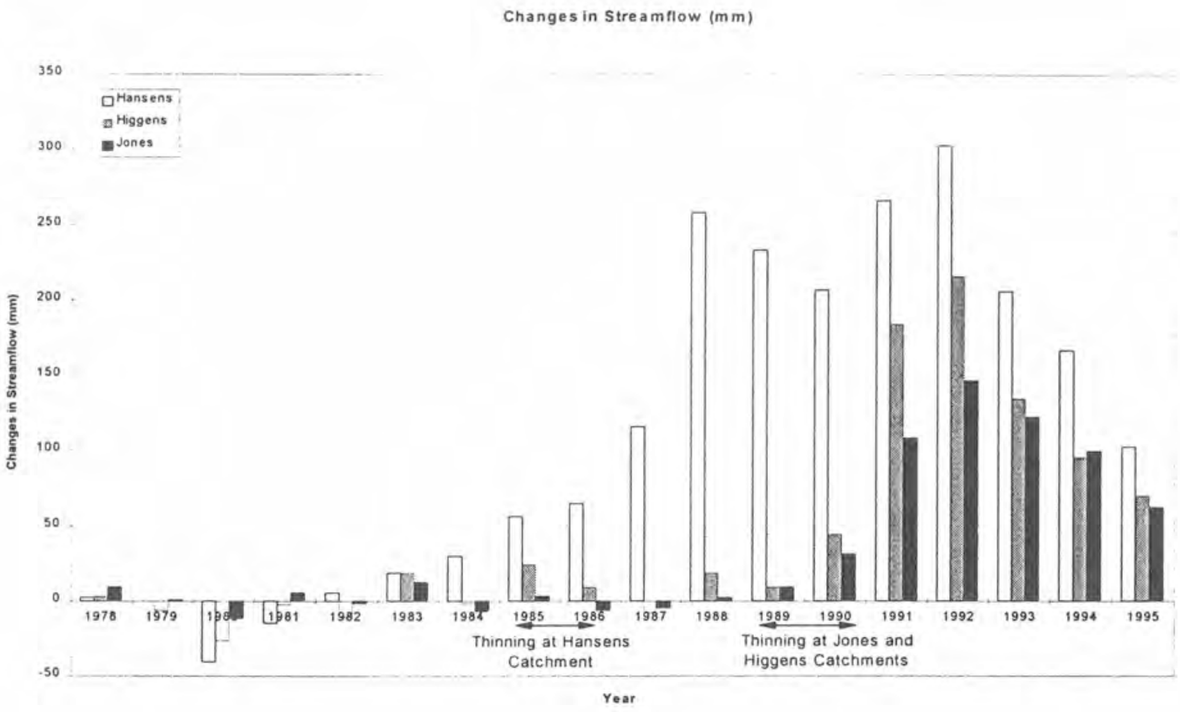


Figure 16: Changes in annual streamflow (mm) for Hansens, Higgens and Jones

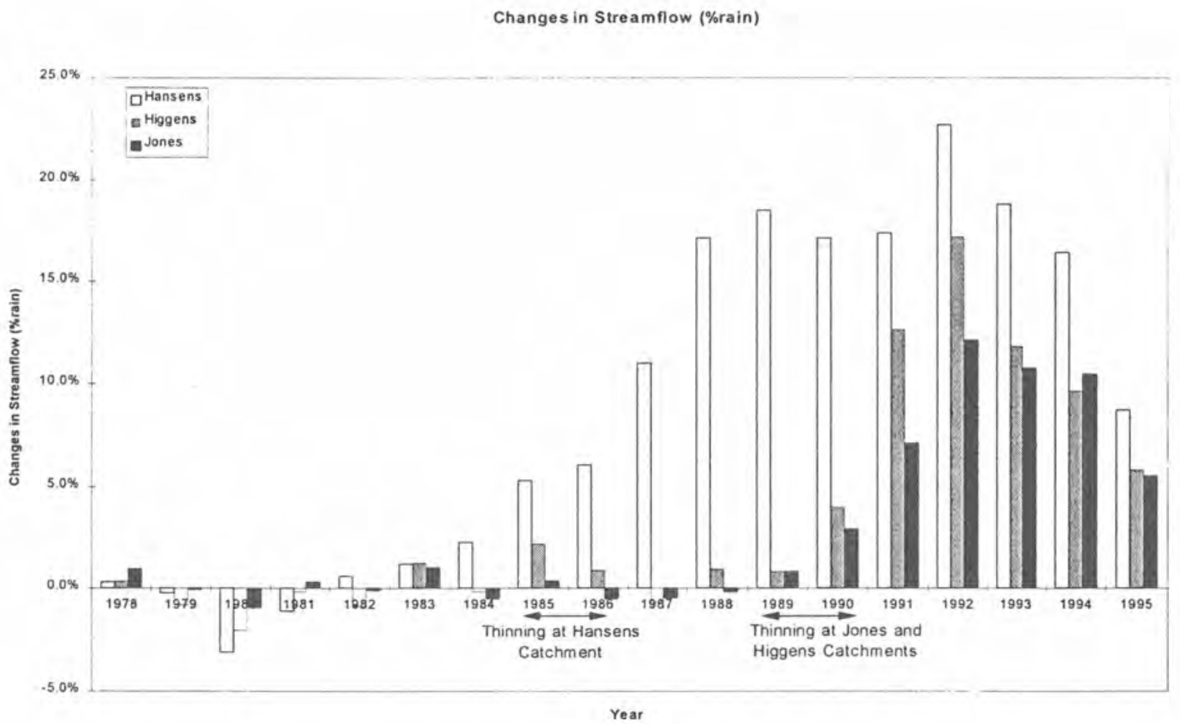


Figure 17: Changes in annual streamflow (%rain) for Hansens, Higgens and Jones

Table 6: Summary of annual streamflow and stream salinity data for Lewis

Year	Annual Rainfall (mm)	Total Flow (1000m^3)	Total Flow (mm)	Total Flow (%rain)	Baseflow/ Quickflow (-)	Load (Tonnes)	FWMS[1] (mg/L)	Peak Flow (m^3/s)
1978	943	136	68	7.2	0.9	16.2	119	0.119
1979	1047	56	28	2.7	1.0	6.9	123	0.033
1980	1322	118	59	4.4	1.0	13.4	114	0.040
1981	1229	204	101	8.3	0.9	21.2	104	0.123
1982	1145	119	59	5.2	1.0	13.4	113	0.027
1983	1301	227	113	8.7	1.0	22.7	100	0.112
1984	1278	218	109	8.5	1.0	24.1	110	0.059
1985	1095	134	67	6.1	1.0	14.9	111	0.077
1986	1112	92	46	4.1	1.0	10.4	114	0.037
1987	1090	73	36	3.3	1.0	8.3	113	0.077
1988	1450	246	123	8.5	0.9	24.1	98	0.127
1989	1233	158	78	6.4	0.9	17.8	113	0.071
1990	1200	162	81	6.7	1.0	18.3	113	0.051
1991	1488	375	186	12.5	1.0	36.1	96	0.320
1992	1261	400	199	15.8	1.0	41.8	105	0.138
1993	1078	250	124	11.5	1.0	27.5	117	0.106
1994	950	166	83	8.7	1.0	18.4	117	0.062
1995	1156	154	76	6.6	1.0	17.9	117	0.099

1. FWMS: Flow Weighted Mean Salinity
2. There was no forest thinning treatment on Lewis

Table 7: Summary of annual streamflow and stream salinity data for Hansens

Year	Annual Rainfall (mm)	Total Flow (1000m^3)	Total Flow (mm)	Total Flow (%rain)	Baseflow/ Quickflow	Load (Tonnes)	FWMS[1] (mg/L)	Peak Flow (m^3/s)
1978	1110	38	48	4.4	0.8	5.1	136	0.034
1979	1007	21	26	2.6	0.6	2.6	128	0.017
1980	1337	37	48	3.6	0.9	4.4	119	0.021
1981	1259	46	59	4.7	0.8	5.0	110	0.023
1982	1219	56	72	5.9	0.9	6.2	110	0.041
1983	1374	89	114	8.3	0.9	9.7	109	0.077
1984	1314	88	113	8.6	0.9	10.2	115	0.044
1985	1075	75	96	8.9	1.0	8.7	117	0.060
1986	1062	79	101	9.5	1.0	9.3	118	0.020
1987	1051	117	151	14.3	1.0	13.6	116	0.087
1988	1466	289	371	25.3	0.9	28.1	97	0.116
1989	1265	240	308	24.3	1.0	26.2	109	0.158
1990	1212	211	271	22.4	1.0	23.2	110	0.199
1991	1484	298	382	25.7	1.0	29.6	100	0.202
1992	1332	304	390	29.3	1.0	30.8	101	0.152
1993	1098	194	249	22.7	1.1	22.7	117	0.179
1994	996	149	191	19.1	1.0	17.0	114	0.184
1995	1199	129	165	13.8	1.0	15.1	117	0.169

1. FWMS: Flow Weighted Mean Salinity.
2. The treatment period for Hansens was in 1985-1986.

Table 8: Summary of annual streamflow and stream salinity data for Higgens

Year	Annual Rainfall (mm)	Total Flow ($1000m^3$)	Total Flow (mm)	Total Flow (%rain)	Baseflow/ Quickflow	Load (Tonnes)	FWMS[1] (mg/L)	Peak Flow (m^3/s)
1978	1113	15	26	2.3%	0.8	2.1	136	0.015
1979	979	1	2	0.2%	0.5	0.2	139	0.003
1980	1289	8	14	1.1%	0.9	1.1	128	0.008
1981	1277	22	36	2.8%	0.8	2.5	115	0.017
1982	1141	9	15	1.3%	0.6	1.1	127	0.008
1983	1354	39	65	4.8%	0.9	4.2	109	0.032
1984	1318	25	41	3.1%	0.9	3.1	125	0.012
1985	1120	28	47	4.2%	0.9	3.6	127	0.023
1986	1101	18	30	2.8%	0.9	2.4	133	0.009
1987	1078	7	11	1.0%	0.6	0.9	142	0.012
1988	1456	45	76	5.2%	0.9	5.2	115	0.015
1989	1161	22	36	3.1%	0.8	2.8	128	0.016
1990	1146	42	70	6.1%	0.9	5.4	128	0.015
1991	1426	143	238	16.7%	1.0	16.7	117	0.128
1992	1258	152	253	20.1%	1.0	18.3	121	0.081
1993	1141	96	159	14.0%	1.0	12.4	130	0.048
1994	965	61	102	10.6%	1.0	7.9	129	0.033
1995	1222	62	103	8.4%	1.0	6.9	111	0.05

1. FWMS: Flow Weighted Mean Salinity
2. The treatment period for Higgens was 1988-1989.

Table 9: Summary of annual streamflow and stream salinity data for Jones

Year	Annual Rainfall (mm)	Total Flow ($1000m^3$)	Total Flow (mm)	Total Flow (%rain)	Baseflow/ Quickflow	Load (Tonnes)	FWMS (mg/L)	Peak Flow (m^3/s)
1978	1056	11	16	1.6%	0.7	1.7	149	0.10
1979	972	0	0	0.0%	-	0.0	-	0
1980	1246	8	12	1.0%	0.9	1.2	146	0.013
1981	1302	23	34	2.6%	0.9	2.9	126	0.031
1982	1031	2	3	0.3%	0.8	0.4	162	0.020
1983	1241	24	35	2.8%	0.9	3.0	123	0.16
1984	1248	12	17	1.4%	0.9	1.6	133	0.007
1985	1084	9	13	1.2%	0.8	1.1	127	0.014
1986	1088	2	3	0.3%	0.8	0.3	142	0.004
1987	1038	0	0	0.0%	0.4	0.1	172	0.001
1988	1438	30	43	3.0%	0.9	3.5	117	0.018
1989	1208	21	30	2.5%	0.9	2.7	131	0.017
1990	1105	30	43	3.9%	1.0	3.9	132	0.016
1991	1444	103	149	10.3%	1.0	11.4	111	0.063
1992	1209	115	166	13.8%	1.0	13.0	113	0.032
1993	1134	93	135	11.9%	1.0	11.5	123	0.031
1994	923	65	95	10.2%	1.0	8.4	128	0.022
1995	1147	53	77	6.7%	1.0	7.3	137	0.024

1. FWMS: Flow Weighted Mean Salinity.
2. The treatment period for Jones was 1988-1989.

Figure 16 and Figure 17 show the difference between recorded and predicted streamflows for the period 1978 to 1995. The figures indicate that there is a large increase in flow during the post treatment period (1986-1995) that we attribute to thinning treatments. The small changes in streamflows during the pre-treatment period (1978-1985) are due to lack of fit in the pre-treatment relationships.

Jones Catchment

Like Higgens, Jones was treated in 1988/89. The average post-treatment streamflow was 8.5% of rainfall or 99 mm, which is about eight times the pre-treatment streamflow.

The coefficients of variation decreased considerably from around 0.9 pre-treatment to 0.5 post-treatment, indicating a considerable reduction in inter-annual streamflow variability.

To examine changes in streamflow attributable to forest treatments on Jones we used the same approach as adopted on Hansens and Higgens catchments. Appendices E and F present the analysis. The analysis shows that the increase in streamflow reached a peak in 1992 then decreasing throughout the remainder of the study period. The reduction from 150 mm in 1992 to 70 mm in 1995 was much less than on either Hansens or Higgens (Figure 16 and Figure 17). We attribute this to very slow regeneration of Higgens where there was very little change in both crown cover and basal area since treatment (Table 3). However, this also suggests that there has been a reduction in streamflow despite no change in the measured vegetation density.

4.4.3 Streamflow basal area relationship

Figure 18 shows a plot of streamflow against basal area for the years where basal area was measured. It indicates that there is a general increase in streamflow with a reduction in basal area. However, there is not an exact relationship between basal area and streamflow. There are a number of reasons for this: (i) the time it takes for the catchment to establish a new balance between streamflow and vegetation cover, (ii) climate characteristics, and (iii) differences between each catchments' geomorphological and soil characteristics. It may also depend upon the catchments' vegetation history.

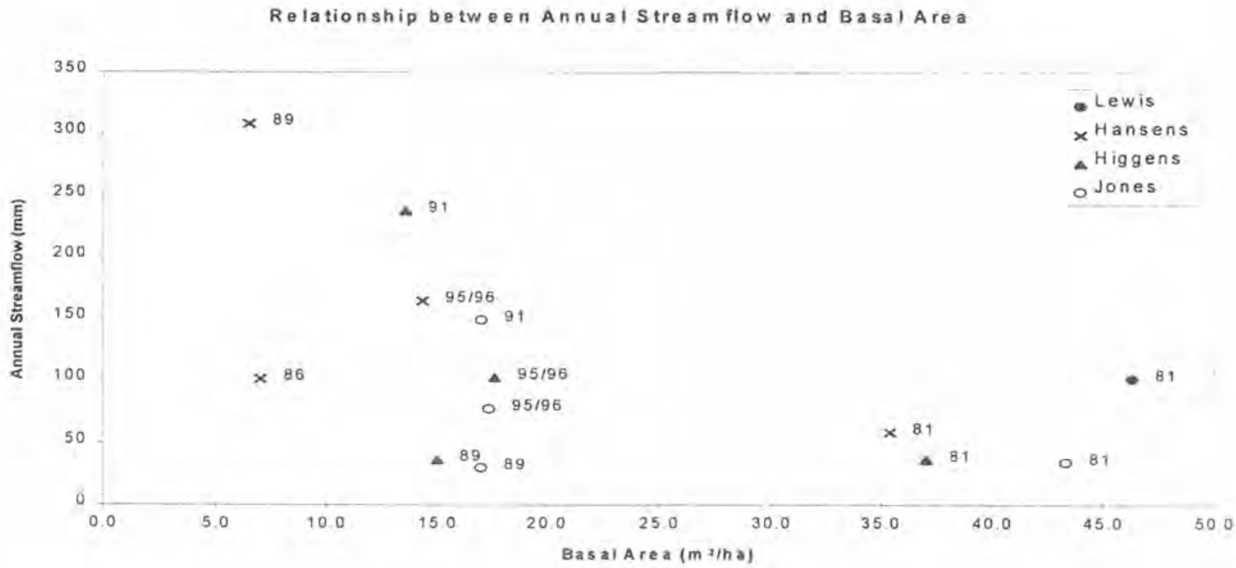


Figure 18: Relationship between annual streamflow and forest density

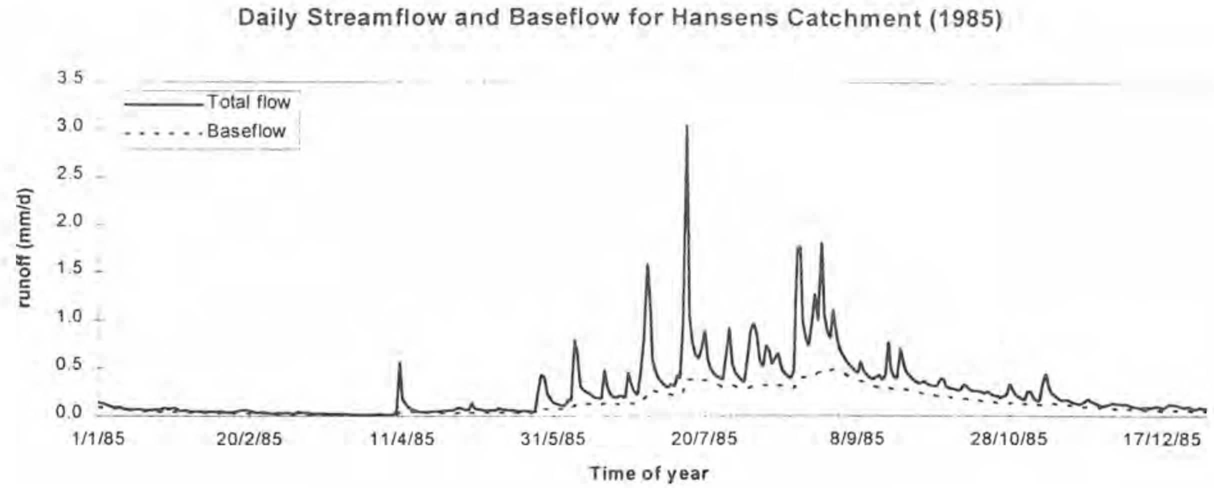


Figure 19: Baseflow separation for Hansens catchment

4.5 Baseflow and Quickflow

The examination of the seasonal variation in streamflow indicated that the duration of baseflow increased during the post-treatment period. To examine the changes in the amount of baseflow we used Chapman and Maxwell's (1996) separation algorithm to separate each catchments' streamflows into baseflow and quickflow components:

$$Q_b(i) = \frac{k}{2k} Q_b(i-1) + \frac{1-k}{2-k} Q(i)$$

where Q(i), Q_b(i) are the streamflow and baseflow at time $i\Delta t$ (Δt being the sampling interval), and k is recession constant that we set to a value of 0.95. Figure 19 shows, for an example, the separation obtained for Hansens during 1995.

The proportion of baseflow to quickflow for the study period is given in Table 6. The results indicate that on Lewis the baseflow to quickflow ratio remained around 1.0 for the entire study period, indicating that there is about the same amount of quickflow as baseflow (i.e 50% baseflow and 50% quickflow). On Hansens, Higgens and Jones the ratio pre-treatment was around 0.8 and then increases to 1.0 post-treatment, suggesting that the forest treatments have only resulted in a small increase in the total proportion of baseflow. However, there is a substantial increase in total baseflow because of the increase in total streamflow during the period of post-treatment. These results differ from that obtained by Ruprecht *et al.* (1991) because of the different separation algorithm used.

4.6 Annual Maximum Streamflow

The short periods of record prevent detailed analysis of the effects of forest treatments upon the catchment's flood frequency characteristics. However, Figure 20 to Figure 22 show the flood frequency curves derived for each catchment using the available data. One for the pre-treatment period and another the post-treatment period.

Figure 20 shows that the 2 year average recurrence interval (ARI) flood for Hansens is 0.03 m^3/s pre-treatment and 0.15 m^3/s post-treatment. However, the post-treatment flood frequency curve is much flatter so that the difference would be less for the larger, less frequent floods such as the 100 yr ARI. At Higgens the increase is from 0.01 m^3/s to 0.04 m^3/s (Figure 21) and at Jones the increase is from 0.007 m^3/s to 0.025 m^3/s (Figure 22). The slope of Higgens' flood frequency curve is about the same both pre- and post treatment while Jones' flood frequency is much flatter post-treatment.

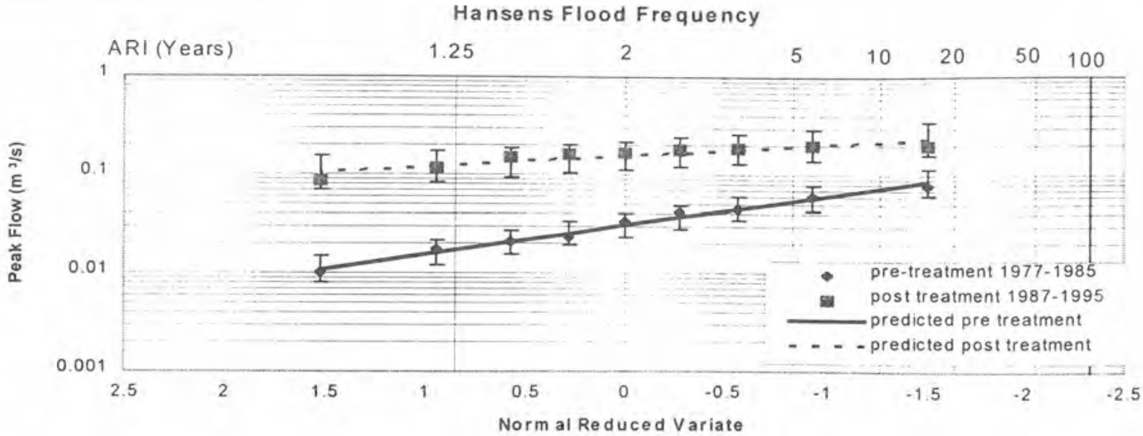


Figure 20: Flood frequency curves for Hansens

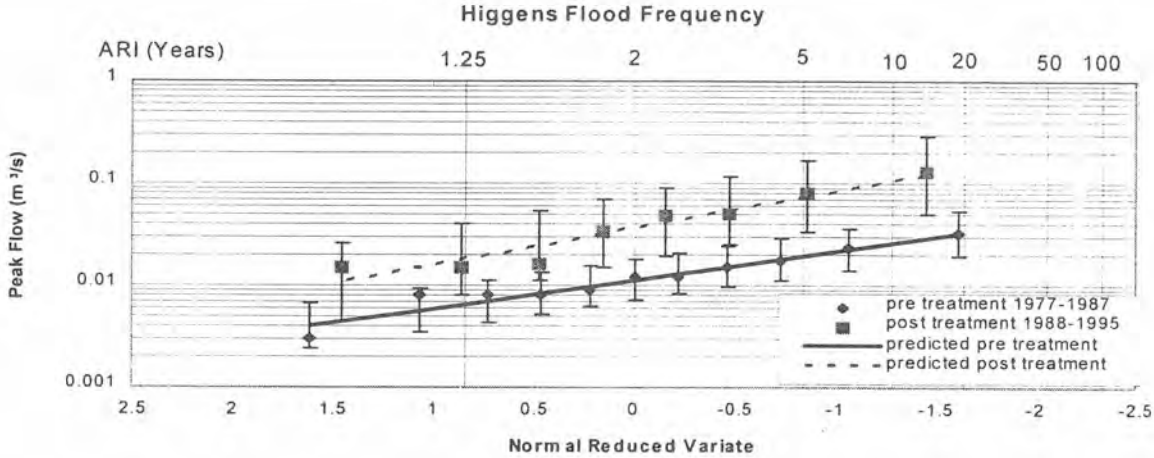


Figure 21: Flood frequency curves for Higgens

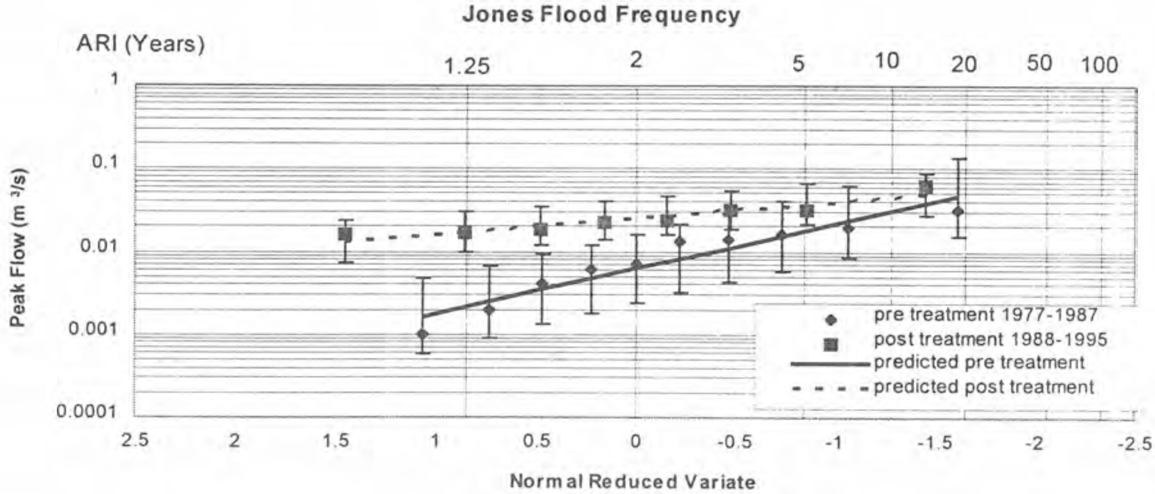


Figure 22: Flood frequency curves for Jones

4.7 Discussion

4.7.1 Seasonal Variation in Streamflow

Most of the streamflow on all four catchments occurred during the winter period. The effect of the thinning treatments was to increase the duration of this period, beginning about one month earlier and ending about two months later in December. Baseflow was also much more persistent. The baseflow on Hansens persisted throughout the year, and the baseflow on Higgens and Jones persisted until early March.

The physical mechanism for this change is the increased groundwater levels, following thinning, reducing the soil moisture deficit. This smaller deficit requires less rainfall to fill, and therefore streamflow is able to begin earlier. Similarly, the flow persists for longer.

These findings are similar to those observed in other studies in the Southwest of Western Australia (Bari and Boyd, 1993 and Moulds *et al.*, 1994). Bari and Boyd (1993), for the March Road catchment, which was clear felled, observed that the streamflow started two months earlier than in their control catchment, a year after logging. However, following subsequent regrowth, the seasonal variation returned to being approximately the same as at the control.

For our catchments, because of the instability at Lewis, it is unclear whether the seasonal variation is returning to the pre-treatment seasonal regime. The available evidence suggests that Higgens and Jones catchments are returning to their pre-treatment regime where in 1995, the streamflow for Lewis (the control), Higgens and Jones began at about the same time. For Hansens, in 1995, the streamflow is still significantly different from that of Lewis (Figure 13 c).

4.7.2 Annual Streamflow

After thinning there was a large increase in streamflow on all catchments. The streamflow then decreased following subsequent forest regeneration. This result is similar to other studies (Bosch and Hewlett, 1982; Bari and Boyd, 1993 and Moulds *et al.*, 1994). Hansens, recorded the largest increase, 300 mm, followed by Higgens, 220 mm, and Jones, 150 mm. These increases then reduced to 110, 65 and 55 mm, respectively, by the end of the study period.

Bosh and Hewlett (1982) predicted a 40 mm increase in streamflow per 10% reduction in forest cover for eucalypt forest types. Ruprecht *et al.* (1991) found that the increase in streamflow on Hansens catchment was approximately same as Bosh and Hewlett's (1982) prediction. Using basal area as a surrogate for forest cover the reduction in forest density on Hansens was 80% which corresponds to a predicted increase of 320 mm. This compares well to the estimated increase of 300 mm (Figure 16). As the forest regenerated the reduction in forest density from pre-treatment conditions was 60% in 1996 which corresponds to a predicted increase in streamflow of 230 mm. This prediction is much more than the estimated increase of 110 mm increase in 1995.

For Jones and Higgens catchments the predicted increase in streamflow was 240 mm (60% reduction in forest density in 1988/89) for both catchments. Following regeneration on Jones the predicted increase was 200 mm in 1995 corresponding to a 50% reduction in forest density (Table 3). There was no significant regeneration at Higgens. These figures correspond, respectively, for Higgens and Jones, to the observed increases of 220 mm and 150 mm in 1992 to increases of 65 mm and 55 mm at the end of the study period. These results suggest that Bosh and Hewlett's (1982) prediction provides a reasonable estimate of the initial streamflow response following thinning. However, after subsequent regeneration the observed increase in streamflow (from pre-treatment) is much less than that predicted.

One explanation for these results is that there may be some other processes operating to reduce runoff during the period of forest regrowth. For example, the catchments' vegetation structure may have changed. The field visit indicated a large amount of undergrowth on all catchments. Another explanation is that evaporative demand during the regrowth period is higher for a given vegetation density than the old forest that was thinned. That is the regrowth forest with a smaller basal area may, for example, have the same evaporative demand as the "old growth" forest with a larger basal area. There is not sufficient data to determine whether the streamflow would return to pre-treatment conditions if the catchments were allowed to fully regenerate.

The other explanation of our results is that our analysis of the data does not take full account of the climatic history. Our analysis relates annual streamflow to annual rainfall of that year. It does not take the rainfalls of previous years into account. Perhaps the high increase in runoff during 1992 is due to high rainfall in the previous years, 1987-1981. The decrease, in the period 1993-1995 may be due to the sequence of lower rainfall between 1992 and 1995. This may also be an explanation for the instability in the control catchment, Lewis where the streamflow between 1991-1995 was significantly higher than between 1978-1990. However, we do not consider that this is the case because there was no evidence in instability in the control in the high rainfall period between 1988-1990.

In conclusion, the annual streamflow had a rapid increase in streamflow after forest thinning. During regeneration the rate of streamflow decrease was higher than expected. Further investigations are required to find the mechanism for this decrease.

4.7.3 Annual Maximum Streamflow

All catchments showed large increases in their annual maximum floods, post-treatment, with the 2 year ARI floods increasing by between 500% (Hansens) 280% (Jones).

The variability in the peakflows (i.e the slope of the flood frequency curve) was lower on Hansens and Jones post-treatment than pre-treatment. This suggests that the forest treatments are unlikely to increase flood magnitudes of extreme events (eg. 100 yr ARI event). This is an expected result because the extreme floods are less sensitive to antecedent conditions.

The variability at Higgens was slightly larger post-treatment than pre-treatment, which is an unexpected result. However, we can see that this is consistent with the daily streamflow plots, (Figure 13) that show the streamflow at Higgens becomes more peaked in the post-treatment years. The likely explanation for Higgens' flood frequency appearing not to converge for large ARIs is that a lack of data in the extremes. If more data was available we would probably find that the post-treatment slope would decrease for large ARI events

5. Stream And Groundwater Salinity

5.1 Salt Storage

A measure of the potential stream salinity is the amount of salt stored in the soil profile. There is no soil salt storage information available for Jones, Higgens or Hansens catchments. However, ALCOA have recently installed boreholes on Lewis Catchment. For the 12 bores from which undisturbed soil samples were taken, the average, minimum and maximum mean volumetric soil salt storage was 0.093, 0.04 and 0.39 kg/m^3. These values compare to average values for the High Rainfall Zone of 0.15, 0.18 and 0.28 kg/m^3 for ridge, slopes and valley floor landscape locations (Tsykin and Croton, 1988). Thus, the soil salt storage for Lewis is typical for the High Rainfall Zone and it is likely that salt storage for Jones, Higgens or Hansens catchments also have typical low salt storage of the High Rainfall Zone.

5.2 Groundwater Salinity

Groundwater salinity monitoring at all catchments has been fairly irregular. A year of weekly and/or monthly monitoring occurred at Jones and Hansens catchments over 1984/85. Monitoring then ceased until 1988 when salinity measurements were recorded once or twice a year at most bores in all catchments. From this data average salinity was calculated for each year using at least one monitored bore, monitored on at least one occasion. Table C2 in Appendix C presents the averaged annual groundwater salinity (mg/L TSS) at each bore. Data was averaged for valley and upslope bores for each catchment. The time series generated from this data is displayed in Figure 23.

Data from the bores at Hansens and Jones that were monitored weekly in 1984 and 1985 indicate that groundwater salinity can change by up to 80 mg/L TSS over one season (Figure 23). In the later monitored period, for many bores, only one or two data points per year were available for analysis. The time series in Figure 23 have maximum variations between 90 and 117 mg/L TSS over the monitored period. There is no evidence of time trends in the data.

All catchments had measured groundwater salinity levels between 90 and 180 mg/L TSS, typical for the High Rainfall Zone. All levels were well below 500 mg/L TSS and thus classified as fresh water. Average Groundwater salinity levels ranged between 97 to 128 mg/L TSS at Lewis catchment. The average soil solute concentration for Lewis was 290 mg/L TSS from the twelve undisturbed core samples. This is much less than 500 mg/L TSS and means that even if all the salt in the profile were mobilised into the groundwater it would still be classified as fresh. It is likely that similar groundwater salinities at Hansens, Higgens and Jones catchments would also be explained by low average soil solute concentrations.

5.3 Stream Salinity and Salt Loads

Stream salinity was mostly measured by manual sampling. Lewis has had continuous salinity measurement since 1992. There is considerable variability in the number of samples taken per year varying between 2 to 67. Most of the low sampling years occurred in the first four years (1978 to 1982) after which the sampling rate increased to about 60 per year on Hansens and Lewis catchments and 20 per year on Higgens and Jones catchments (Table 10). The table shows that even in the low sampling years there is only a small standard error ~0.5%. This is because the variation in stream salinity is low on these catchments. Figure 23 shows flow weighted mean stream salinities and salt loads for each catchment.

Figure 23 indicates that stream salinity on Hansens and Lewis catchments is about 110-120 mg/L TSS while the stream salinities on Higgens and Jones are slightly higher and are in the range 120-130 mg/L TSS. These salinities are about the same as the groundwater salinities. Thus, streamflow on all four catchments is fresh (<500 mg/L TSS).

There is generally a log-log linear relationship between streamflow and stream salinity. As streamflow increases the salt concentration tends to decrease. This is because "low" streamflows contain proportionally more "high" salinity groundwater flow and less low salinity storm runoff. Figure 25 shows the streamflow-stream salinity regression relationships for each catchment derived using measurements from the pre-treatment periods. The figures show that the 95% confidence intervals are very large for the high post-treatment streamflows. This is because the post-treatment streamflows are outside the range of pre-treatment streamflows. Thus, it is impossible to assess if any change in stream salinity has taken place.

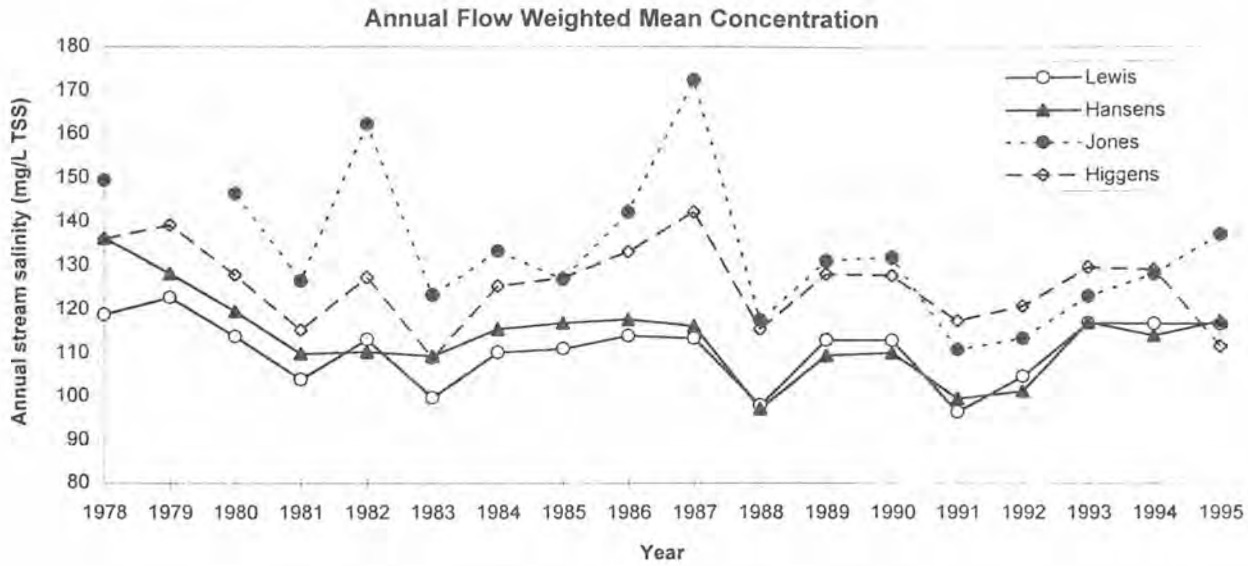


Figure 23: Annual flow weighted mean salinity concentration

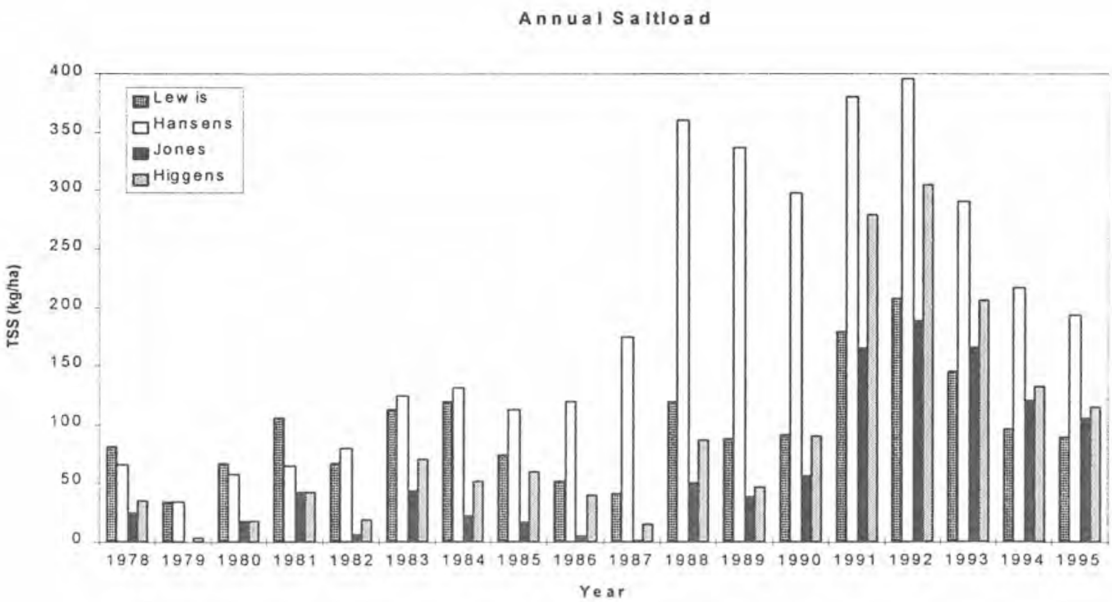


Figure 24: Annual salt load

Table 10: Summary of stream salinity sampling and concentrations

	Lewis				Hansens			
Year	No. Salinity Samples	Mean Stream Salinity (mg/L TSS)	Standard error in Mean Salinity (mg/L TSS)	Flow Weighted Mean Salinity (mg/L TSS)	No. Salinity Samples	Mean Stream Salinity (mg/L TSS)	Standard error in Mean Salinity (mg/L TSS)	Flow Weighted Mean Salinity (mg/L TSS)
1978	59	118	2	119	7	136	5	136
1979	52	118	2	123	5	128	6	128
1980	43	115	2	114	4	122	7	119
1981	62	115	1	104	8	111	5	110
1982	86	112	1	113	22	112	3	110
1983	51	112	2	100	40	115	2	109
1984	77	114	1	110	59	120	2	115
1985	56	116	2	111	51	122	2	117
1986	59	121	2	114	63	122	2	118
1987	52	124	2	113	60	122	2	116
1988	41	110	2	98	54	110	2	97
1989	63	120	1	113	61	115	2	109
1990	46	119	2	113	47	115	2	110
1991	55	113	2	96	50	112	2	100
1992	30	117	2	105	40	107	2	101
1993					44	118	2	117
1994					41	119	2	114
	Higgens				Jones			
Year	No. Salinity Samples	Mean Stream Salinity (mg/L TSS)	Standard error in Mean Salinity (mg/L TSS)	Flow Weighted Mean Salinity (mg/L TSS)	No. Salinity Samples	Mean Stream Salinity (mg/L TSS)	Standard error in Mean Salinity (mg/L TSS)	Flow Weighted Mean Salinity (mg/L TSS)
1978	4	136	6	136	4	8	4	149
1979	2	136	9	139	0	-	-	-
1980	2	128	9	128	3	9	3	146
1981	4	116	6	115	4	8	4	126
1982	14	131	3	127	9	5	9	162
1983	22	120	3	109	20	4	20	123
1984	29	128	2	125	26	3	26	133
1985	24	131	3	127	11	5	11	127
1986	21	133	3	133	11	5	11	142
1987	10	142	4	142	2	11	2	172
1988	26	121	2	115	20	4	20	117
1989	20	133	3	128	22	3	22	131
1990	15	132	3	128	15	4	15	132
1991	17	121	3	117	26	3	26	111
1992	35	127	2	121	35	3	35	113
1993	44	131	2	130	44	2	44	123
1994	25	135	3	129	40	3	40	128

Notes: Continuous Sampling at Lewis since 1992.

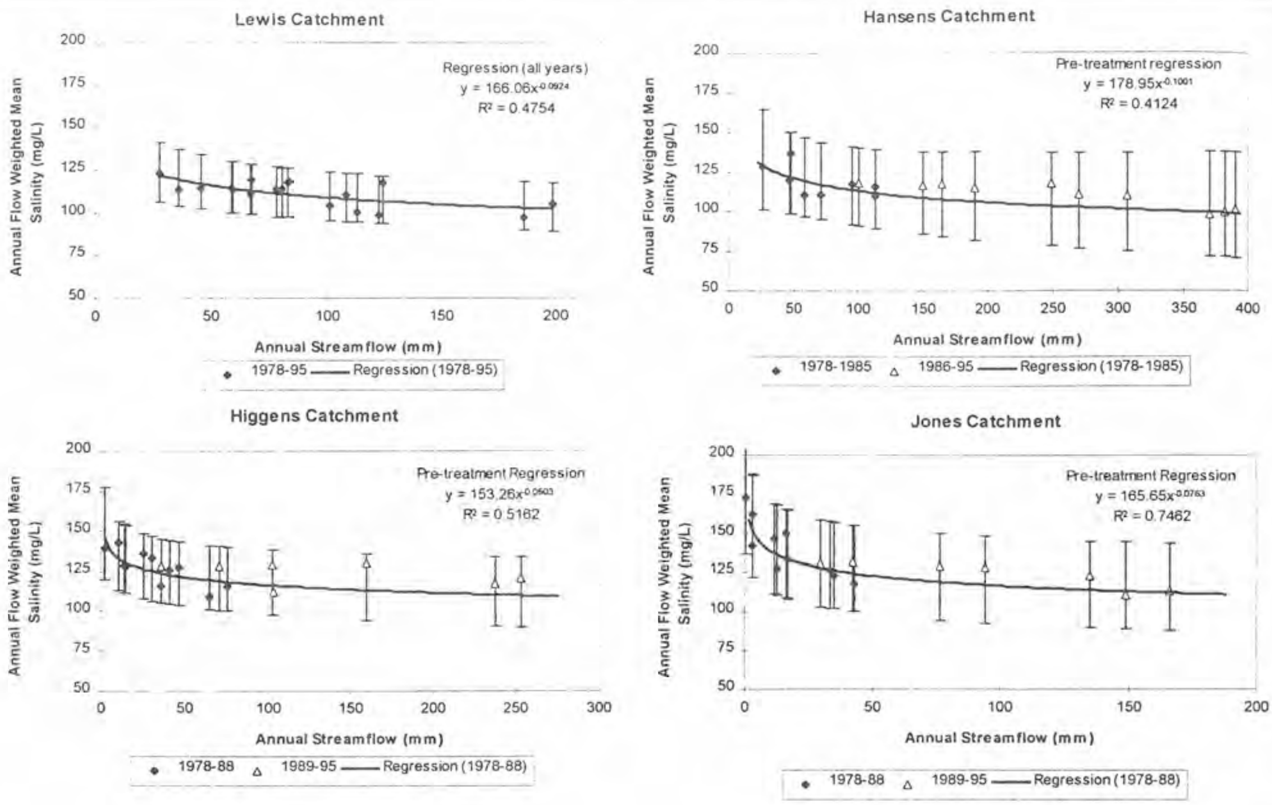


Figure 25: Stream salinity-streamflow relationships

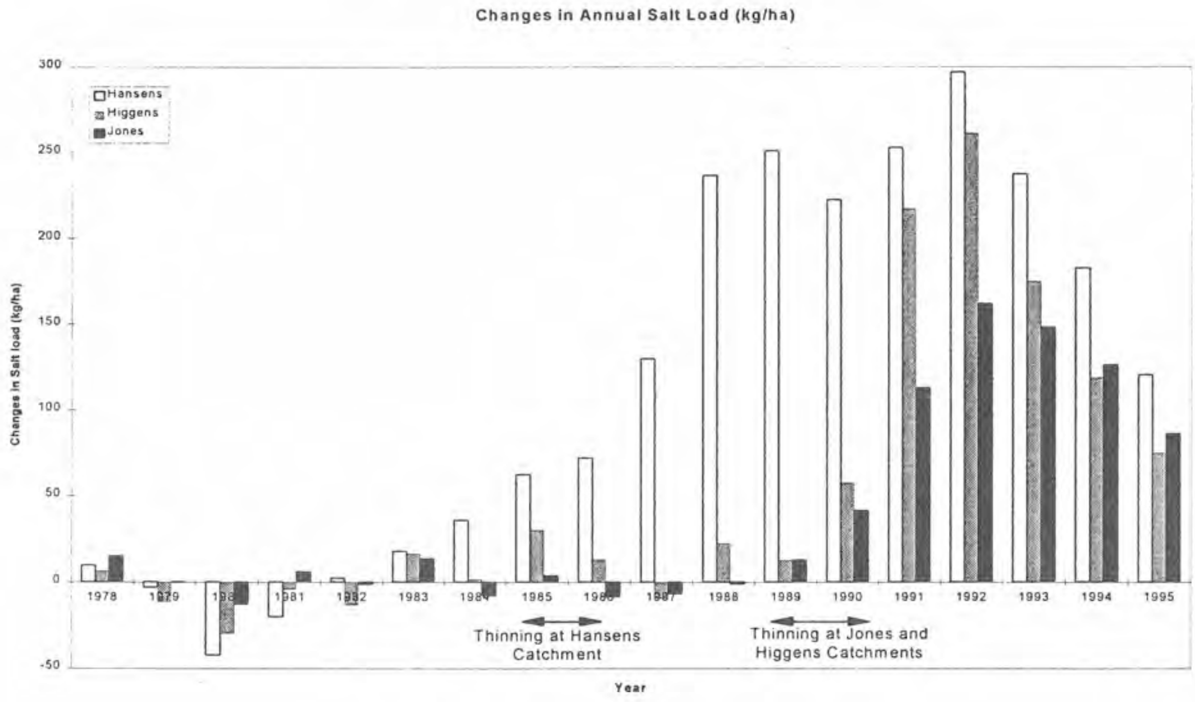


Figure 26: Changes in annual salt loads

Despite there being no evidence for changes in salinity concentrations, there is an increase in salt load post-treatment due to increased streamflow. Figure 24 shows the salt loads estimated for each catchment. The average salt load in the pre-treatment periods was 35.4, 17.8, and 94.5 kg/ha for Higgens, Jones and Hansens catchments, respectively and the post-treatment averages are 177, 123 and 286 kg/ha.

To estimate the increase in salt load we adopted a similar approach to that used to estimate the streamflow increase. We first developed pre-treatment relationships between salt load and rainfall and then used these relationships to estimate the salt load if no treatment had take place. The difference between this estimated salt load and the recorded salt load provides an estimate of the increase in salt load due to treatment alone. Appendix G shows the pre-treatment relationships for each catchment and Figure 26 shows the estimated change in salt load.

The trend in increase in salt load is very similar to the increase in streamflow (Figure 16), with Hansens having the highest increase and Jones the lowest increase. The increase at Hansens catchment was about 300 kg/ha with an maximum increase of 300 kg/yr in 1992. The increase in salt load then declined to the end of the study period. The increase in salt load at Higgens and Jones reached a maximum in 1992 of 250 kg/ha and 150 kg/ha, respectively. The increase in salt load then declined to the end of the study period.

5.4 Summary

Streamflow on all catchments is fresh (<500 mg/L TSS) for the entire study period. This result is typical for streamflow in the high rainfall zone because of low salt storage.

There is no evidence for an increase in groundwater of stream salt concentrations. There is however an increase in the total salt load due to increased streamflow.

6. Conclusions

6.1 Vegetation Regeneration

(i) After treatment Hansens had the largest increase in vegetation cover. Basal area at Hansens doubled from its thinned density of 7 m^2/ha in 1985/86 to 14 m^2/ha in 1996. Basal area at Higgens increased from 14 m^2/ha in 1988/89 to 18 m^2/ha. There was no significant regeneration at Jones since treatment in 1988/89. The basal area at Jones has remained around 17 m^2/ha.

6.2 Groundwater Level and Salinity

(i) After treatment groundwater levels have increased on all three catchments. The increase reached at maximum 3 to 4 years after treatment then decreased for the remainder of the study period. Hansens catchment had the most severe thinning treatment and the lowest increase in groundwater levels. It had an average increase between 1985 and 1990 of 2.28 m and 3.88 m in valley and upslope bores, respectively. In contrast, Jones had the least severe thinning treatment and the highest increase in groundwater levels. It had an average increase between 1988 and 1992 of 5.9 m and 7.3 m in valley and upslope bores, respectively. Higgens catchment had an increase between 1988 and 1993 of 3.6 m and 5.34 m in valley and upslope bores.

(ii) All catchments had low groundwater salinity concentrations (90 to 180 mg/L TSS). There was no evidence of an increase in salinity concentration during the study period.

6.3 Streamflow and Stream salinity

(i) Most of the streamflow on all four catchments occurred during the winter period. The effect of the thinning treatments was to increase the duration of this period. After subsequent regrowth the streamflow at Higgens and Jones appears to be returning to its pre-treatment regime. Hansens, in contrast, shows no signs of returning to its pre-treatment seasonal regime.

(ii) During the pretreatment period, streamflow ranged from 0.1% to 5.4% of annual rainfall across the catchments. Hansens catchment had the highest annual streamflow, ranging from 26 mm to 114 mm with an average of 69 mm. The annual streamflow at Higgens catchment ranged from 6.6 mm to 39 mm and averaged 29 mm. Jones catchment had the lowest annual streamflow during the pretreatment period, ranging from nil to 35 mm. The mean annual streamflow was 12 mm with the mean runoff rate being 1.1%.

(iii) After thinning there was a large increase in streamflow on all catchments. Hansens recorded the largest increase, 300 mm, followed by Higgens, 220 mm, and Jones, 150 mm. The increases then reduced to 110, 65 and 55 mm, respectively, by the end of the study period. This reduction is higher than expected given the small amount of regrowth on the catchments. There is insufficient data to assess whether the catchments will return to their pre-treatment conditions if the they were allowed to fully regenerate.

(iv) There was a large increase in the flood magnitude for low ARI floods. For the 2 year average recurrence interval (ARI) for Hansens is 0.03 m^3/s pre-treatment and 0.15 m^3/s post-treatment. At Higgens the increase is from 0.01 m^3/s to 0.04 m^3/s and at Jones the increase is from 0.007 m^3/s to 0.025 m^3/s. However, the data from Hansens and Jones suggest that the reduced variability of flood peaks will result in only small increases in the magnitudes of higher (eg 100 yr) ARI floods. More data is required to fully assess the effect of forest thinning on flood magnitude.

(v) Streamflow on all catchments is fresh (<500 mg/L TSS) for the entire study period. A typical result for catchments in the High Rainfall Zone. Lewis had annual mean salinities in the range 96 to 123 mg/L TSS and Hansens had salinities in the range 107 to 136 mg/L TSS. Higgens and Jones had salinities in the ranges 109 to 139 mg/L TSS and 111 to 149 mg/L TSS, respectively.

(vi) There is no evidence in an increase in stream salt concentrations. However, there is an increase in total salt load due to increased streamflow.

7. Recommendations

This report outlined a number of areas that require further investigation. These are outlined below.

1. The reason for the instability of the control catchment Lewis, requires investigation. It is recommended that an evaluation of all control catchments within the region be under taken.
2. It is recommended that monitoring of streamflow and rainfall be continued on all catchments. However, monitoring of groundwater levels and salinity, and stream salinity should be reduce to annual measurement.
3. It is recommended that a repeat thinning treatment should occur on one catchment to determine if the initial increase water yield can be sustained though continuous thinning.
4. It is recommended that a study be undertaken to combine the results of this study with other studies to develop a relationship between forest density and streamflow that can be used for water supply catchments.
5. It is recommended that a study be undertaken into the environmental impact of forest thinning upon the catchments.

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Appendix A: Filling Gaps in Streamflow and Rainfall Record

B.1 Rainfall

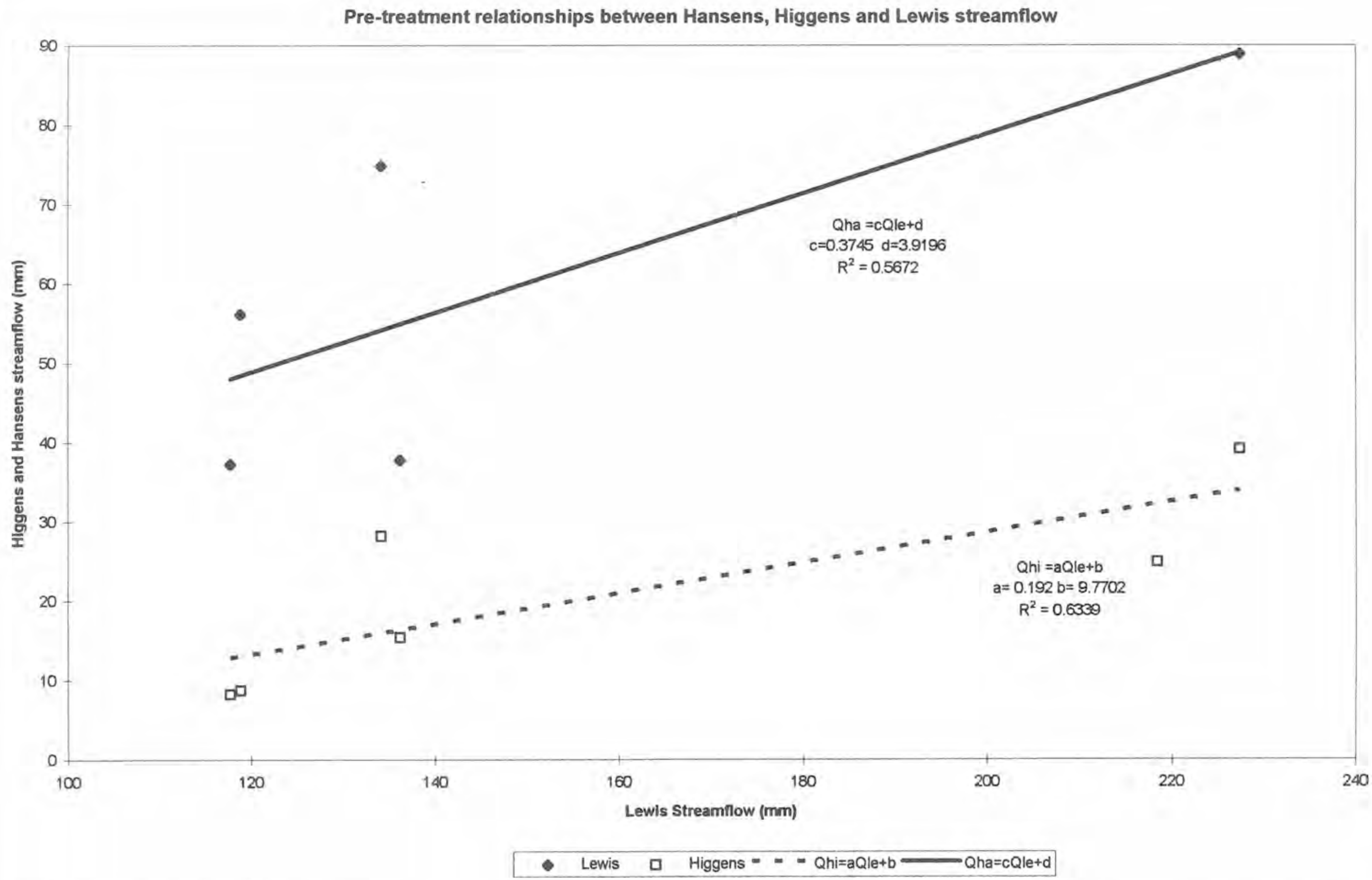
There were only a few gaps in the rainfall record that did not occur simultaneously. The gaps were filled using the average of rainfalls from the other catchments.

B.2 Streamflow

The gaps in the streamflow record are shown in Table B1. It shows that all the missing records occur pre-treatment. None of the missing days occur simultaneously. To fill the missing days relationships between annual streamflow at Lewis Catchment and annual streamflows on Higgens and Hansens Catchments were developed. Figure B1 shows these relationships.

Table A1: Missing days in streamflow record

	Hansen	Higgens	Jones	Lewis
Year	No. Missing Days	No. Missing Days	No. Missing Days	No. Missing Days
1978	0	0	0	0
1979	8	0	0	8
1980	0	0	0	0
1981	42	19	0	12
1982	0	0	0	0
1983	0	0	0	0
1984	22	0	0	0
1985	0	0	0	0
1986	0	0	0	0
1987	0	0	0	0
1988	0	0	0	0
1989	0	0	0	0
1990	0	0	0	0
1991	0	0	0	0
1992	0	0	0	0
1993	0	0	0	0
1994	0	0	0	0
1995	0	0	0	0



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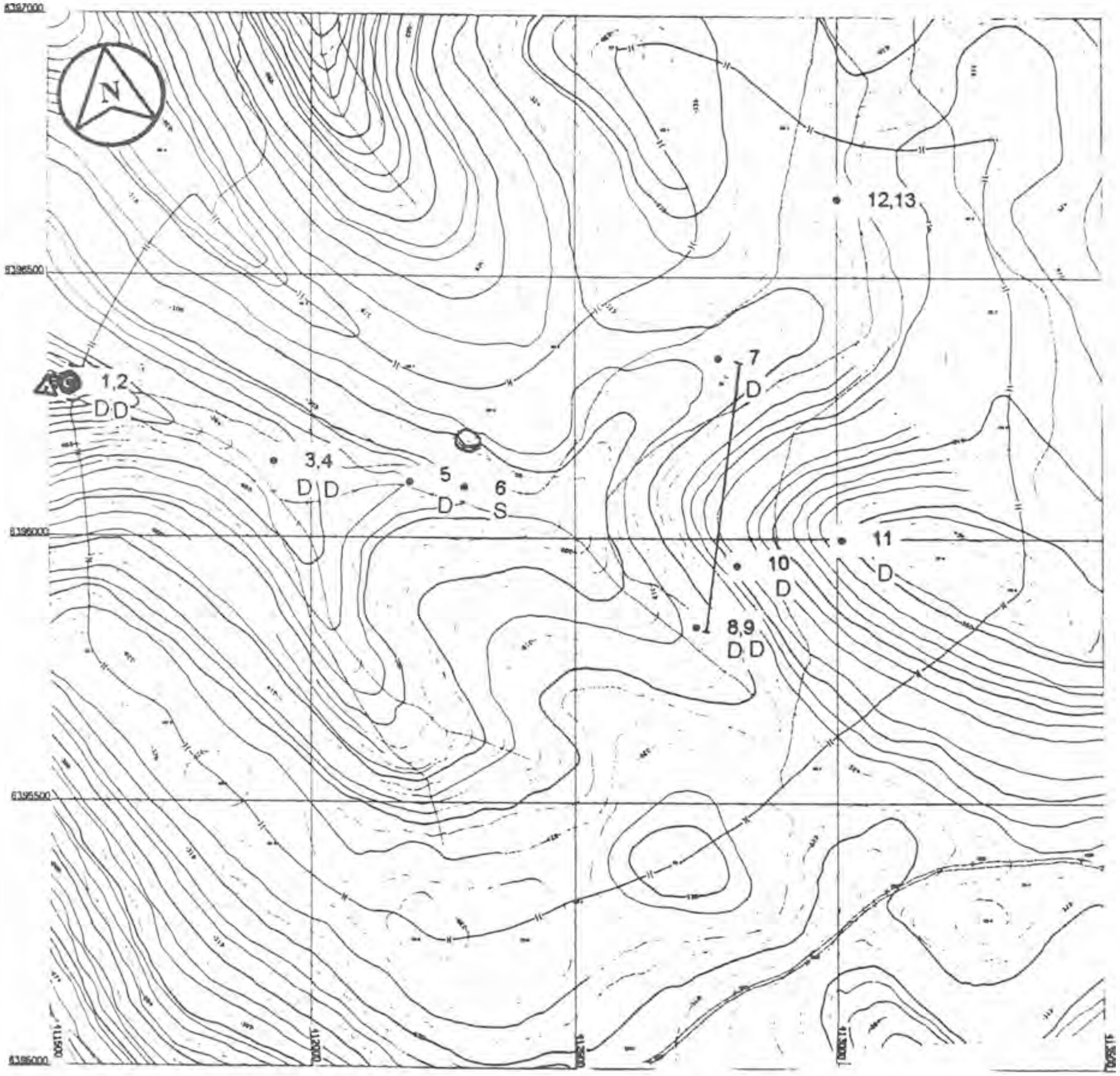
ACN 067 295 569 CONSULTANT HYDROLOGISTS PO BOX 117 SUBIACO W.A. 6008 Ph: 388 2436 Fax: 381 9279		Checked By:	**Hydrological Impact of Forest Thinning**
		Approved By:	Figure A1: Pre-treatment relationship between
	© COPYRIGHT JIM DAVIES & ASSOCIATES PTY. LTD. 1996	Date Issued:	Hansens, Higgens and Lewis Streamflow

Appendix B: Topographic and Hydrometric Network of Experimental Catchments



0 200m 400m 600m 800m

LEGEND

LEWIS	CATCHMENT BOUNDARY	—)(—
GAUGING STATION; PLUVIOMETER		O ; △
BORE (No. 614195) 09		09 ●
CONTOUR (A.H.D. DATUM)		— 304 —
DEEP BORE		D
SHALLOW BORE		S
CROSS SECTION TRANSECT		⊢—⊣

LEWIS CATCHMENT

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CONSULTANT HYDROLOGISTS
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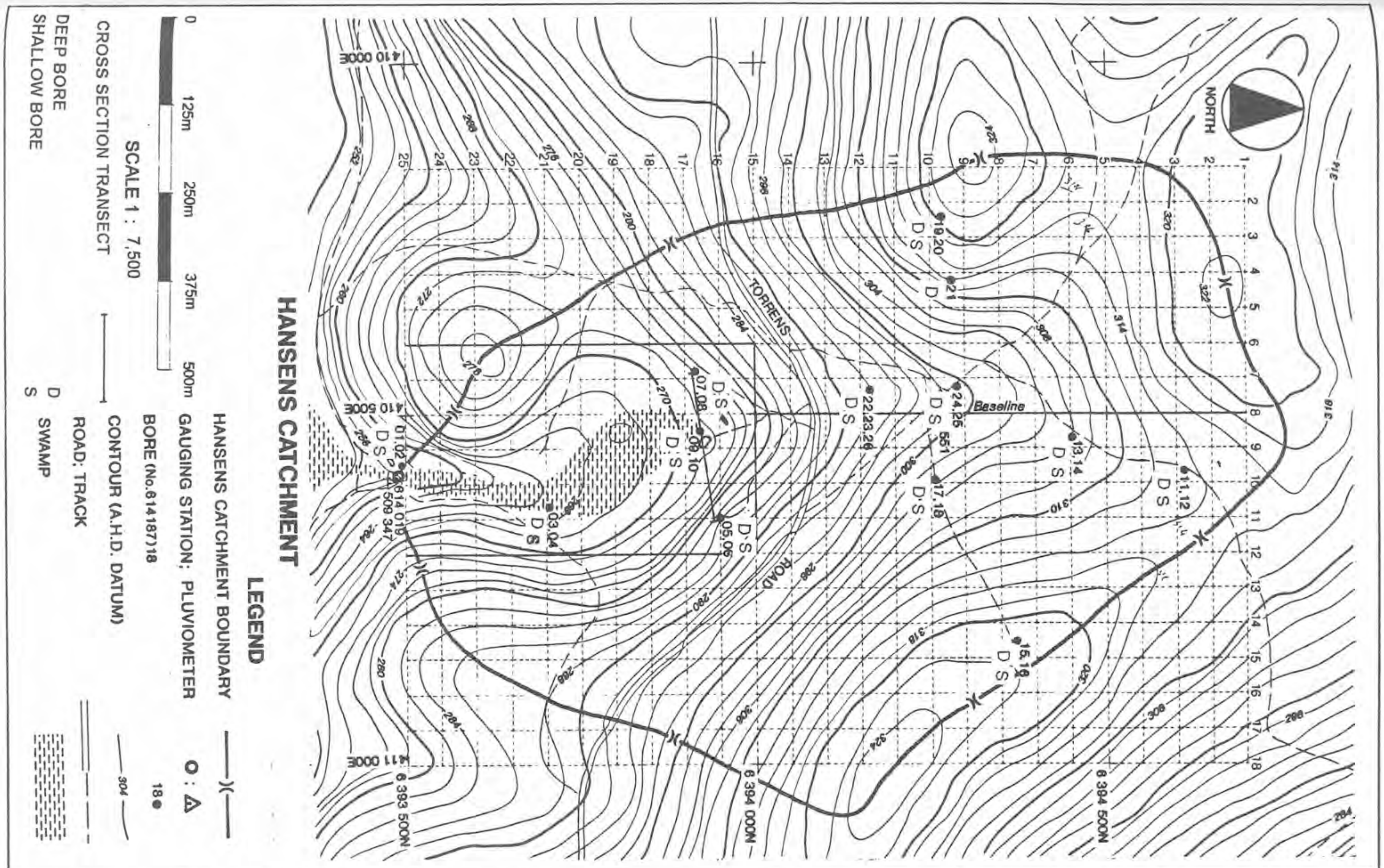
Prepared By:	**Water and Rivers Commission**
Checked By:	**Hydrological Impacts of Forest Thinning**
Approved By:	Figure B1: Lewis Catchment
Date Issued:	



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CONSULTANT HYDROLOGISTS		Approved By:	Figure B2: Hansens Catchment
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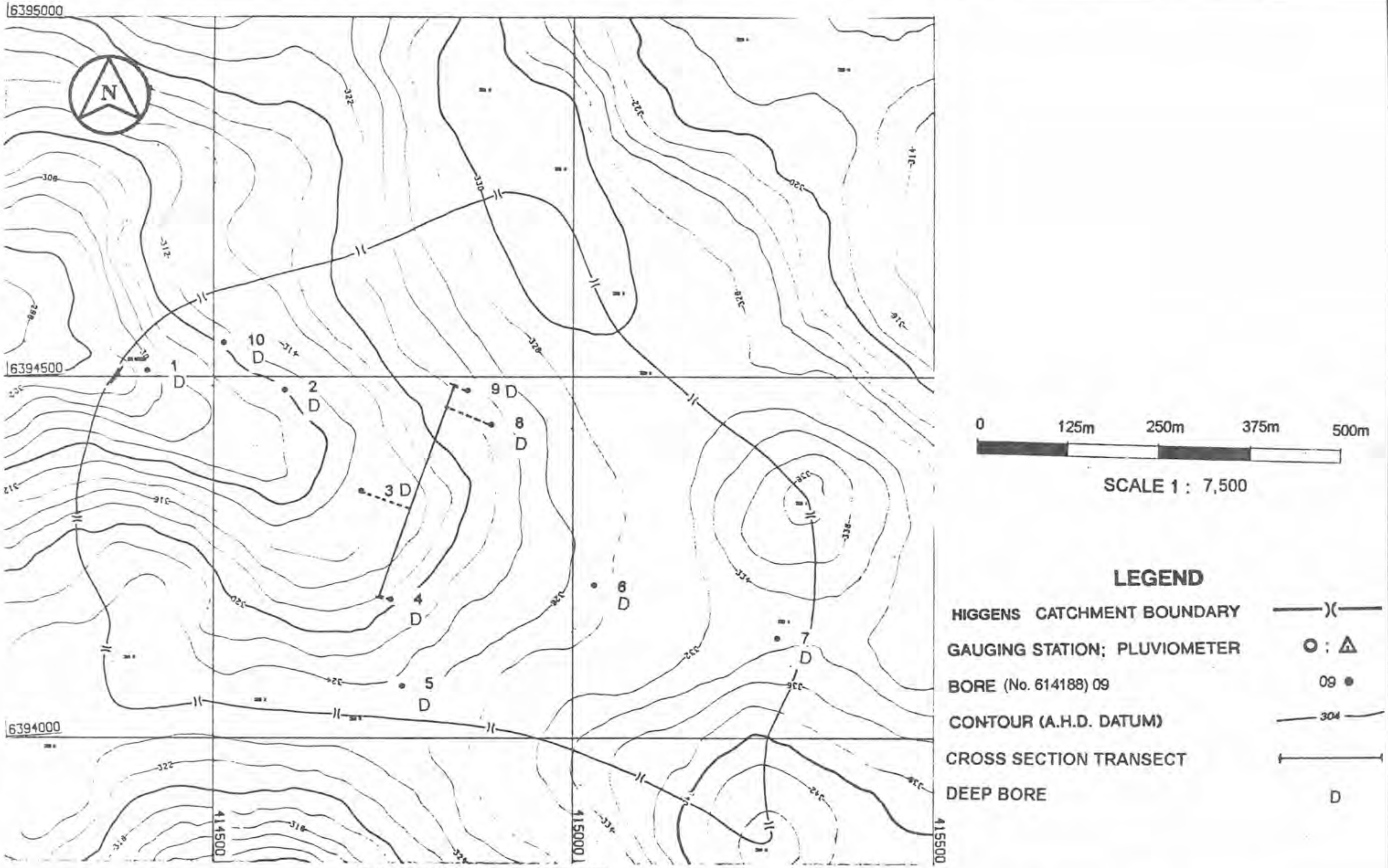

HIGGENS CATCHMENT

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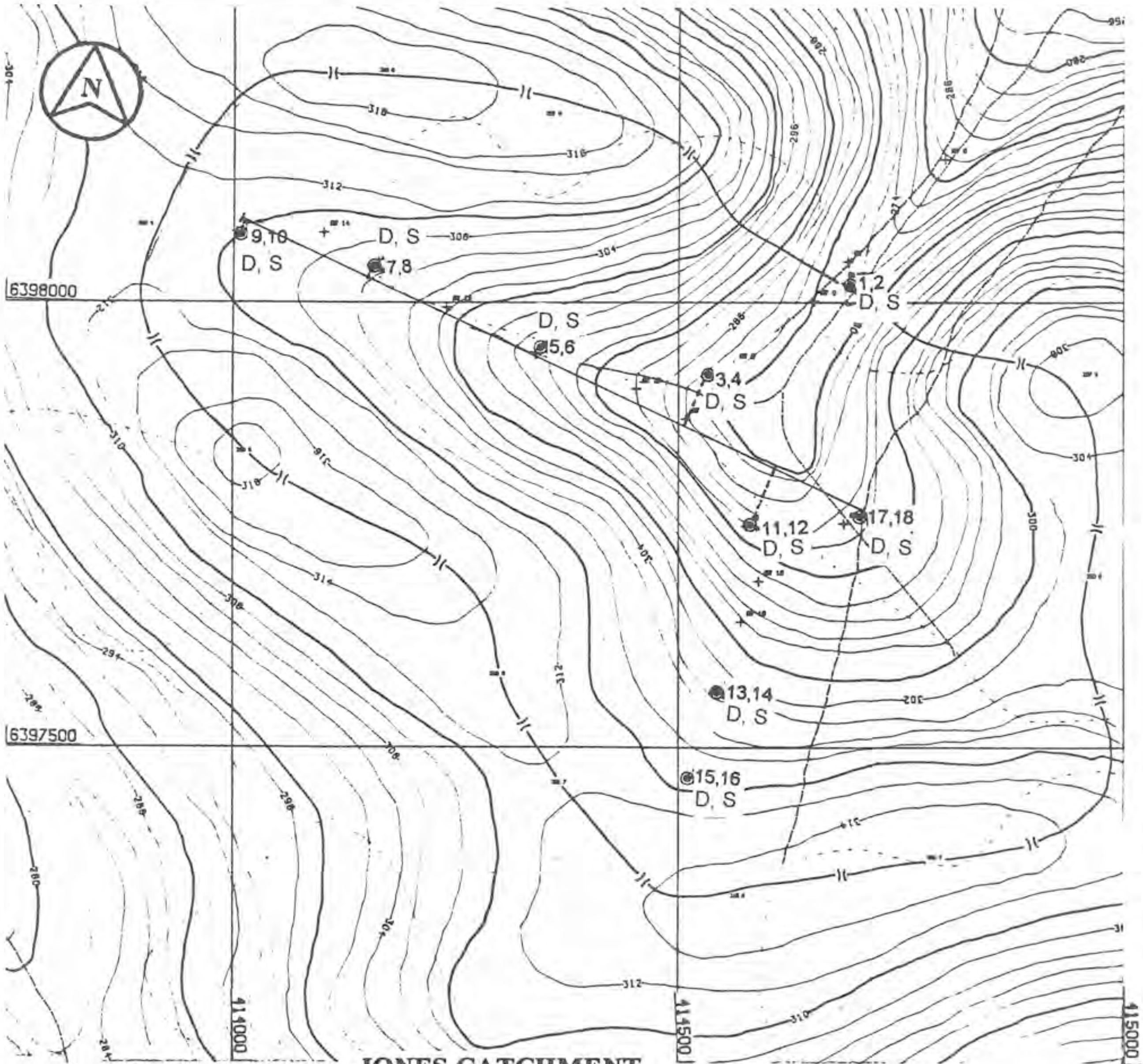
		Date Issued:	



JONES CATCHMENT

0 | 125m | 250m | 375m | 500m

SCALE 1 : 7,500

LEGEND

JONES CATCHMENT BOUNDARY	—)(—
GAUGING STATION; PLUVIOMETER	O : △
BORE (No. 614186) 09	09 ●
CONTOUR (A.H.D. DATUM)	— 304 —
CROSS SECTION TRANSECT	
DEEP BORE	D
SHALLOW BORE	S

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Water and Rivers Commission

Hydrological Impacts of Forest Thinning

Figure B4: Jones Catchment

Appendix C: Average Groundwater Salinity and Annual Minimum Groundwater Levels of Monitoring Bores

Table C1: Salinity in Monitor Bores (mg/L TSS)

Lewis - Bore No. 614195: 01 to 10

Bore No.	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	Average	Bore Type	Location
1	-	-	-	-	94.5	97.0	98.0	103.0	97.0	92.0	-	**96.9**	Deep	Valley
2	-	-	-	-	91.0	92.5	93.0	98.5	93.3	93.0	-	**93.6**	Deep	Valley
3	-	-	-	-	109.5	110.0	110.0	117.5	111.7	106.0	-	**110.8**	Deep	Valley
4	-	-	-	-	84.0	93.0	95.0	100.5	96.3	103.0	-	**95.3**	Deep	Valley
5	-	-	-	-	120.5	117.0	117.0	120.0	112.7	105.0	-	**115.4**	Deep	Valley
6	-	-	-	-	84.0	80.0	100.0	100.0	-	-	-	**91.0**	Shallow	Valley
7	-	-	-	-	112.5	124.0	126.0	127.5	119.0	119.0	-	**121.3**	Deep	Valley
8	-	-	-	-	96.7	98.0	105.0	108.0	101.0	92.0	-	**100.1**	Deep	Valley
9	-	-	-	-	108.5	67.0	113.5	85.0	96.7	94.0	-	**94.1**	Deep	Valley
10	-	-	-	-	104.5	104.0	98.5	106.5	96.7	95.0	-	**100.9**	Deep	Upslope
11	-	-	-	-	-	-	-	-	-	-	-	-	Deep	Upslope
Average	-	-	-	-	**100.6**	**98.3**	**105.6**	**106.7**	**102.7**	**99.9**	-	**101.9**		

Notes

1. Salinity Levels calculated as average of measured values in that particular year.

2. "-" Represents No SampleTaken.

Table C1: Salinity in Monitor Bores (mg/L TSS)

***Hansens** - Bore No 614187: 01 to 25*

Bore No.	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	Average	Bore Type	Location
1	148.3	148.5	-	-	-	150.0		145.0	146.0	139.0	140.0	**145.3**	Deep	Valley
2	169.4	181.0	-	-	-	-	-	81.0	108.5	155.0	168.0	**143.8**	Shallow	Valley
3	151.3	133.3	-	-	-	146.5	-	147.0	140.5	143.5	141.5	**143.4**	Deep	Valley
4	104.1	131.2	-	-	-	-	-	136.0	147.0	141.5	142.0	**133.6**	Shallow	Valley
5	105.2	101.8	-	-	-	131.5	-	113.0	123.0	121.0	117.0	**116.1**	Deep	Valley
6	65.6	65.2	-	-	-	-	-	-	-	-	-	**65.4**	Shallow	Valley
7	91.5	90.3	-	-	-	121.0	-	98.0	102.5	92.5	90.0	**98.0**	Deep	Valley
8	81.6	74.2	-	-	-	-	-	67.0	100.0	105.0	123.0	**91.8**	Shallow	Valley
9	111.9	113.5	-	-	-	108.0	-	112.0	112.0	112.0	111.0	**111.5**	Deep	Valley
10	63.6	81.8	-	-	-	-	-	95.0	98.5	99.5	126.5	**94.1**	Shallow	Valley
11	98.0	100.3	-	-	-	145.5	-	111.0	113.0	109.0	106.0	**111.8**	Deep	Upslope
12	-	-	-	-	-	-	-	-	-	-	-	-	Shallow	Upslope
13	104.9	111.8	-	-	-	116.0	-	112.0	80.5	108.5	113.0	**106.7**	Deep	Upslope
14	-	-	-	-	-	-	-	-	110.0	45.0	-	**77.5**	Shallow	Upslope
15	-	-	-	-	-	153.0	-	120.0	99.0	125.0	164.5	**132.3**	Deep	Upslope
16	-	-	-	-	-	-	-	-	-	-	-	-	Shallow	Upslope
17	117.0	120.3	-	-	-	85.5	-	99.0	137.5	108.0	114.0	**111.6**	Deep	Upslope
18	-	-	-	-	-	-	-	-	-	-	-	-	Shallow	Upslope
19	-	-	-	-	-	-	-	-	-	-	-	-	Deep	Upslope
20	-	-	-	-	-	-	-	-	-	-	-	-	Shallow	Upslope
21	-	-	-	-	-	-	-	-	-	-	-	-	Deep	Upslope
22	104.4	108.0	-	-	-	99.0	-	97.0	98.0	105.0	103.5	**102.1**	Deep	Upslope
23	-	-	-	-	-	-	-	71.0	88.0	89.0	88.0	**84.0**	Shallow	Upslope
24	38.1	42.9	-	-	-	72.0	-	71.0	126.5	82.5	84.0	**73.9**	Deep	Upslope
25	-	-	-	-	-	-	-	-	-	-	-	-	Shallow	Upslope
Average	**103.7**	**106.9**	-	-	-	**120.7**	-	**104.7**	**113.6**	**110.6**	**120.8**	**107.9**		

Notes

1. Salinity Levels calculated as average of measured values in that particular year.

2. "-" Represents No SampleTaken.

Table C1: Salinity in Monitor Bores (mg/L TSS)

Higgens - Bore No. 614188: 01 to 10

Bore No.	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	Average	Bore Type	Location
1	-	-	-	-	283.0	178.0	159.8	149.0	150.5	159.5	140.0	**174.3**	Deep	Valley
2	-	-	-	-	80.0	74.0	59.8	73.0	91.0	86.5	90.0	**79.2**	Deep	Valley
3	-	-	-	-	38.0	35.0	38.5	55.0	57.5	85.0	115.0	**60.6**	Deep	Valley
4	-	-	-	-	145.5	140.0	129.5	131.0	135.5	145.5	149.0	**139.4**	Deep	Valley
5	-	-	-	-	-	-	-	-	-	-	-	**-**	Deep	Upslope
6	-	-	-	-	134.5	123.0	123.3	120.0	118.5	121.0	117.0	**122.5**	Deep	Upslope
7	-	-	-	-	134.5	115.0	109.8	111.5	110.0	118.5	112.5	**116.0**	Deep	Upslope
8	-	-	-	-	224.5	233.0	198.0	144.5	130.0	131.5	124.0	**169.4**	Deep	Upslope
9	-	-	-	-	107.0	106.0	107.3	106.5	104.0	108.5	101.5	**105.8**	Deep	Upslope
10	-	-	-	-	-	-	104.0	121.5	131.0	113.5	114.0	**116.8**	Deep	Upslope
Average	-	-	-	-	**143.4**	**125.5**	**114.4**	**112.4**	**114.2**	**118.8**	**118.1**	**120.4**		

Notes

1. Salinity Levels calculated as average of measured values in that particular year.
2. "-" Represents No SampleTaken.

Table C1: Salinity in Monitor Bores (mg/L TSS)

Jones - Bore No. 614186: 01 to 18

Bore No.	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	Average	Bore Type	Location
1	120.5	115.0	-	-	114.0	101.0	99.5	99.0	99.0	104.5	101.0	**105.9**	Deep	Valley
2	120.8	-	-	-	94.0	95.0	112.0	95.0	106.5	114.0	111.0	**106.0**	Shallow	Valley
3	182.5	187.1	-	-	149.0	143.0	128.0	114.5	128.0	130.5	126.0	**143.2**	Deep	Valley
4	-	-	-	-	96.0	66.0	-	79.0	-	-	-	**80.3**	Shallow	Valley
5	106.7	109.0	-	-	105.0	100.0	98.0	111.5	96.5	101.5	97.5	**102.9**	Deep	Valley
6	-	-	-	-	315.0	83.0	51.0	50.0	58.0	44.0	-	**100.2**	Shallow	Valley
7	161.2	151.8	-	-	-	115.0	89.0	88.0	88.0	90.5	87.0	**108.8**	Deep	Upslope
8	-	-	-	-	-	-	-	-	-	-	-	-	Shallow	Upslope
9	-	-	-	-	-	104.0	85.5	75.5	83.5	100.5	92.0	**90.2**	Deep	Upslope
10	-	-	-	-	-	-	-	-	-	-	-	-	Shallow	Upslope
11	127.8	128.4	-	-	138.0	119.0	116.5	109.0	114.5	120.5	116.5	**121.1**	Deep	Valley
12	-	-	-	-	-	62.0	-	-	-	-	-	**62.0**	Shallow	Valley
13	186.6	183.7	-	-	57.0	206.0	158.5	155.0	154.5	156.5	154.0	**156.9**	Deep	Upslope
14	-	-	-	-	-	-	-	-	-	-	-	-	Shallow	Upslope
15	-	-	-	-	-	-	-	-	157.5	162.5	125.0	**148.3**	Deep	Upslope
16	-	-	-	-	-	-	-	-	-	-	-	-	Shallow	Upslope
17	146.1	135.7	-	-	53.0	118.0	117.0	128.5	117.5	122.0	121.5	**117.7**	Deep	Valley
18	89.9	-	-	-	145.0	54.0	60.0	65.0	-	64.0	-	**79.7**	Shallow	Valley
Average	**138.0**	**144.4**	-	-	**126.6**	**105.1**	**101.4**	**97.5**	**109.4**	**109.3**	**113.2**	**108.8**		

Notes

1. Salinity Levels calculated as average of measured values in that particular year.
2. "-" Represents No SampleTaken.

Table C2:Minimum Water Levels in Monitor Bores

Lewis - Bore No. 614195: 01 to 11

Bore No.	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	Rise (m)	Natural Surface (mAHD)	Bottom of Bore (mAHD)	Bore Type	Location
1					271.8	271.6	271.7	271.6	271.8	271.9	271.9	270.8	0.0	272.04	245.77	Deep	Valley
2					271.8	271.6	271.7	271.6	271.7	271.9	271.8	271.7	0.0	272.11	258.45	Deep	Valley
3					282.2	280.7	281.0	280.8	281.2	281.4	280.9	280.5	-0.8	284.96	264.35	Deep	Valley
4					282.2	280.8	281.0	280.8	281.3	281.4	280.9	280.5	-0.8	284.84	274.31	Deep	Valley
5					295.9	295.0	295.6	294.0	295.2	295.0	293.5	293.0	-0.9	297.45	289.78	Deep	Valley
6					D	D	D	D	D	D	D	D	-	299.96	297.70	Shallow	Valley
7					312.6	313.3	313.8	313.4	314.5	314.6	313.7	313.0	2.0	315.96	288.01	Deep	Valley
8					308.5	309.7	310.3	309.6	310.9	311.0	309.8	308.6	2.5	314.91	284.53	Deep	Valley
9					308.5	310.0	310.3	309.6	310.6	311.0	309.8	308.8	2.5	314.95	304.33	Deep	Valley
10					312.1	314.5	314.8	314.1	315.7	315.8	314.4	312.9	3.7	332.67	303.25	Deep	Upslope
11					D	D	D	D	D	D	D	D	-	349.24	335.44	Deep	Upslope

Notes

1. D: Dry Bore
2. Rise calculated between first complete year of data and year of maximum groundwater level.
3. -: Rise cannot be calculated due to dry bores.

Table C2:Minimum Water Levels in Monitor Bores

***Hansens** - Bore No 614187: 01 to 25*

Bore No.	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	Rise (m)	Natural Surface (mAHD)	Bottom of Bore (mAHD)	Bore Type	Location
1	255.4	254.9	255.1	255.2	255.1	255.2	255.5	255.3	255.4	255.5	255.2	0.6	258.5	225.6	Deep	Valley
2	255.6	255.2	255.1	D	255.2	255.6	255.6	256.4	255.5	255.4	255.2	0.4	258.4	254.9	Shallow	Valley
3	263.5	262.5	262.7	263.3	263.3	264.1	264.2	263.8	264.0	264.1	263.6	1.7	265.4	244.8	Deep	Valley
4	263.3	262.2	262.5	263.0	263.1	264.0	264.2	264.4	263.9	263.9	263.4	2.0	265.4	261.9	Shallow	Valley
5	271.2	269.8	269.9	271.2	271.6	272.9	272.9	274.8	272.3	272.0	271.4	3.1	283.2	262.7	Deep	Valley
6	D	D	D	D	D	D	D	D	D	D	D	-	283.3	279.3	Shallow	Valley
7	269.5	268.5	268.3	269.3	269.6	270.4	270.5	270.2	270.4	270.3	270.0	2.0	274.3	255.4	Deep	Valley
8	D	D	D	D	D	D	D	D	D	D	D	-	274.4	270.4	Shallow	Valley
9	270.2	268.0	269.0	269.9	270.2	271.0	271.0	270.5	270.8	270.6	270.3	3.0	271.6	250.7	Deep	Valley
10	269.3	267.9	268.0	268.9	269.1	269.6	269.7	270.8	269.4	269.4	269.0	1.8	271.5	267.5	Shallow	Valley
11	300.1	299.9	299.3	301.3	302.5	303.0	302.8	302.3	302.7	302.3	301.7	2.8	314.3	293.4	Deep	Upslope
12		D	D	D	D	D	D	D	D	D	D	-	314.2	307.3	Shallow	Upslope
13	294.9	294.3	294.0	296.2	297.8	299.1	299.1	301.6	298.5	298.1	297.3	4.7	306.5	285.5	Deep	Upslope
14		D	D	D	D	D	D	D	D	D	D	-	306.5	300.5	Shallow	Upslope
15		300.6	300.8	300.8	301.4	302.4	302.1	301.7	302.2	301.9	301.2	1.6	321.5	300.6	Deep	Upslope
16		D	D	D	D	D	D	D	D	D	D	-	321.4	314.4	Shallow	Upslope
17	291.2	290.2	290.0	292.1	293.8	295.1	295.1	294.2	294.5	294.2	293.6	4.9	303.8	284.2	Deep	Upslope
18		D	D	D	D	D	D	D	D	D	D	-	303.6	298.7	Shallow	Upslope
19		D	D	D	D	D	D	D	D	D	D	-	321.5	305.6	Deep	Upslope
20		D	D	D	D	D	D	D	D	D	D	-	321.5	316.8	Shallow	Upslope
21		D	D	D	D	D	D	D	D	D	D	-	313.2	304.5	Deep	Upslope
22	282.3	280.4	280.5	282.3	283.6	285.0	284.8	288.2	284.1	283.8	283.3	4.4	292.6	269.8	Deep	Upslope
23		286.6	286.8	286.8	286.7	287.9	286.8	289.6	283.8	286.7	286.6	0.2	292.7	286.7	Shallow	Upslope
24	290.1	289.2	289.0	291.2	292.5	293.9	294.0	293.2	293.3	293.2	292.5	4.8	299.8	284.6	Deep	Upslope
25		D	D	D	D	D	D	D	D	D	D	-	299.6	294.9	Shallow	Upslope

Notes

1. D: Dry Bore
2. Rise calculated between first treatment year and year of maximum groundwater levels
3. -: Rise cannot be calculated due to dry bores.

Table C2:Minimum Water Levels in Monitor Bores

Higgens *- Bore No. 614188: 01 to 10*

Bore No.	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	Rise (m)	Natural Surface (mAHD)	Bottom of Bore (mAHD)	Bore Type	Location
1					298.1	298.8	299.3	299.3	300.9	300.9	300.2	2.8	303.1	Unknown	Deep	Valley
2					304.4	305.2	305.3	305.8	307.0	307.1	306.6	2.6	309.9	Unknown	Deep	Valley
3					303.2	303.4	304.9	306.0	307.5	307.5	306.7	4.3	311.2	Unknown	Deep	Valley
4					307.8	309.5	311.2	311.9	312.5	312.0	311.5	4.7	316.8	Unknown	Deep	Valley
5					D	D	D	D	D	D	D	-	323.9	312.2	Deep	Upslope
6					311.0	312.9	314.4	315.7	317.1	316.5	315.8	6.1	325.8	Unknown	Deep	Upslope
7					314.7	316.6	318.4	318.6	320.9	320.8	320.4	6.2	331.9	Unknown	Deep	Upslope
8					307.3	309.0	309.7	311.2	313.0	312.6	311.9	5.7	319.8	Unknown	Deep	Upslope
9					307.6	309.2	305.7	311.5	313.5	313.1	312.3	5.9	323.8	Unknown	Deep	Upslope
10					312.5	312.5	312.8	314.0	315.3	314.9	314.3	2.8	328.2	Unknown	Deep	Upslope

Notes

1. D: Dry Bore
2. Rise calculated between first treatment year and year of maximum groundwater level
3. -: Rise cannot be calculated due to dry bores.

Table C2:Minimum Water Levels in Monitor Bores

Jones - Bore No. 614186: 01 to 18

Bore No.	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	Rise (m)	Natural Surface (mAHD)	Bottom of Bore (mAHD)	Bore Type	Location
1		272.5	272.2	272.0	271.3	273.1	273.9	274.1	275.5	275.7	275.5	4.4	277.366	258.87	Deep	Valley
2		D	D	D	D	D	D	D	275.7	275.8	275.7	-	277.301	274.6	Shallow	Valley
3		276.9	276.4	276.2	275.4	278.1	273.0	276.7	272.4	280.5	280.0	5.0	283.94	252.94	Deep	Valley
4		D	D	D	D	D	D	D	D	D	D	-	283.904	281.2	Shallow	Valley
5		287.9	287.5	287.0	286.5	290.1	292.0	292.5	291.0	293.4	292.7	6.9	295.424	258.42	Deep	Valley
6		D	D	D	D	D	D	D	D	D	D	-	295.575	292.88	Shallow	Valley
7		290.5	290.1	289.5	288.9	291.9	293.4	295.1	296.9	296.8	295.9	7.9	306.284	275.78	Deep	Upslope
8		D	D	D	D	D	D	D	D	D	D	-	306.219	303.52	Shallow	Upslope
9		291.5	D	D	D	292.4	294.3	295.5	297.5	297.3	296.4	-	310.238	291.24	Deep	Upslope
10		D	D	D	D	D	D	D	D	D	D	-	310.224	307.52	Shallow	Upslope
11		278.3	278.0	277.6	276.7	279.5	280.5	280.9	282.9	283.6	282.8	6.9	287.3	262.4	Deep	Valley
12		D	D	D	D	D	D	D	D	D	D	-	287.256	284.56	Shallow	Valley
13		281.3	280.8	280.3	279.7	282.5	279.2	284.0	284.8	288.8	287.6	9.1	303.808	268.41	Deep	Upslope
14		D	D	D	D	D	D	D	D	D	D	-	303.856	301.16	Shallow	Upslope
15		D	D	D	D	D	D	D	D	D	D	-	309.926	289.43	Deep	Upslope
16		D	D	D	D	D	D	D	D	D	D	-	309.774	307.07	Shallow	Upslope
17		276.7	276.2	276.1	275.3	277.5	278.5	278.8	280.9	281.8	280.9	6.5	285.786	258.29	Deep	Valley
18		D	D	D	D	D	D	D	D	D	D	-	285.725	283.03	Shallow	Valley

Notes

1. D: Dry Bore
2. Rise calculated between first treatment year and year of maximum groundwater level
3. -: Rise cannot be calculated due to dry bores.

Appendix D: Stability of Lewis Catchment

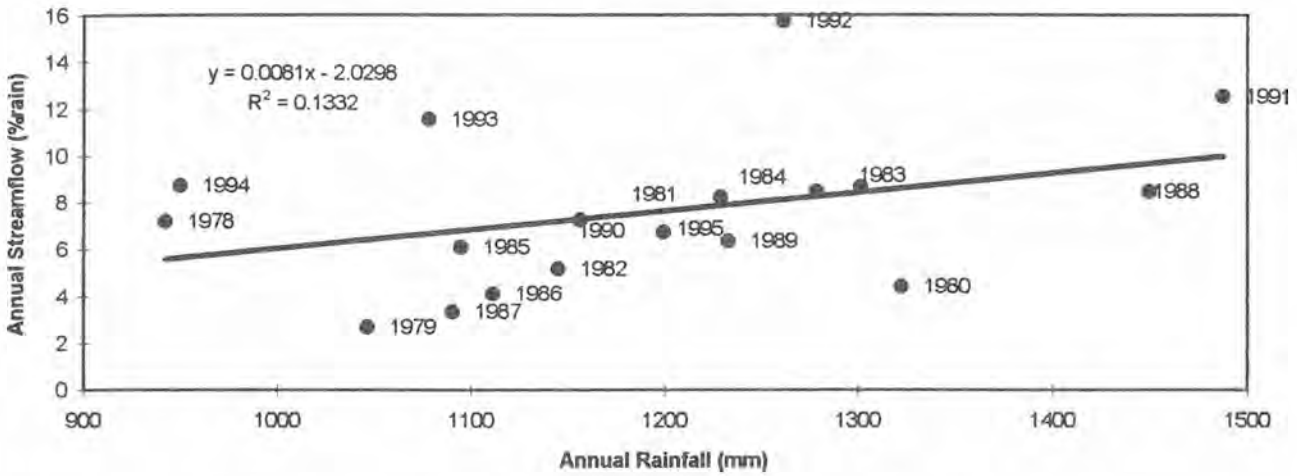
D.1 Methodology

The stability of Lewis Catchment was checked using the following steps:

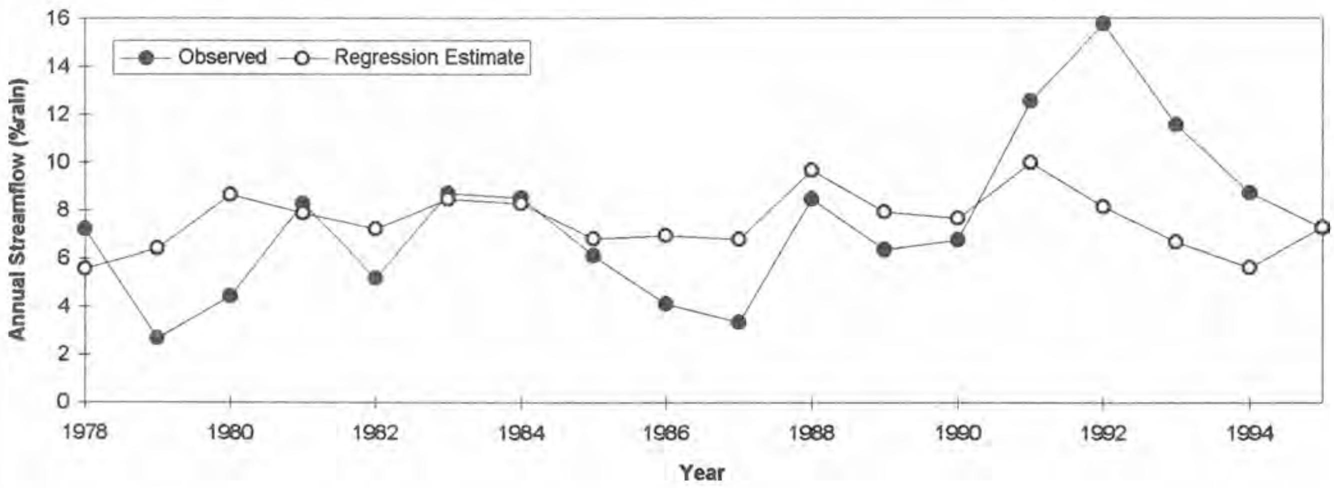
1. Determine relationship between annual rainfall and annual streamflow (as a percentage of rainfall) coefficient using data for the entire study period.
2. Determine residuals around this relationship.
3. Determine whether the difference in the mean residuals between 1978-91 and 1991-95 periods are significantly different. This was done using standard statistical analysis to find the differences between means.

Figure D1 shows the above steps. The difference in means between the residuals is 4.6% ± 2.66% (95% confidence limits). Thus, the results indicate there has been significant change in the rainfall-streamflow relationship for Lewis over the last five years.

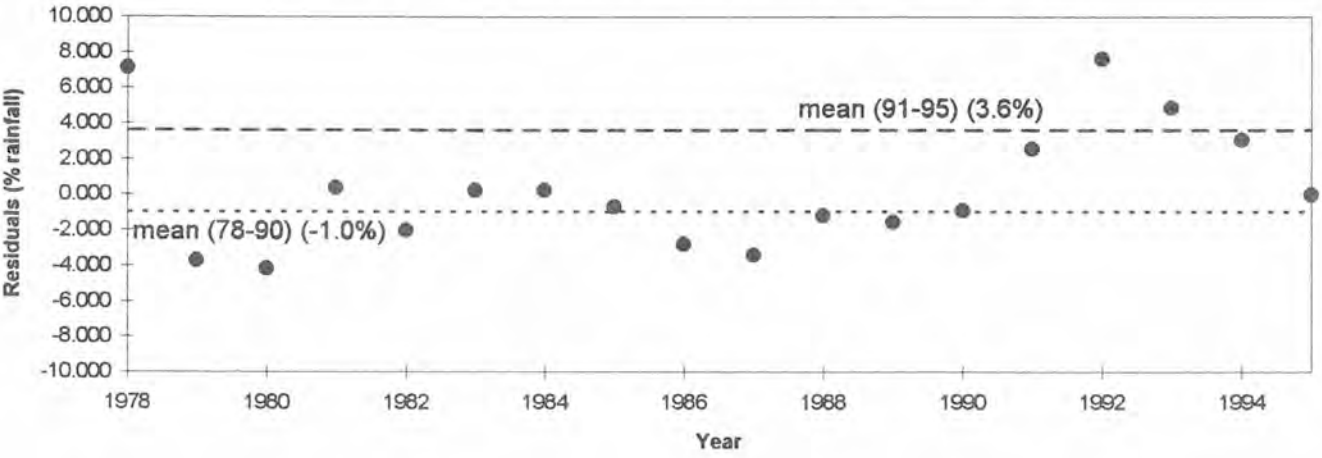
Annual streamflow - annual rainfall relationship



Comparison between observed streamflow and estimate from regression



Residuals: observed streamflow minus estimate from regression



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CONSULTANT HYDROLOGISTS PO BOX 117 SUBIACO W.A. 6008	Approved By:	Figure D1: Stability of Lewis Catchment
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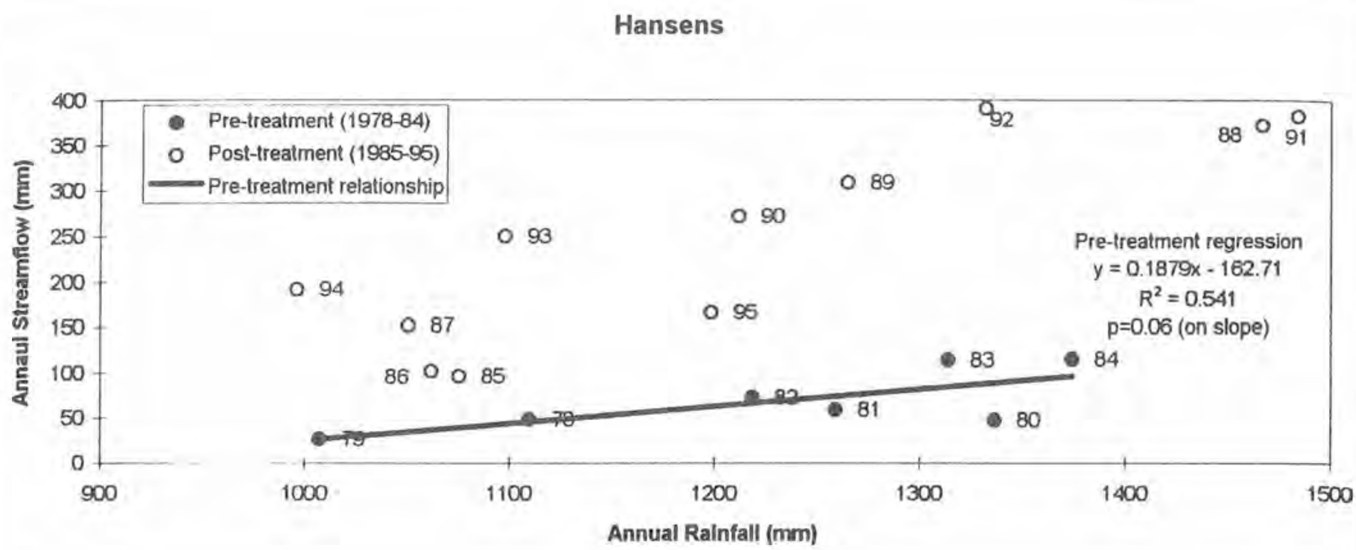
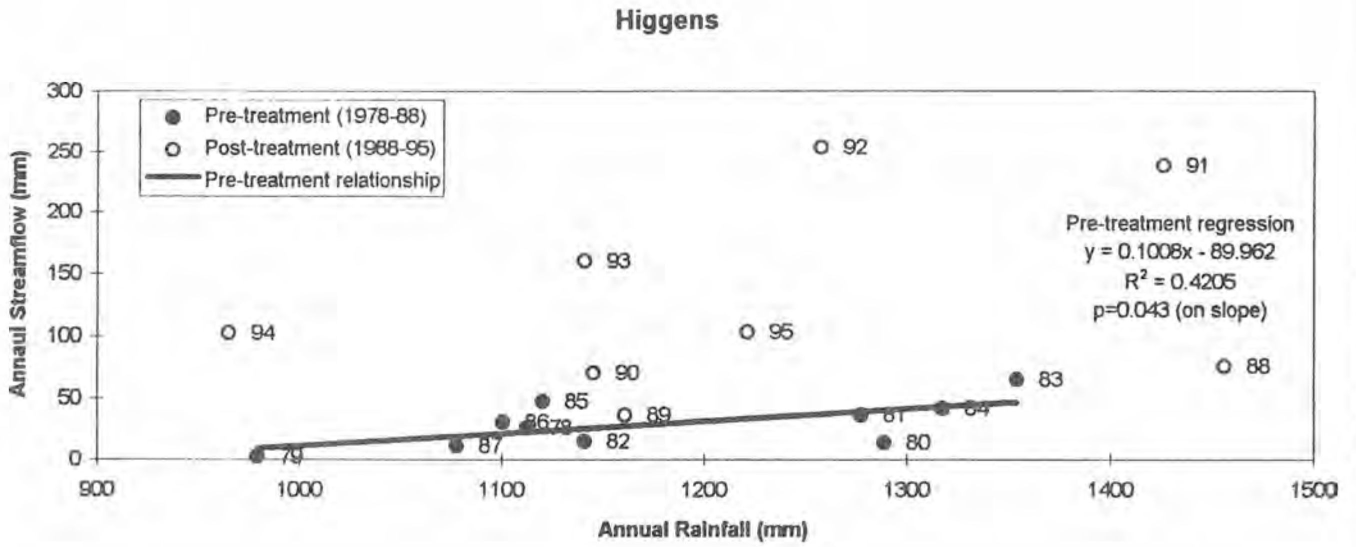
Appendix E: Estimation of changes in annual streamflow

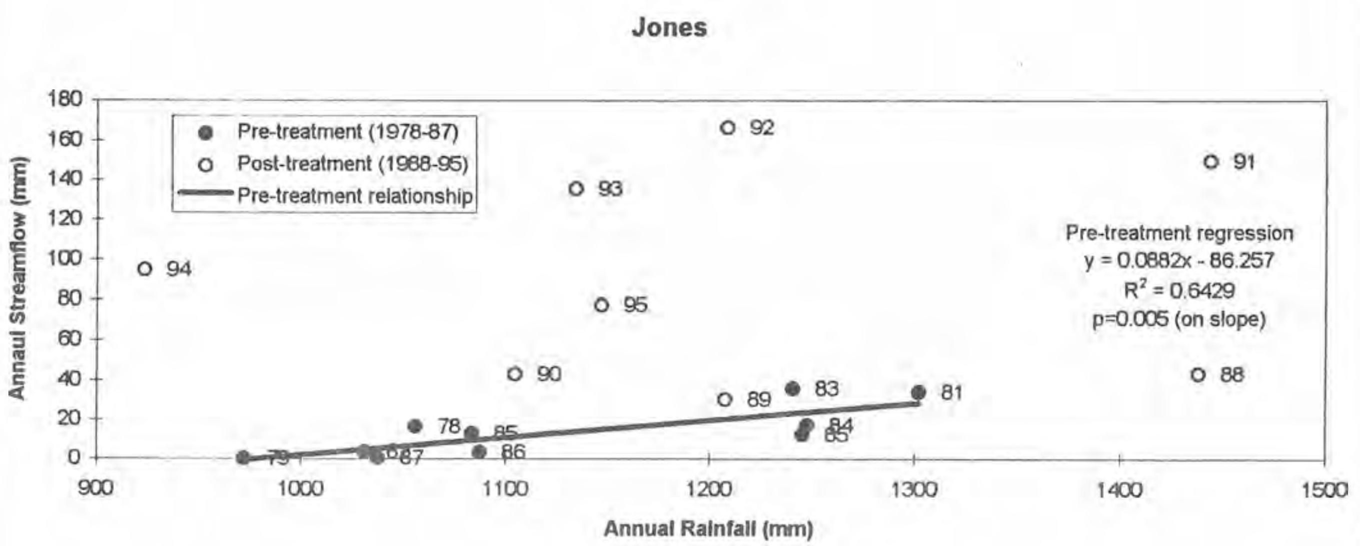
E.1 Methodology

The change in streamflow for Hansens, Higgens, and Jones was determined using the following steps:

1. Determine the relationships between annual streamflow and annual rainfall using data from the pre-treatment period. Figures E1 and E2 show the relationships derived for Hansens, Higgens and Jones Catchments. Figure E1 is the relationship between rainfall (mm), and annual streamflow, and Figure D2 is the relationships between streamflow (as a percentage of rainfall) and annual rainfall (mm).
2. Determine if there is any trend in the residuals of the pre-treatment relationship between streamflow (% of rainfall) and time. Figure E3 show these results.
3. Predict post treatment streamflow (both %rain and mm) using pre-treatment relationships developed in step 1.
4. Subtract post-treatment estimates from measured streamflows to calculate the change in annual streamflow.







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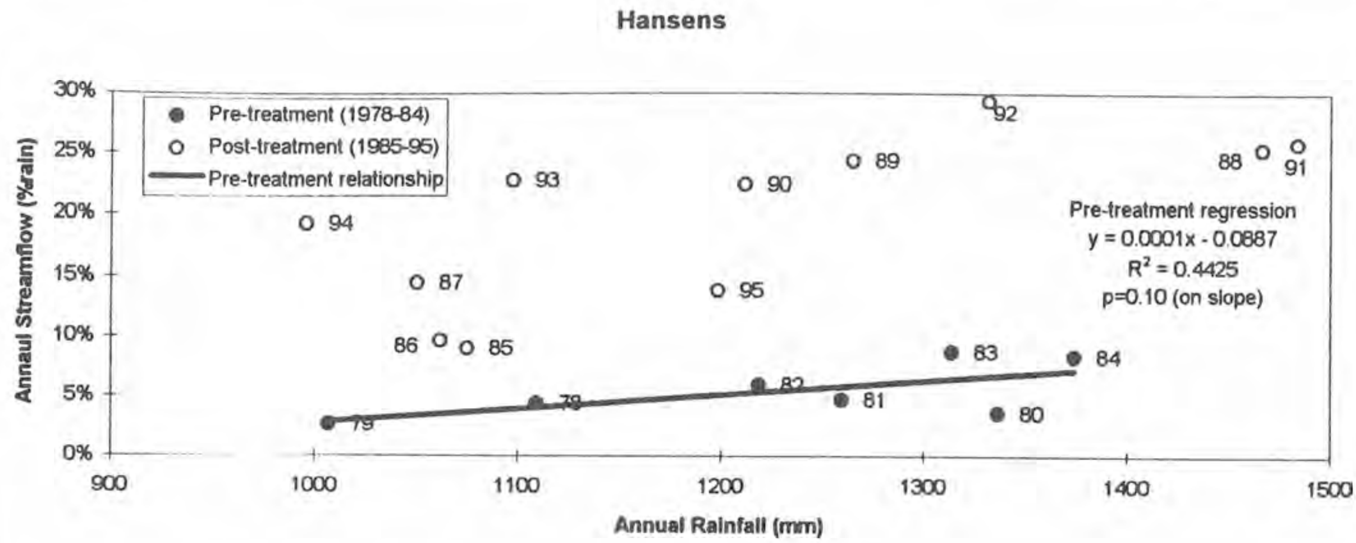
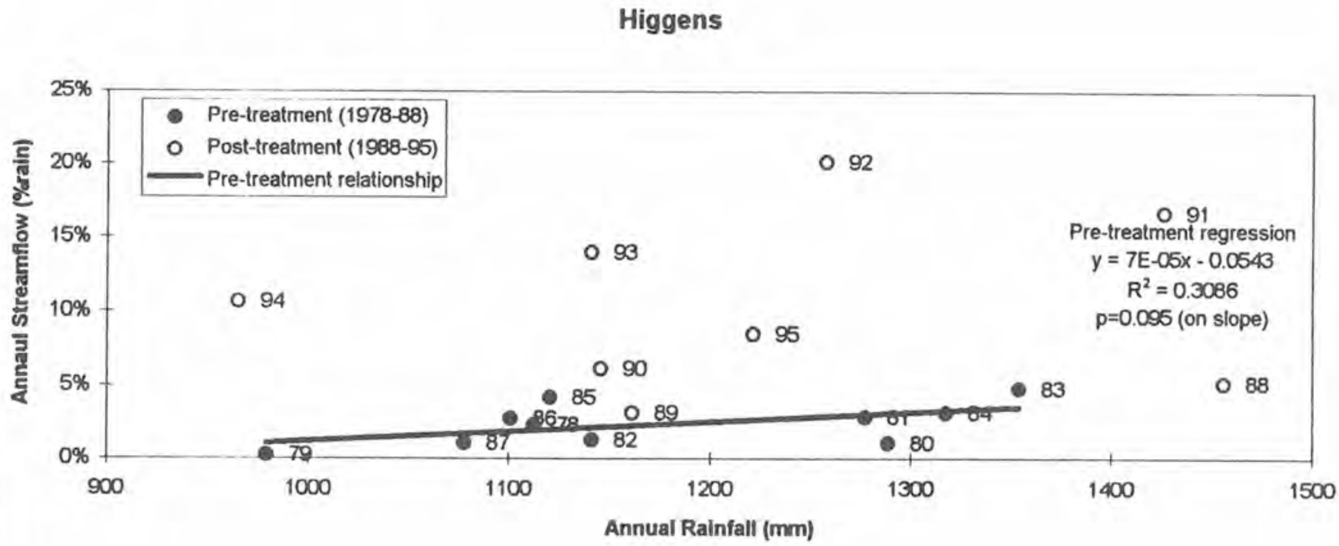
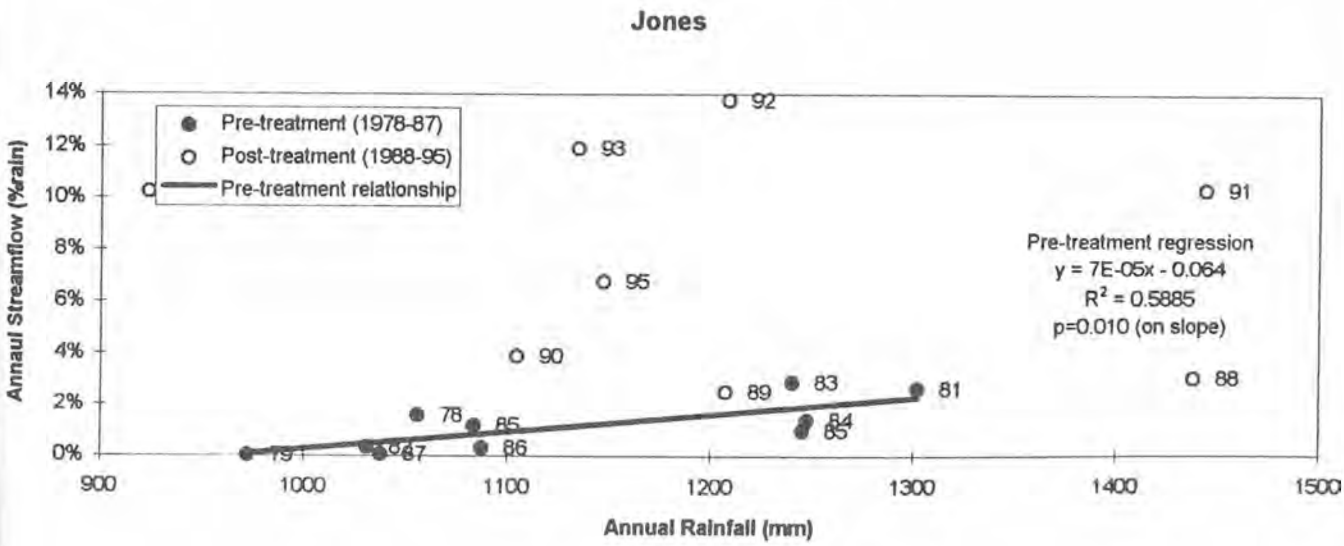
PO BOX 117 SUBIACO W.A. 6008	Approved By:	Figure E1: Pre-treatment relationships between
Ph: 388 2436 Fax: 381 9279	Date Issued:	streamflow (mm) and rainfall







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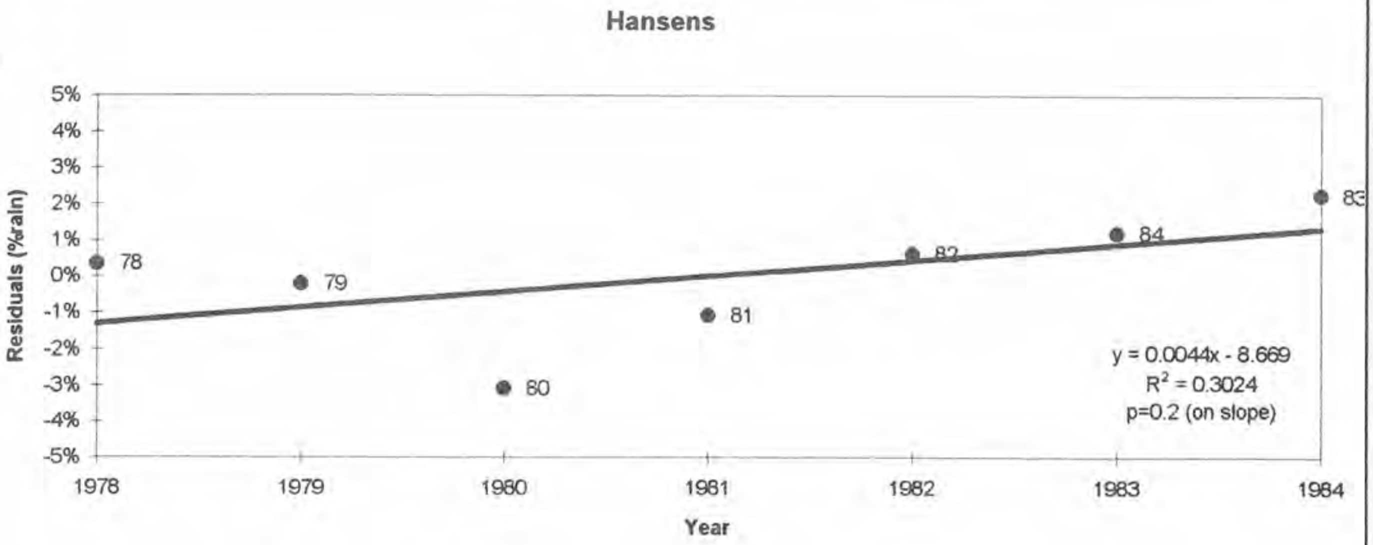
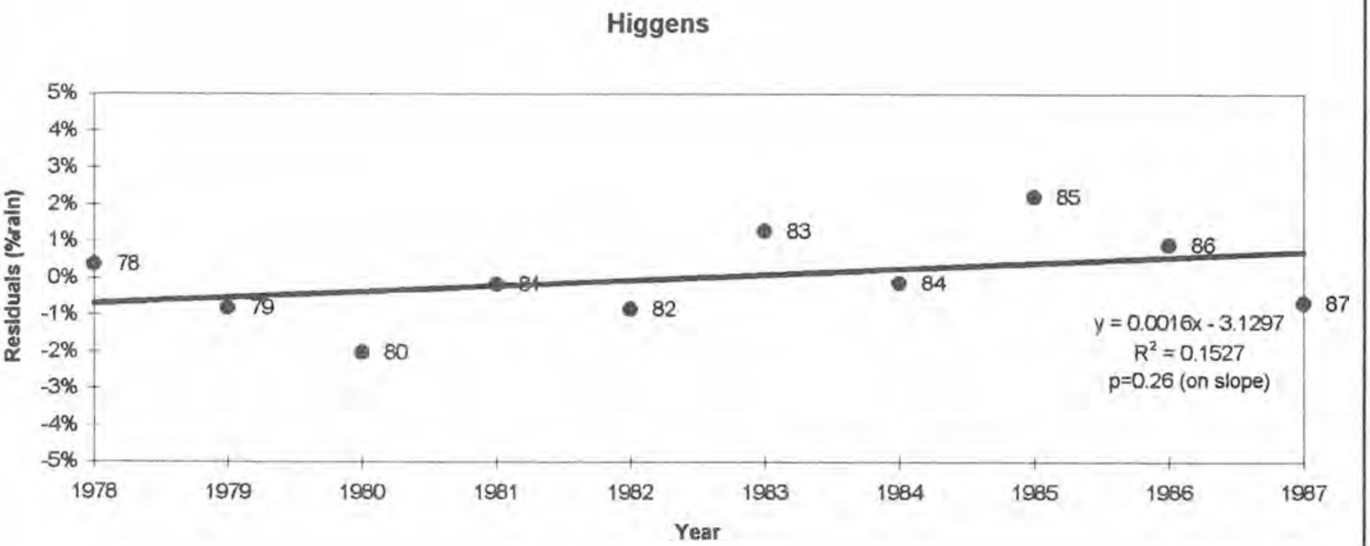
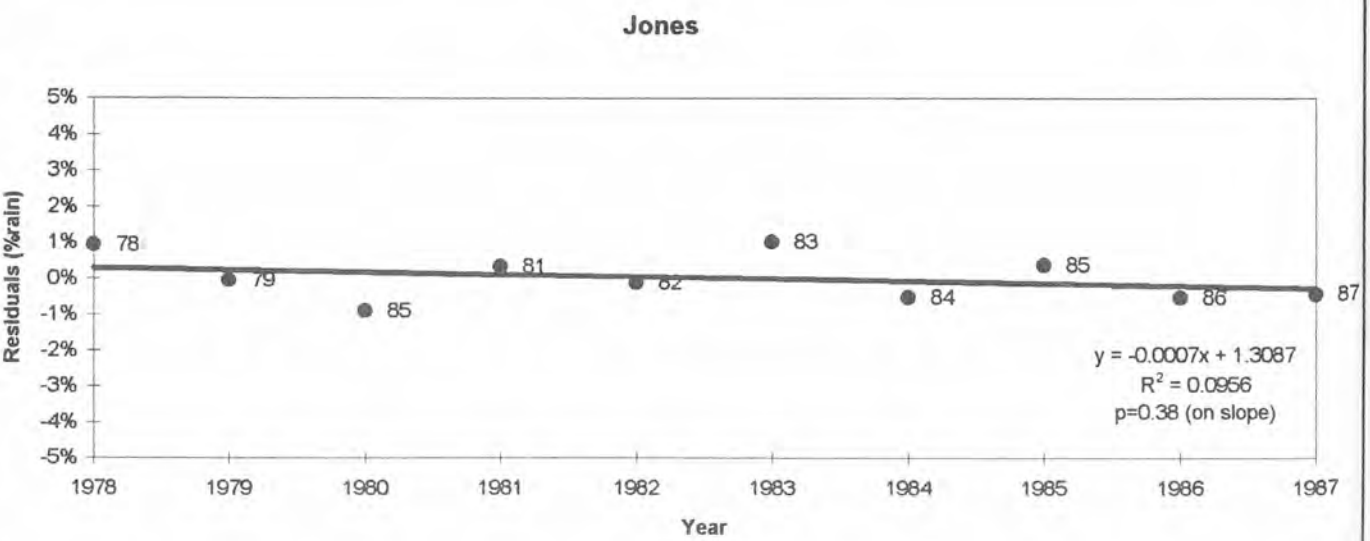
CONSULTANT HYDROLOGISTS	Approved By:	Figure E2: Pre-treatment relationships between
PO BOX 117 SUBIACO W.A. 6008 Ph: 388 2436 Fax: 381 9279	Date Issued:	streamflow (% of rainfall) and rainfall







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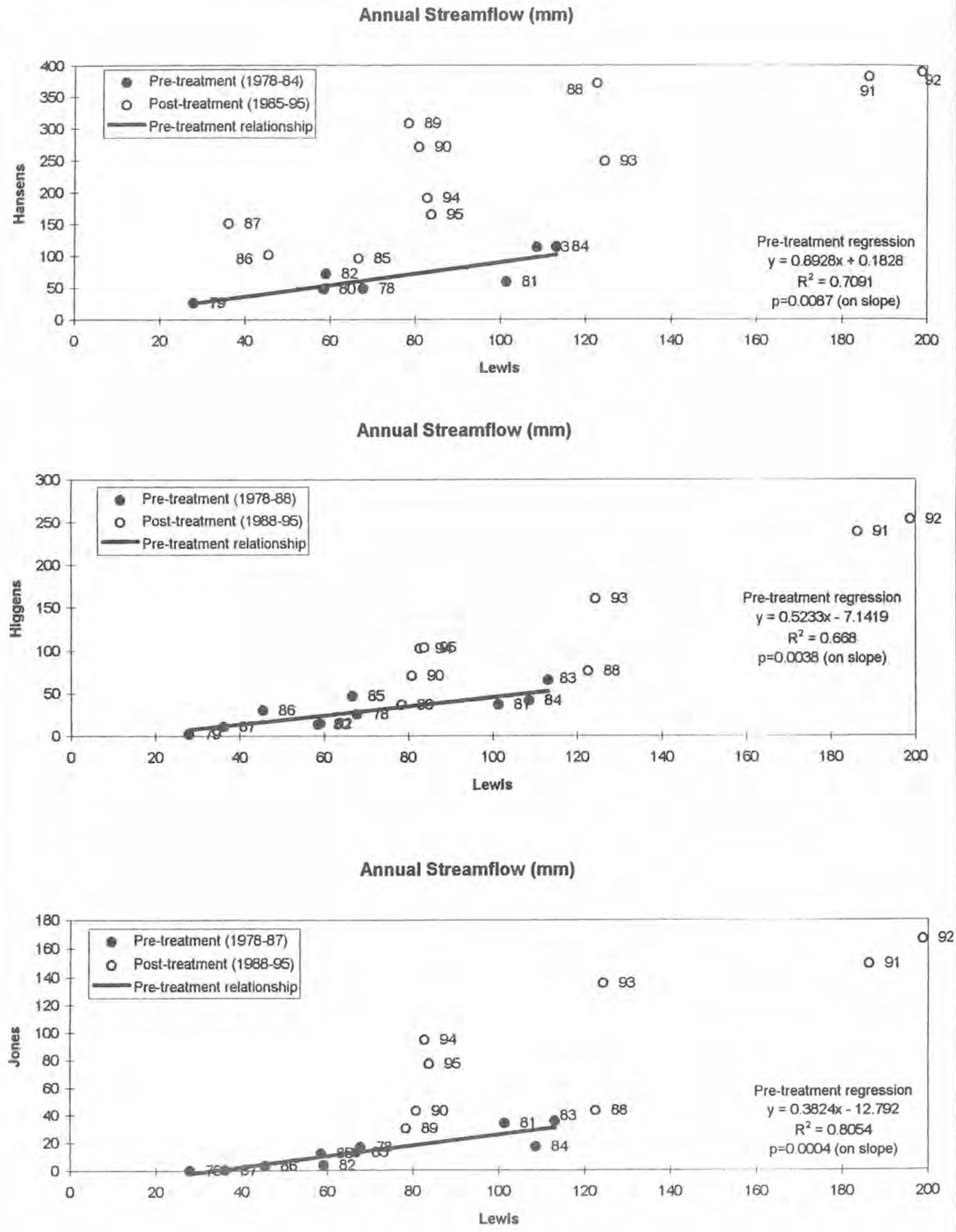
CONSULTANT HYDROLOGISTS PO BOX 117 SUBIACO W.A. 6008	Approved By:	Figure E3: Analysis of the residuals for the
Ph: 388 2436 Fax: 381 9279	Date Issued:	pre-treatment relationships

Appendix F: Estimation of changes in annual streamflow using Lewis as a Control Catchment

F.1 Methodology

The change in streamflow for Hansens, Higgens, and Jones was determined using the following steps:

1. Using data from the pre-treatment period, determine, for Hansens, Higgens and Jones, the relationships between annual streamflow and the annual streamflow at Lewis. Figure F1 shows the relationship between streamflow (mm), and Figure D2 shows the relationships with streamflow as a percentage of rainfall.
2. Predict post treatment streamflow (both %rain and mm) using pre-treatment relationships developed in step 1.
3. Subtract post-treatment estimates from measured streamflows to calculate the change in streamflow. Figures F3, and F4 shows these estimates.



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CONSULTANT HYDROLOGISTS	Approved By:	Figure F1: Pre-treatment relationships
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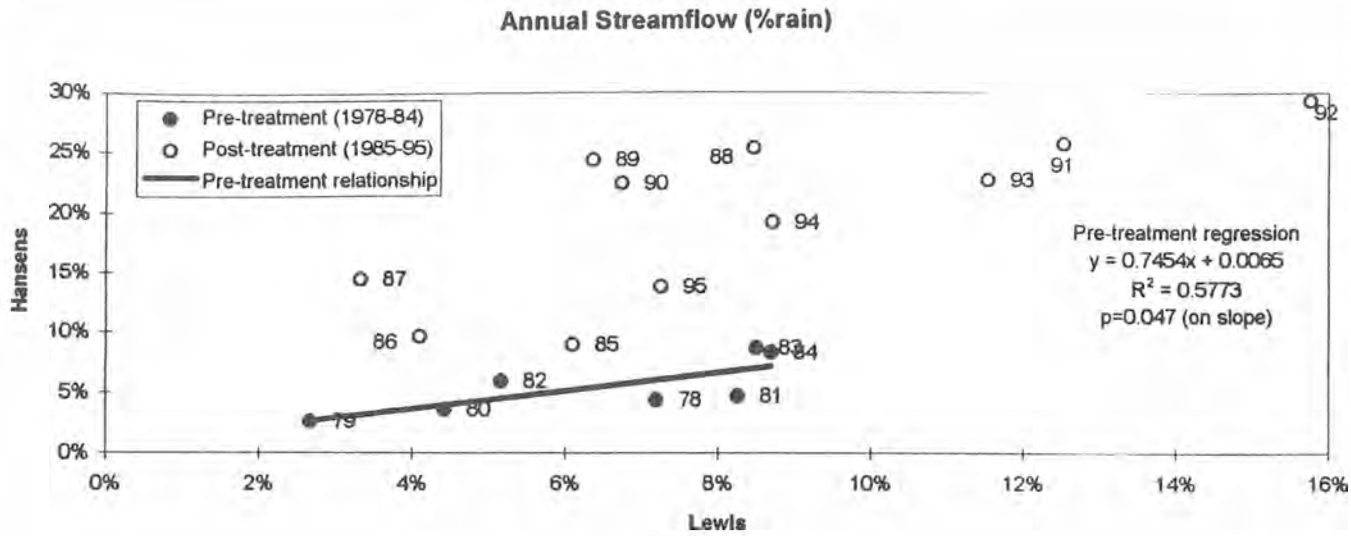

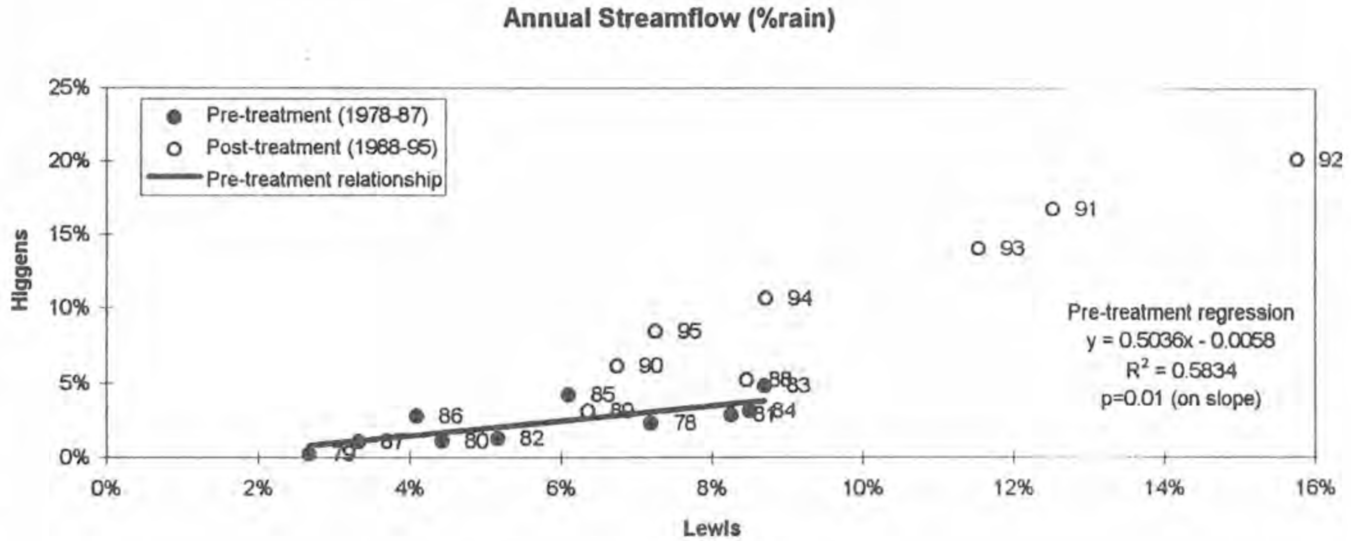

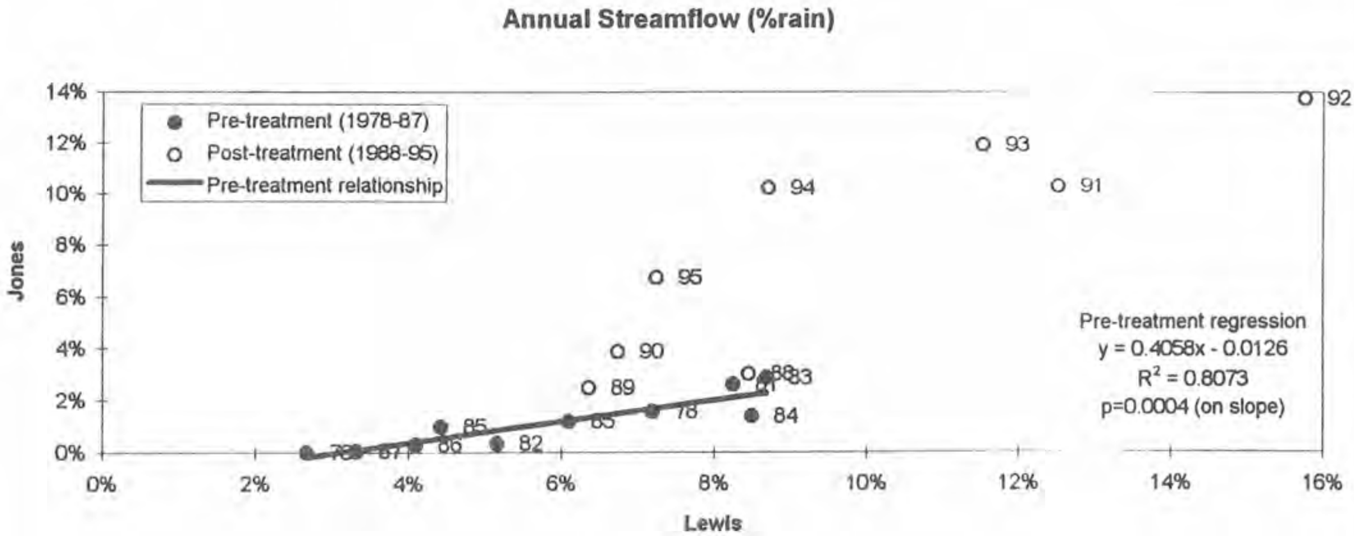

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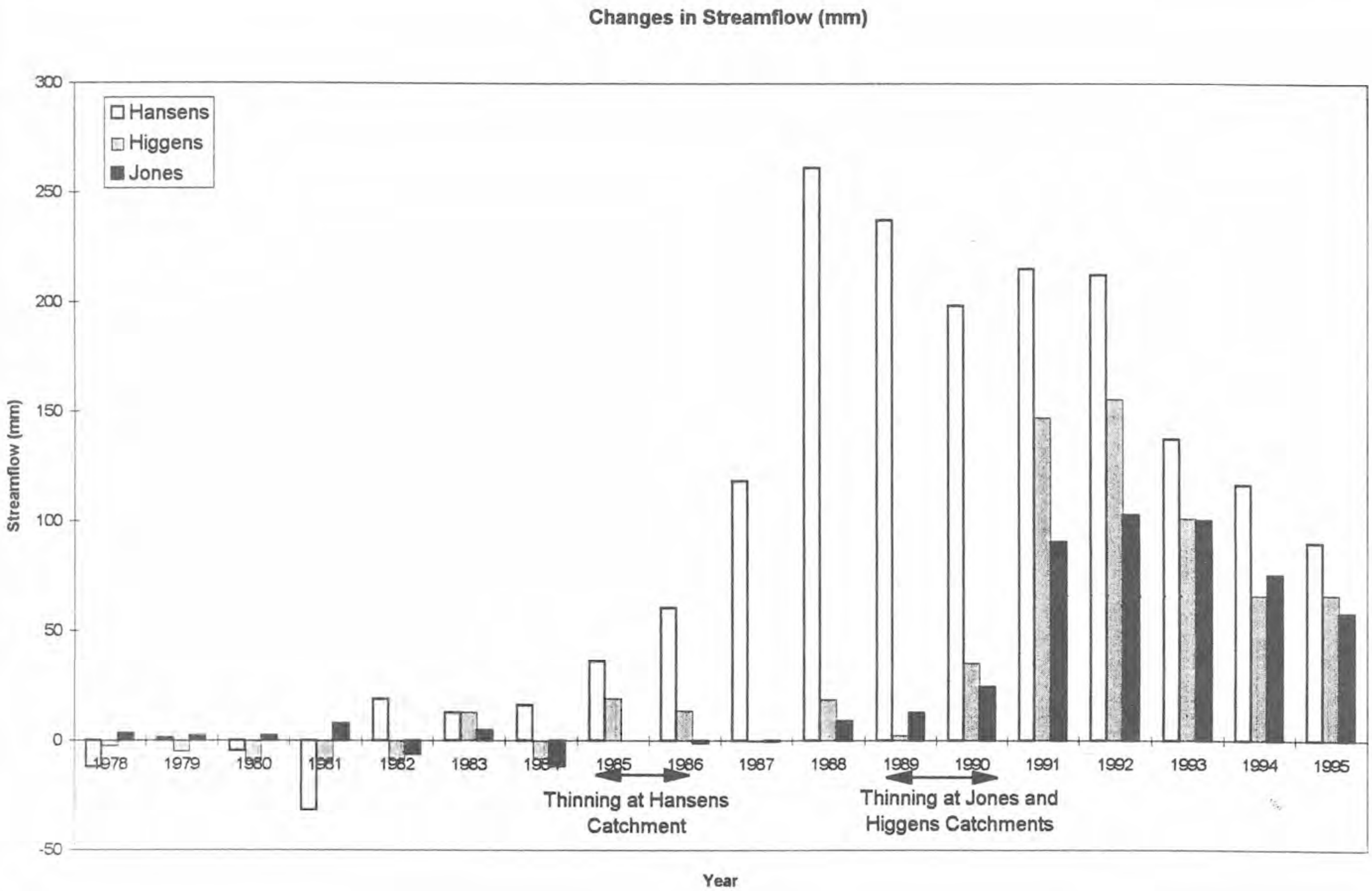
PO BOX 117 SUBIACO W.A. 6008	Approved By:	Figure F2: Pre-treatment relationships
Ph: 388 2436 Fax: 381 9279	Date Issued:	between annual streamflow (%rain)



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CONSULTANT HYDROLOGISTS		Approved By:	Figure F3: Changes in annual streamflow (mm)
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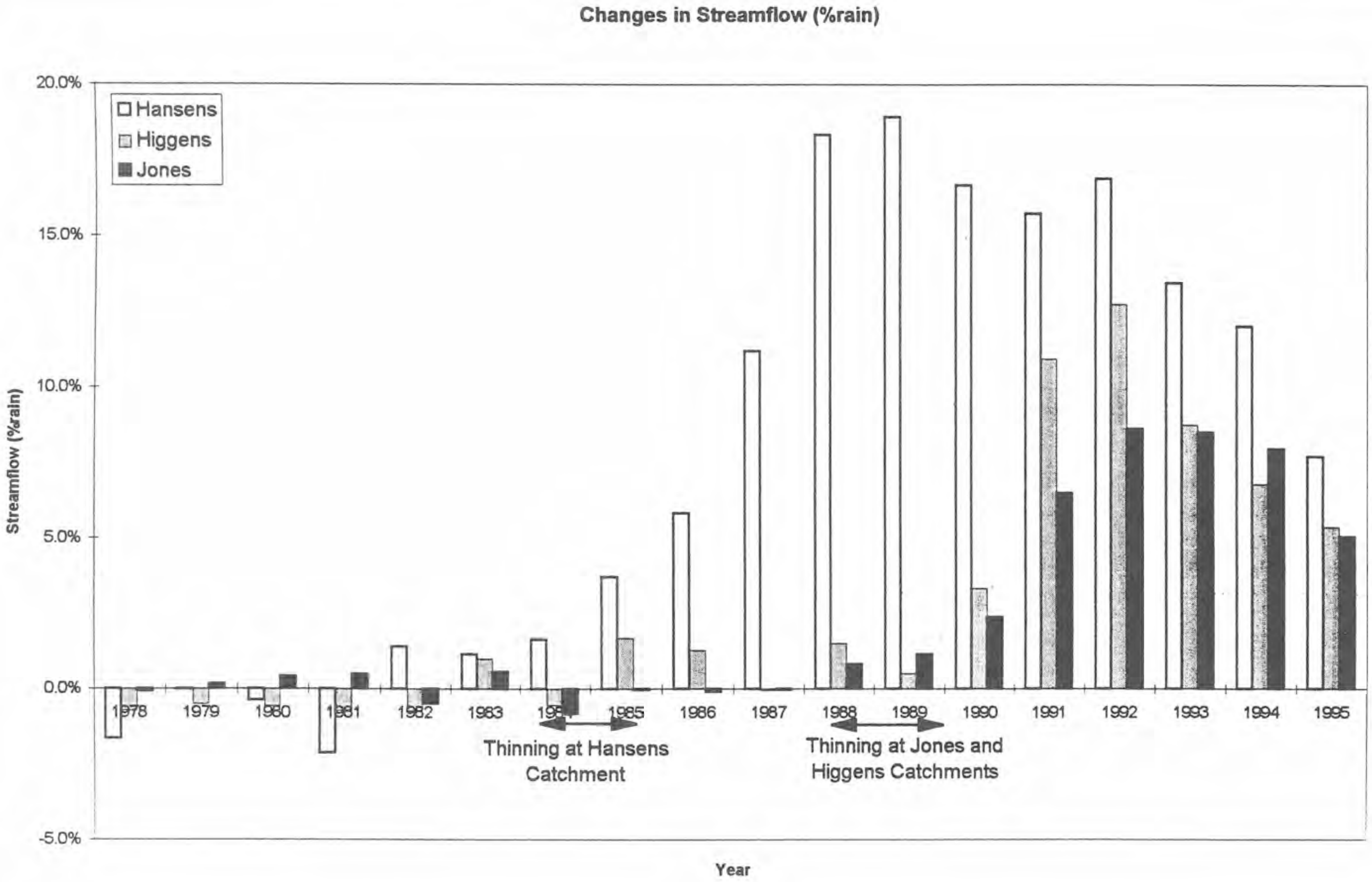

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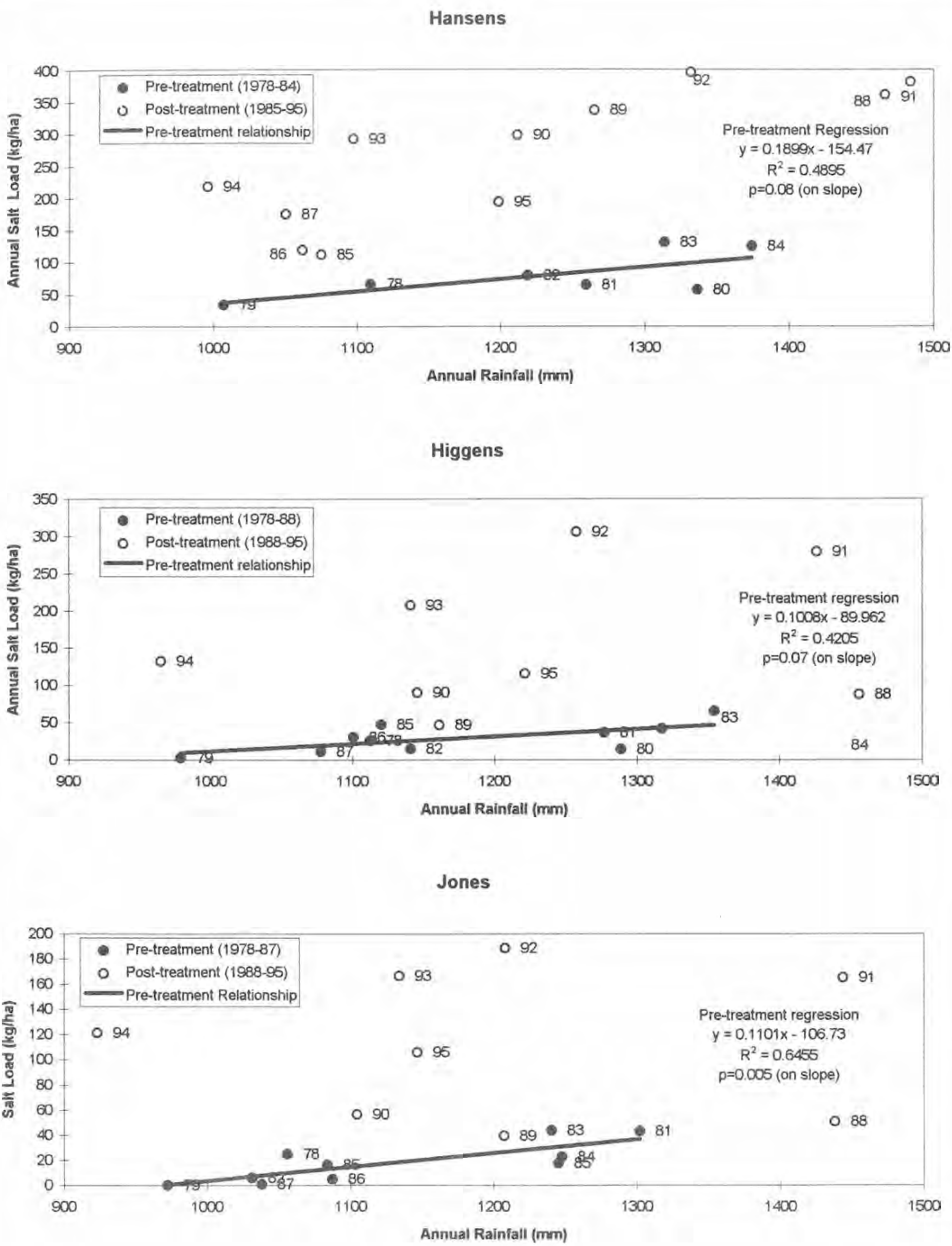
		Approved By:	Figure F4: Changes in Annual Streamflow (% Rain)
		Date Issued:	

Appendix G: Estimation of changes in annual salt load

G.1 Methodology

The change in salt load for Hansens, Higgens and Jones was determined using the following steps:

1. Using data from the pre-treatment period, determine relationships between annual salt load and rainfall (Figure G1).
2. Predict post treatment salt load using pre-treatment relationships developed in step 1.
3. Subtract post-treatment estimates from measured loads to calculate the change in salt load.



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CONSULTANT HYDROLOGISTS PO BOX 117 SUBIACO W.A. 6008	Approved By:	Figure G1: Pre-treatment relationships
Ph: 388 2436 Fax: 381 9279	Date Issued:	between annual salt load and rainfall