Analysis of water quality and water yield in response to forest harvesting in two catchments on highly erodible granitic soils in north east Tasmania

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EXECUTIVE SUMMARY

This report summarises data from two experimental sites commissioned by Forestry Tasmania in 1989 whose aim was to investigate changes to water yield and quality as a result of forest harvesting practices. The report is divided into two parts: *Gentle Annie Catchments* and *Deacons Creek*. The catchments are based on erodible granite soils near St Helens, Tasmania. A further study on changes in water quality and yield resulting from harvesting on doleritic soils, is presented in Thompson et al., (2002).

Gentle Annie Catchments: The pretreatment phase of the Gentle Annie trial, including roading and logging was undertaken during a period of below average rainfall, whereas the post logging phase occurred during a period of higher rainfall. About 45% of the treatment catchment was harvested and a double mass analysis showed a change in the discharge relationship between the control and the treatment catchment. This change coincided with the logging phase in 1991, and was not related to rainfall. The change in the relationship was due to an increase in the rainfall-runoff ratio in the treatment catchment after logging which equated to a 4 fold increase in runoff in the treatment catchment. This was relative to the pre-treatment monitoring phase however, which was short (11 months).

The influence of the logging treatments on turbidity was difficult to determine. This was partially due to the quality of the data and the timing of event sampling as well as the low rainfall during the pre-treatment phase compared to the high rainfall in the post logging phase. Notwithstanding these caveats, there appeared to be no change in mean event turbidity (NTU) for either the treatment or the control sites, both with treatment and over time. Although NTU was found to be variable, there was no evidence to support an increase in turbidity due to harvesting and roading in the treatment catchment.

The total suspended solid (TSS) and total dissolved solid (TDS) data was restricted to only the post-logging phase. This data was of poor quality and no relationship with turbidity could be supported for either variable. There was a similar range of values for both the treatment and the control catchment in the post-logging period. This may imply that harvesting and roading has not resulted in increased levels of suspended and dissolved solids in the treatment catchment compared to the control. However it is difficult to be conclusive as there is no pre-treatment data with which to compare the values. Concentrations of TDS were consistently higher than TSS for both the treatment and control.

The nitrogen (measured as total Kjeldahl nitrogen, TKN) and phosphorus (measured as total phosphorus, TP) data was also restricted to the post logging period and was of poor quality. TKN concentrations were similar for both the control and treatment sites. A temporal analysis showed that initial concentrations of TKN in particular, were higher in the treatment catchment than the control. However they appeared to converge with those of the control catchment over the post-logging monitoring phase of 4 years. This may indicate a possible elevation of concentrations due to the fire within the treatment catchment and harvesting however it is not conclusive. TP data showed a similar range of values for both the control and treatment sites.

Overall, the data from Gentle Annie support an increase in catchment discharge in the harvesting phase, which persisted until the end of the trial. Weaker evidence support an increase in TKN concentrations in the post harvesting phase, although this appeared to persisted for about 4 years. There was no firm evidence to support an increase in turbidity, TSS or TDS values, although the data was generally poor.

Deacons Creek catchments: There was considerable annual variability of rainfall throughout the study period, the roading and logging phases occurring during the driest year (1994). The double mass analysis of discharge showed no detectable influence of catchment treatment on discharge. However a significant increase in runoff ratio occurred in December 1993 within the control catchment prior to the commencement of treatment activities. The cause of this increase is unknown.

Mean NTU values increased by up to a factor of three in the treatment catchment during roading and harvesting, compared to the control. However mean event turbidity returned to pre-treatment levels once logging had ceased. TSS data for the treatment catchment was much higher than that of the control catchment during pre-treatment monitoring. Nonetheless, the TSS data showed a further increase in concentration for discharge events during the roading phase which reduce again during the logging phase in the treatment catchment. The TDS data showed significant increases in concentration during both the roading and logging phases in the treatment catchment, although they returned to pre-treatment levels once harvesting had ceased. TKN and TP data also indicated slightly increased concentration during logging, no roading data was available. These variables then returned to pre-treatment concentration levels once harvesting had ceased.

Synthesis of findings between Gentle Annie and Deacons Creek. Although the treatment catchments were about the same size and contained about the same relative area of harvested forest, Gentle Annie showed a significant increase in water yield, following forest harvesting, whereas Deacons Creek did not. Conversely, NTU and solids concentrations in Deacons Creek showed up to a factor of 3 influence from roading, while Gentle Annie had no discernable sediment response. The reasons for this contradictory behavior are not well understood.

Both catchments had higher concentrations of TDS over TSS, (especially at Gentle Annie) indicating that much of the mineral phases may be transported in solution in these catchment systems. Furthermore, the TSS levels reduced during the logging phase yet TDS did not (especially at Deacons Creek). However concentrations in both catchments had returned to pre-treatment levels of TDS after logging had ceased, showing no influence of logging on TDS beyond harvesting operations themselves. Both catchments showed some evidence of slightly elevated levels of TKN co-incident with roading and harvesting, although these had reduced to pretreatment levels after a period of about 4 years. The TP data was less clear although both catchments showed no statistical impacts after harvesting.

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Background.

In 1989 Forestry Tasmania, established monitoring programs aimed at quantifying the impact of forestry operations on water quality and yield in selected Tasmanian Rivers. There were two regions of primary interest identified for a monitoring program i) the dry sclerophyll forests based on highly erodible granitic soils in NE Tasmania, near St Helens (Gentle Annie and Deacons Creek.) and ii) the more stable doleritic soils near Launceston, (Musselboro Creek). Flow and water quality monitoring stations were established in each of the three catchments. Forestry Tasmania initially engaged the Australia Centre for Catchment Hydrology (ACCH) to collaborate in the experimental program by assisting in site selection and development as well as monitoring, data analysis, and technology transfer. The ACCH evolved into the Co-operative Research Centre for Catchment Hydrology (CRCCH) which continued the work. The first major report of the project dealing with runoff and erosion on slopes following harvesting was published as "Part A: Impact of logging and Natural fires on runoff and soil loss in Erodible granite terrain, Northeast Tasmania" in CSIRO Land and Water Technical report 19/99. This dealt with the issue of onslope runoff and sediment redistribution, and was designed to augment the instream water quality monitoring which is presented here. The data from the granitic catchments is presented in this report. An analysis of data from the doleritic terrain comprises a companion second report. The titles of these reports are given below.

Granitic terrain: Gentle Annie (NE Tasmania); Deacons Creek (NE Tasmania)
Thompson, C. J., Wallbrink, P. J., and Crapper, P.F. 2002. "Analysis of water quality and water yield in response to harvesting in two catchments on highly erodible granite soils in north east Tasmania". CSIRO Technical Report 02/02.

Doleritic terrain: Musselboro Creek
Thompson, C. J. Wallbrink, P. J., and Crapper, P.F. 2002. "Analysis of Water quality and water yield in response to harvesting on Doleritic soils in the Musselboro Creek catchment, Tasmania". CSIRO Technical Report 01/02.

Data collected from each of these experimental areas are given as Appendices in these respective reports.

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SECTION I : GENTLE ANNIE

1.0 INTRODUCTION

The Gentle Annie catchment trial was part of ‘the granite erosion study’ seeking to assess the effects of forest operations on erosion, water quality and water quantity on highly erodible granitic soils. These soils occupy an estimated 60 000 ha of state forest in the region. Runoff from the dry forest granite soils is also an extremely valuable resource providing municipal water to communities such as St. Helens. The vegetation is dry sclerophyll forest dominated by *Eucalyptus sieberi* and *E. amygalina* (Forestry Commission file).

Timber harvesting in Gentle Annie was undertaken using uphill snigging in which the aim is to confine soil disturbance to spurs and ridge tops, although hillslopes can also be disturbed (Wallbrink and Murray, 1996). This method attempts to avoid disturbance to adjacent drainage lines which is where coarse grain sediments have accumulated as a result of natural hill slope erosion, these deposits have high erosion potential (Forestry Commission file).

2.0 METHODS

2.1 Experimental design

The Gentle Annie catchment is located in Eastern Tasmania, approximately 10 Km north west of St. Helens. The Gentle Annie experimental catchment was set up as a simple ‘nested design’ with an upper control site (310) and lower treatment site (311) (Figure 1). Each site was instrumented with cut-throat flumes. The treatment site includes 73 ha of harvested forest, 91 ha that was not harvested, as well as 40 ha of unharvested forest within the control (Table 1). The experimental program began in January 1990 with the pre-treatment monitoring phase. Forestry operations themselves commenced with construction of road infrastructure in December 1990 and concluded with the cessation of logging in mid April 1991. At the completion of the harvesting operation a small natural bush fire burned a small portion of the logged catchment (Wilson *et al*. 1999). The data from the stations was divided into different treatment periods which are given in table 2. Because the roading and logging operation periods overlap, the roading period is described as the period 8/12/90 to 14/01/91 for analysis purposes. It is acknowledged that the overlap in treatment periods will impair the separation of potential impacts of roading and logging.

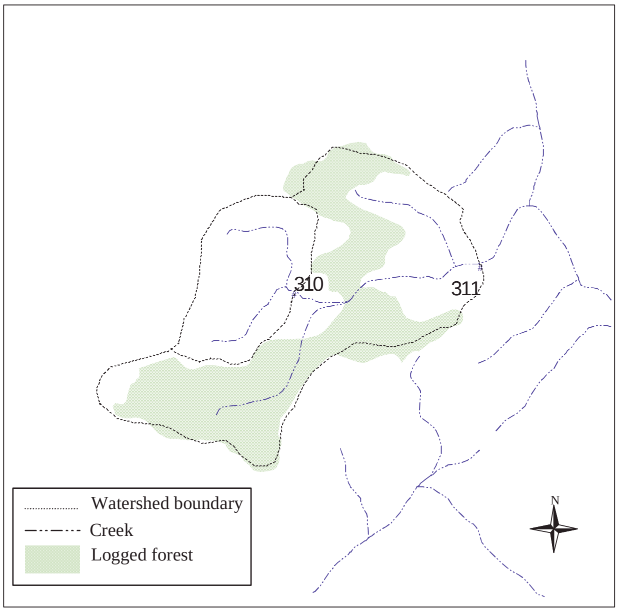


Figure 1. Gentle Annie Creek with upper control site (station 310) and lower treatment site (station 311). Watershed boundary indicated with dashed lines.

Table1. Catchment areas of monitoring stations.

Site	Station	Sub-catchment land-use	Catchment Area (ha)
Control	310	unharvested	40
Treatment	311	73 ha of harvested (45%) + 91 ha unharvested including Control	164

Table 2.. Treatments periods for Gentle Annie experimental catchment.

Periods	Start	End	Months
Pre-treatment, PT	1/01/90	7/12/90	11
Roading, R	8/12/90	18/02/91	2
Logging, L	15/01/91	16/04/91	3
Post-logging, PL	17/04/91	1/04/95	47

2.2 Data sampling

2.2.1 Rainfall Data

Rainfall was measured at control and treatment sites, however the record for the control covered only three months in the pretreatment period (9/01/90 – 11/04/90). The treatment site rainfall records commenced on 3/08/90 and continued until 13/7/95. As both stations are only separated by 1 km and the rainfall data for the control site is very short, the rainfall for the treatment site was used to interpret rainfall-runoff relationships at both stations. There were also significant periods of missing data for the treatment site, indicated in Figure A1 in Appendix A. Rainfall data from St Helens a distance of 10 km from the catchment was used where necessary to interpret periods of missing data.

2.2.2 Discharge Data

Discharge was recorded with data loggers at each of the cut-throat flumes. Data records commenced at both stations on 1/01/90 and continued until 30/04/95 at station 310 and 3/03/95 at station 311. Discharge data received for the control and treatment sites was expressed in cubic metres per second ($m^3 s^{-1}$).

2.2.3 Water Quality Data

Water quality variables assessed are:

- Turbidity (NTU),
- Total Suspended Solids (TSS),
- Total Dissolved Solids (TDS),
- Total Kjeldahl Nitrogen (TKN),
- Total Phosphorus (TP).

Automatic water samplers were installed at each of the cut-throat flume sites and programmed to sample throughout storm events. Not all discharge events were sampled due to factors such as equipment malfunction (W.Neilsen per comm.). Water samples collected during events were analysed for turbidity, and selected samples were further analysed for a full suite of elements. Water samples collected for nutrient analysis between May 1990 to December 1992 were analysed by DPI Mt

Pleasant Laboratory and samples collected from February 1993 until February 1995 were analysed at the Tasmanian Government Analyst. Samples sent to DPI Mt Pleasant Laboratory were not analysed for TKN, TP, TSS or TDS. Time periods over which samples were taken are given in Table 3.

Turbidity was sampled at the highest frequency during an event with water samples generally taken every 15 minutes for the first hour then every 3 hours thereafter. However this sampling regime varied considerably. Event samples favoured rising limbs of an event hydrograph, often with no samples being taken for event peaks and falling limbs. TSS and TDS were sampled on average three times during an event as was TKN and TP. The TSS, TDS, TKN and TP data were only available for the post-treatment period. This was more than a year after logging was completed. This severely limits the extent to which the overall data can be interpreted, outlined further in section 3.5.

Table 3. Water quality records for Gentle Annie catchment trial.

	310		**311**	
Variable	Start	End	Start	End
Turbidity (ntu)	5-4-90	13-5-95	5-4-90	31-1-95
TSS (mg/L)	23-12-93	13-5-95	14-12-93	2-2-95
TDS (mg/L)	23-12-93	13-5-95	14-12-93	2-2-95
TKN (mg/L)	6-3-93	13-5-95	15-2-93	2-2-95
TP (mg/L)	6-3-93	13-5-95	15-2-93	2-2-95

2.3 Analysis methods

2.3.1 Rainfall and Discharge

A series of analyses were undertaken on the water quality and yield data from Gentle Annie and Deacons Creek. A full description of these methods is given in Thompson *et al*. (2002) although a summary for each set of variables is given below. Time-series plots and double mass curve analyses were used to describe rainfall and discharge data (RossRakesh 1999; Grayson *et al*. 1996a). In a double mass curve the cumulative sums of two variables are plotted against one another. The degree of correlation between the variables is denoted by the constancy of the relationship. Changes in the trend of one variable are then expressed as a deviation in the slope of the line. For example, if rainfall is plotted against discharge, then a change in slope of the double mass plot indicates a change in the rainfall-runoff ratio and by deduction a change in catchment condition. Further comparison of the rainfall-ratio between the treatment and a control catchment can then be used to determine whether the change is due to rainfall, or some other known treatment factor.

2.3.2 Turbidity

The same procedure was used as described in Thompson et al. (2002). Briefly, the methods used were i) cumulative probability analysis of raw data, ii) an Analysis of variance (ANOVA) of flow weighted mean turbidities, both between sites for events during the various treatment periods, as well as within sites comparing the different treatment periods and iii) plots of flow weighted mean turbidities as a function of event runoff volume. With respect to i) turbidity data for each station was used to construct cumulative probability diagrams in which the probability of selected turbidity values being equaled or exceeded for a percent of time were derived for each station. The methodology employed for ii) required calculating a mean flow weighted turbidity for each event then conducting an ANOVA on the means to test whether or not there has been any change over the treatment periods and if there were differences between stations. The determination of mean flow weighted event turbidity requires that turbidity was recorded throughout the duration of an event. An investigation of the turbidity database, which categorised event samples by date, time and an event code revealed that event sampling did not necessarily commence at the start of an event and/or sample the rising and recession limbs of the hydrograph. Therefore turbidity data was selected from a subset of events that had data for the rising and recession limbs of an event hydrograph.

The flow weighted mean turbidity was then determined for each of the events in the subset. For each event, the discharge volume was calculated by summation of volume increments, calculated as:

Volume increment, $Vol_i = (q_{i+1}+q_i)/2 * t_i$

$$\text{Event Volume} = \sum_{i=1}^{n} \text{Vol}_i$$

$$\text{Flow weighted mean turbidity} = \left[\sum_{i=1}^{n} (\text{Vol}_i * ((\text{ntu}_{i+1}+\text{ntu}_i)/2)) \right] / \text{Event Volume}$$

where q is instantaneous discharge, t is time interval between q_i and q_{i+1} and ntu is turbidity. Single factor ANOVA's were firstly performed to compare discharge event volumes between treatment periods for each station to see if sub-sampling had been biased towards particular sized discharge events. Null hypotheses tested were:

- Control: $H_o:\mu_{pt} = \mu_r = \mu_l = \mu_{pl}$
- Treatment: $H_o:\mu_{pt} = \mu_r = \mu_l = \mu_{pl}$

where μ is mean event volume and the subscripts *pt* = pretreatment, *r* = roading, *l* = logging and *pl* = post logging phases. Single factor ANOVA's were then conducted on flow weighted mean event turbidity, to test for differences in means between treatment periods for each station. Null Hypotheses tested were:

- Control: $H_o:\mu_{pt} = \mu_r = \mu_l = \mu_{pl}$
- Treatment: $H_o:\mu_{pt} = \mu_r = \mu_l = \mu_{pl}$

where μ becomes flow weighted mean turbidity and the subscripts for *pt* etc. denote the same treatments as above. Finally, ANOVA's were conducted on flow weighted mean event turbidities to test for differences between stations for each treatment period. Hypotheses tested were:

- Pre-treatment: $H_o:\mu_{310} = \mu_{311}$
- Roading: $H_o:\mu_{310} = \mu_{311}$
- Logging: $H_o:\mu_{310} = \mu_{311}$
- Post-logging: $H_o:\mu_{310} = \mu_{311}$

where μ is flow weighted mean turbidity, and subscripts remain as above. The probability for determining if a significant difference existed between any of the means was $p < 0.05$. If significant differences were determined, a Tukey test (Zar 1984) was then applied to indicate which group(s) were statistically different.

2.3.3 Total suspended solids (TSS) and dissolved solids (TDS)

TSS and TDS data was only recorded for the post-logging period for stations 310 and 311. Box plots showing medians and percentile values were produced for TSS and TDS. These were used to compare the differences between stations during the post-logging treatment period. TSS and TDS were sampled less frequently than turbidity, thus providing insufficient data to calculate event mean concentrations (EMC) and event fluxes of sediment (Olive and Rieger 1988). To accommodate this, relationships between TSS - TDS and turbidity were explored to see whether they could be used as a surrogate for computing EMC and TSS fluxes (Grayson *et al*. 1996b). This involved determining whether the regression relationships between turbidity and TSS were different for the rising and recession limbs of event hydrographs (Walling 1977, Grayson *et al*. 1993).

2.3.4 Total Kjeldahl nitrogen (TKN) and phosphorus (TP)

TKN and TP data records commenced 23 months after logging operations ceased. Comparisons between treatments were not possible hence, data for TKN and TP are only compared between stations for the post-logging period. Box plots of raw data for each station are derived to compare the range of concentrations. Arithmetic means are determined for each event and plotted to illustrate trends between the control catchment and treatment catchments.

3.0 RESULTS, INTERPRETATION AND DISCUSSION

3.1 Results - Rainfall and discharge data

Time-series plots of daily rainfall and discharge data are presented in Figure A1 in Appendix A. Missing data for both rainfall and discharge records are indicated by arrows on the plots. Both stations have missing discharge data during the logging period (Figure A1b).

A double mass plot of cumulative rainfall for the treatment site and cumulative stream flow for control site is given in Figure 2 and shows four different relationships. 1) The years 1990 and 1991 were comparatively low rainfall and runoff years, 2) At the start of 1992 there was high runoff with apparently no rainfall, 3) 1992 and 1993 were higher rainfall years which established a different relationship to the pre 1992 relationship, and 4) 1994 was a lower rainfall and runoff year and the relationship was similar to the pre 1992 relationship.

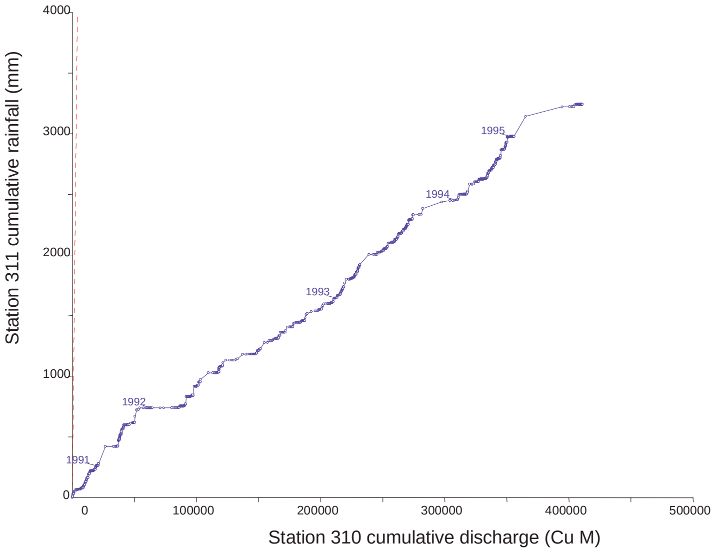


Figure 2. Double mass plot comparing discharge at 310 to rainfall at station 311. 311 rainfall used because no rainfall record at 310. Dashed line (red) indicates the 1:1 unit ratio.

In order to investigate the apparently high runoff at the start of 1992 the cumulative rainfall at the treatment site was plotted against the cumulative rainfall at the St Helens Post Office (092033) (Figure 3). The relationship between the two cumulative rainfalls is quite similar with the treatment site receiving on average approximately 10% more than St Helens. The one exception to the robust relationship was at the start of 1992. When the monthly rainfall totals are compared, St Helens received 149.2mm for January 1992 whereas the treatment site received only 16.2mm, but shows no missing record. As January 1992 is also associated with a period of high runoff from the control site we can only assume that problems were experienced with the rainfall measurement during that month, although these were not formally noted.

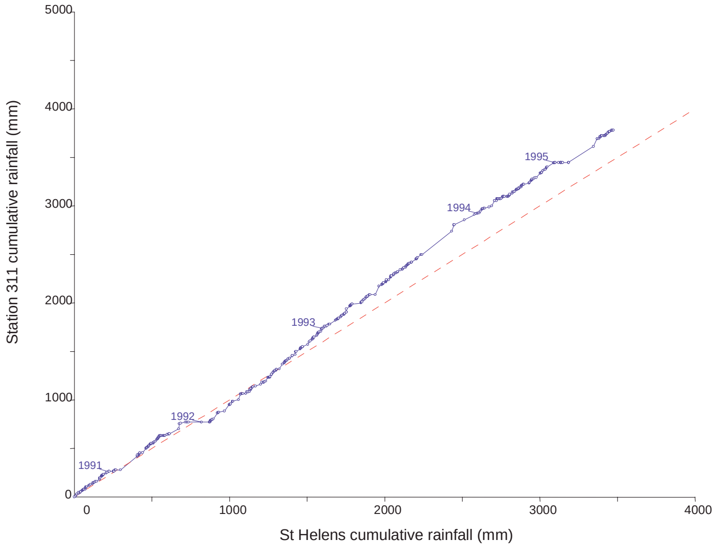


Figure 3. Double mass plot comparing rainfall at station 311 to St Helens Post Office record (92033). Dashed line (red) indicates the 1:1 unit ratio.

The cumulative rainfall (treatment)-runoff (control) plot in Figure 2 has a higher gradient for 1990 and 1991 than for the successive years with the exception of 1994. This was not unexpected as years 1990, 1991 and 1994 each had significantly less rainfall than 1992, 1993 and 1995 (Figure 4) and runoff ratios are dependent on rainfall (ie the higher the rainfall the higher the runoff ratio).

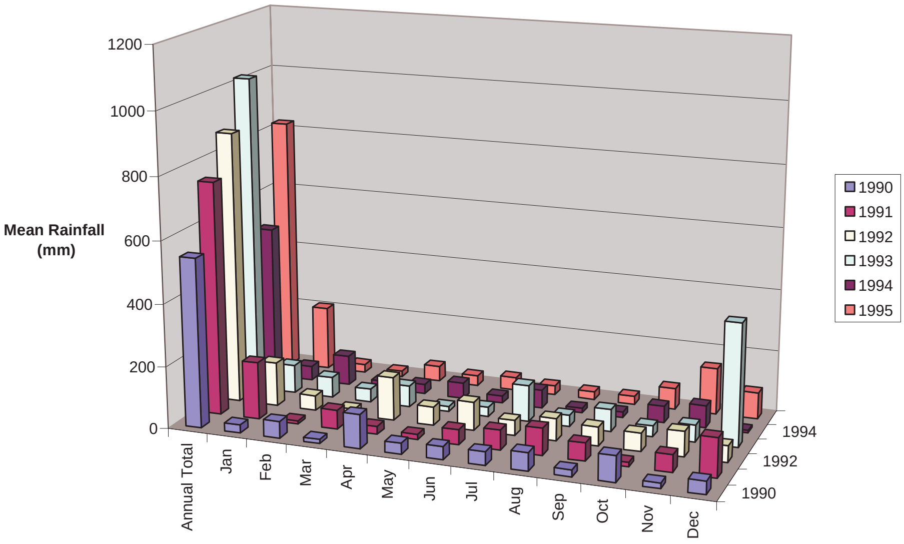


Figure 4. Mean monthly and annual rainfall for St Helens Post Office (092033).

The cumulative rainfall-runoff plot for the treatment site is shown in Figure 5. The treatment catchment is approximately four times the size of the control catchment and the cumulative flows are approximately four times greater. The larger catchment area leads to some spatial averaging. The period of very high runoff and very little rainfall observed at the start of 1992 in the control catchment is present but much smaller than shown for the treatment catchment (Figure 5). Time-series plots illustrate that this is a result of missing flow records in early January 1992 for 311 (Figure A1c in Appendix A). The cumulative rainfall-runoff plot for the treatment site (Figure 5) shows two distinct slopes with a change occurring at approximately the middle of 1991, but for this plot the gradient in 1994 is similar to 1992 and 1993. The decreased slope from mid 1991 onward could be associated with the increased rainfall, logging activities or a combination of both. A double mass analysis of discharge for both sites (Figure 6) shows a significant change in runoff ratio between the treatment station and control station in early 1991, coinciding with the commencement of logging operations. The changed ratio between the stations remains linear until mid 1994 where a further increase in runoff ratio for the treatment site occurs before returning to the 1992 to 1994 ratio.

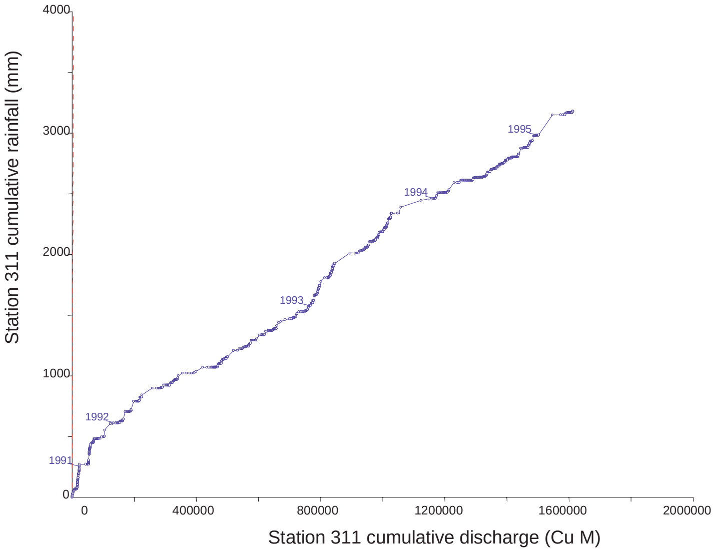


Figure 5. Double mass plot illustrating the rainfall-runoff ratio for station 311.

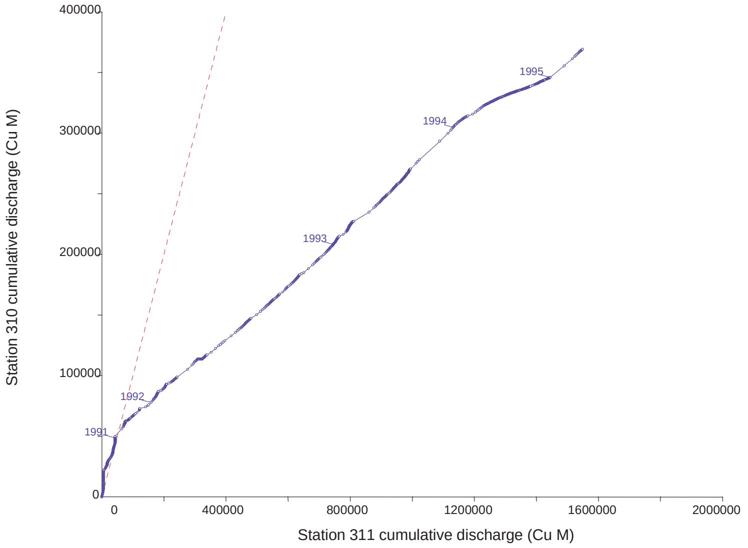


Figure 6. Double mass plot comparing discharge at treatment station 311 to control station 310. Dashed line (red) indicates the 1:1 unit ratio.

3.2 Discussion - Rainfall and Discharge

Years 1990, 1991 and 1994 had low rainfall compared to 1992, 1993 and 1995. Therefore the pre-treatment, roading and logging phases of the trial occurred during low rainfall years and the post-logging monitoring phase occurred during high rainfall years with the exception of 1994.

Forty five percent of the catchment is harvested. A review conducted by Sinclair Knight Mertz (1998) of studies on the effects of forest clearance on water yield suggest an increase in runoff from the treatment site should be detectable. A double mass curve analysis of discharge (Figure 6) showed a significant change in runoff ratio between the control and treatment sites occurring at the start of 1991. Runoff from 311 increased four fold with respect to 310. This coincided with the commencement of forestry operations and suggests this activity may have resulted in increased runoff due to roading and logging. However, with such a short pre-treatment monitoring phase containing much missing data, the outcome is not conclusive. The data plotted for Figure 6 also indicates a temporary increase in runoff ratio for the second half of 1994 indicating a possible further, yet unknown, disturbance to the treatment catchment.

3.3 Results - Turbidity

Cumulative probability plots of turbidity data are presented in Figure 8, which also present the 5 NTU line - the upper limit for drinking water (NHMRC & ARMCANZ 1996). Data for the roading and logging plots are from only two events in each period. The data for the plots suggest that during the pre-treatment period, the treatment site has similar probability as the control for turbidity values greater than or equal to 20 NTU which occur 20% of the time for discharge events. For 80 % of the time turbidity is less than 20 NTU during which time control site has lower NTU than the treatment site. However, for the post-logging period, the data indicates that for 70% of the time for which turbidity measures equal or exceed 5 NTU, control site turbidity exceeds the treatment site. The treatment site has consistently higher NTU's than the control during the roading phase for the two discharge events sampled at each site.

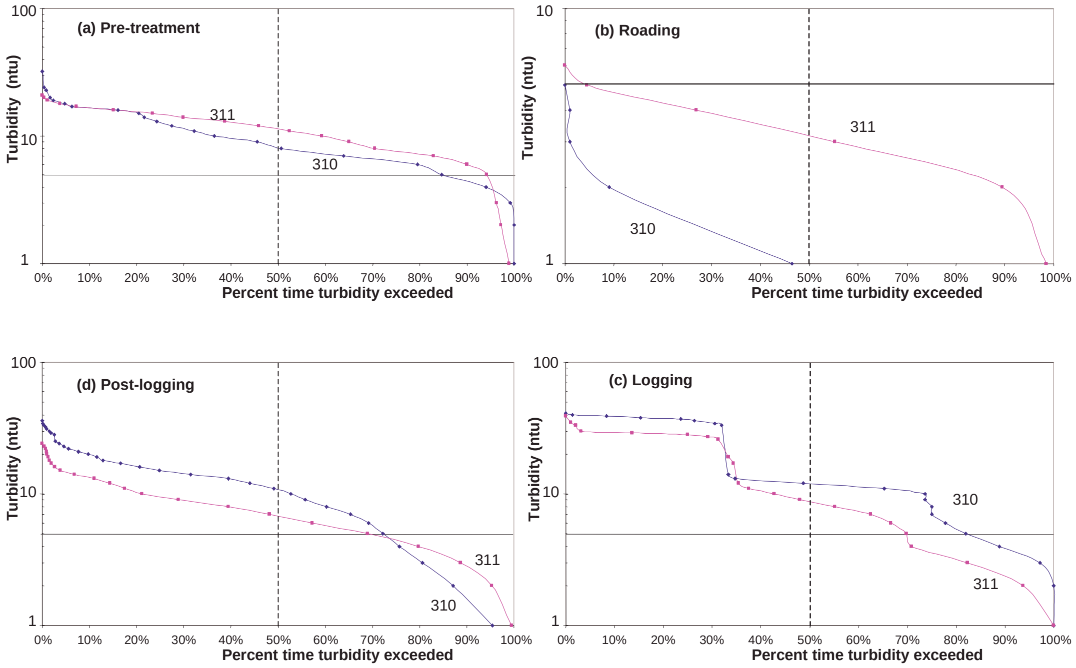


Figure 8. Cumulative probability plot of turbidity for a) pre-treatment, b) roading, c) logging and d) post-logging treatment periods. 5 ntu (solid line) and 50% probability (dashed line) marks are indicated.

Flow weighted event mean turbidity were calculated for a subset of events which had sufficient data. Table 4 and 5 give details on the number of events for which flow weighted event mean turbidity were calculated. There are only two events during the roading and two during the logging periods because of low rainfall for the season (indicated in rainfall results). The discharge event volumes for the pre-treatment and roading periods are relatively small compared to post-logging period. The event -volume standard deviation for the logging period is greater than the mean due to only to two events being sampled, the first event in mid-January (47000 Cu M^{-1} at treatment site) being orders of magnitude greater than the second event in March (1000 Cu M^{-1} at treatment site) (Figure A1b in Appendix A).

An ANOVA was undertaken on event volumes of the selected events for each station. The results are given in Table 4. For each station there was no significant differences ($p<0.05$) in mean event volumes between treatment periods. Significant differences are denoted by different letters. The large standard deviation in event volumes during the logging and post-logging periods (Table 4) exceed any real differences in volumes between the periods.

No significant differences in flow weighted mean turbidity were found between the pre-treatment and post-logging periods at the control site, 310 (ANOVA, $p<0.05$ Table 5). At the treatment site, station 311, post–logging turbidity was found to be significantly lower than turbidity during events of the pre-treatment period (ANOVA, $p<0.05$ Table 5).

Table 4 ANOVA results comparing discharge event volumes between treatment phases for each station. Significant differences between groups are denoted by different letters. Like letters denote no significant difference between group(s).

Group	Number of Events	Mean Event Vol (Cu M)	Standard deviation	Significant differences (p<0.05)
310 - Control				
Pre-treatment	6	201	97	A
Roading	2	226	180	A
Logging	2	1401	1521	A
Post-logging	28	6680	11984	A
311 - Treatment				
Pre-treatment	8	377	313	A
Roading	2	62	54	A
Logging	2	24184	32613	A
Post-logging	37	16811	34170	A

Table 5 ANOVA results for comparison of flow weighted mean event turbidity between treatments for each station. Significant differences between groups are denoted by different letters. Like letters denote no significant difference between group(s).

Group	Number of Events	Mean Turbidity (ntu)	Standard deviation	Significant differences (p<0.05)
310				
Roading	2	1.45	0.02	A
Pre-treatment	6	9.25	2.25	B
Post-logging	28	10.36	5.91	B
Logging	2	21.82	22.14	B
311				
Roading	2	3.72	1.52	A
Post-logging	37	7.56	4.17	A
Pre-treatment	8	14.21	3.24	B
Logging	2	18.55	13.00	B

The Results of ANOVA's on flow-weighted mean event turbidity comparing stations for each treatment period are shown in Table 6. Pre-treatment mean NTU was significantly higher at the treatment site however, the post-logging monitoring phase shows that the mean NTU at the treatment site is significantly lower than NTU at the control site. Turbidity at the control site did not change between pre-treatment and post-logging phases, whereas the treatment site post-logging values were lower than the pre-treatment.

Table 6 ANOVA results for comparison of flow weighted mean event turbidity between stations for each treatment period. Significant differences between groups are denoted by different letters. Like letters denote no significant difference between group(s).

Group	Number of Events	Mean (ntu)	Standard deviation	Significant differences (p<0.05)
Pre-treatment				
310	6	9.25	2.24	A
311	8	14.21	3.24	B
Roading				
310	2	1.45	0.02	A
311	2	3.72	2.30	A
Logging				
310	2	21.82	22.14	A
311	2	18.55	13.00	A
Post-logging				
310	28	10.36	5.91	A
311	37	7.56	4.17	B

Figure 9 describes flow weighted event mean turbidity as a function of event volume. The plot illustrates that for both stations most of the post-logging events are larger than pre-treatment events. However for events that are of similar volume, flow-weighted mean turbidity is generally lower for the post-logging period than for the pre-treatment levels at both stations.

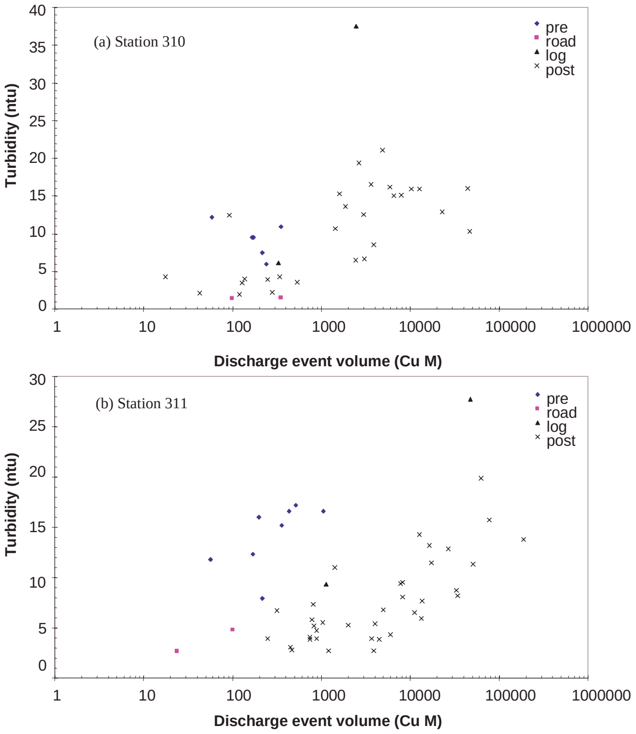


Figure 9. Flow weighted mean turbidity plotted as a function of discharge event volume for each treatment period in a) station 310 and b) station 311.

3.4 Results - Total Suspended Solids and Total Dissolved Solids

Box plots comparing raw total suspended solids and total dissolved solids for the post-logging period between stations are presented in Figure 10. For TSS data the 75th percentile is 7 mg L^{-1} for the control site and 10 mg L^{-1} for the treatment site. The 90th percentile is 14 mg L^{-1} and 18 mg L^{-1} respectively which indicates TSS maximum concentrations during an event are slightly higher for the downstream station. In contrast the TDS data for the 75th and 90th percentiles shows the control catchment having slightly higher concentration peaks than the treatment catchment. TDS data for the post-logging period has about 15 times the concentration of TSS.

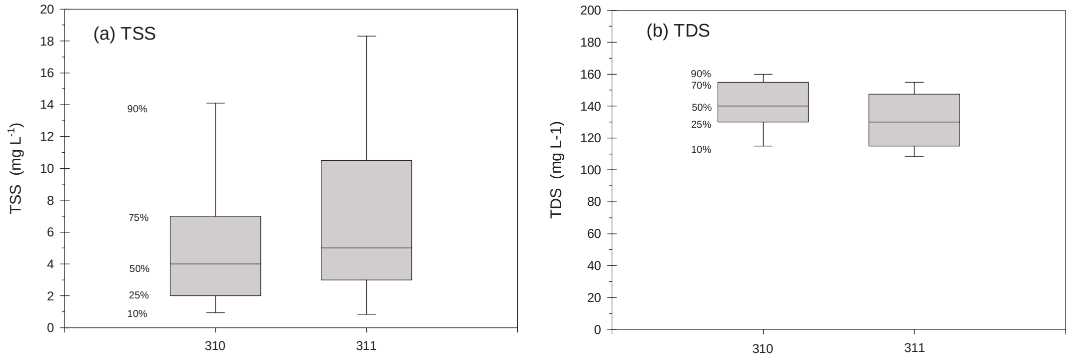


Figure 10. Box plot of (a) TSS and (b) TDS for the post-logging treatment period. Note the change scale for (b) TDS.

Poor relationships were found to exist between TSS and turbidity with R^2 values of 0.007 and 0.07 for control and treatment site respectively (Figure 11). The goodness of fit was improved when the data was separated into rising and recession limb components of event hydrographs but not enough to enable turbidity to be used as a surrogate to fill in event TSS data therefore enabling the calculation of sediment yields and event mean concentrations.

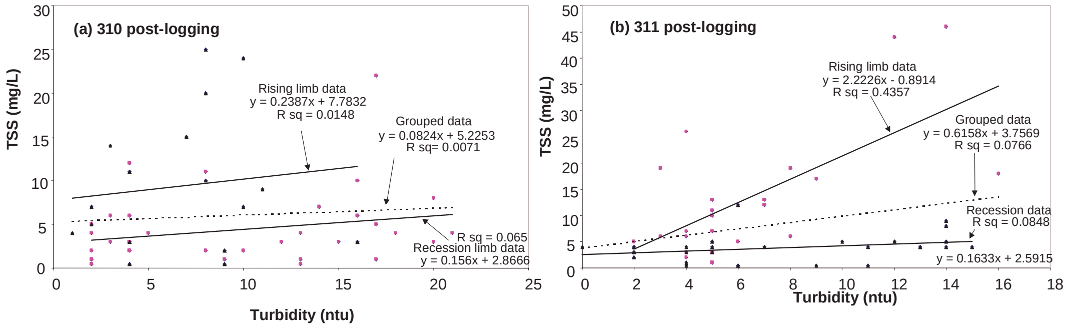


Figure 11. TSS data regressed against turbidity for a) station 310 and b) station 311.

Relationships between turbidity and TDS are stronger (Figure 12). The relationship from the control catchment (310) did not change when the data was separated into rising and recession limbs on the hydrograph. The recession limb relationship for the treatment catchment was relatively robust (R^2 = 0.79) however the rising limb relationship between TDS and turbidity was still poor (R^2 = 0.30).

The relationship between TSS and turbidity, while poorly defined, does indicate a positive and linear association. The inverse is apparent for the relationship between

TDS and turbidity. The association between TDS and turbidity was best defined by a negative logarithmic curve where highest TDS measures occur at low turbidity

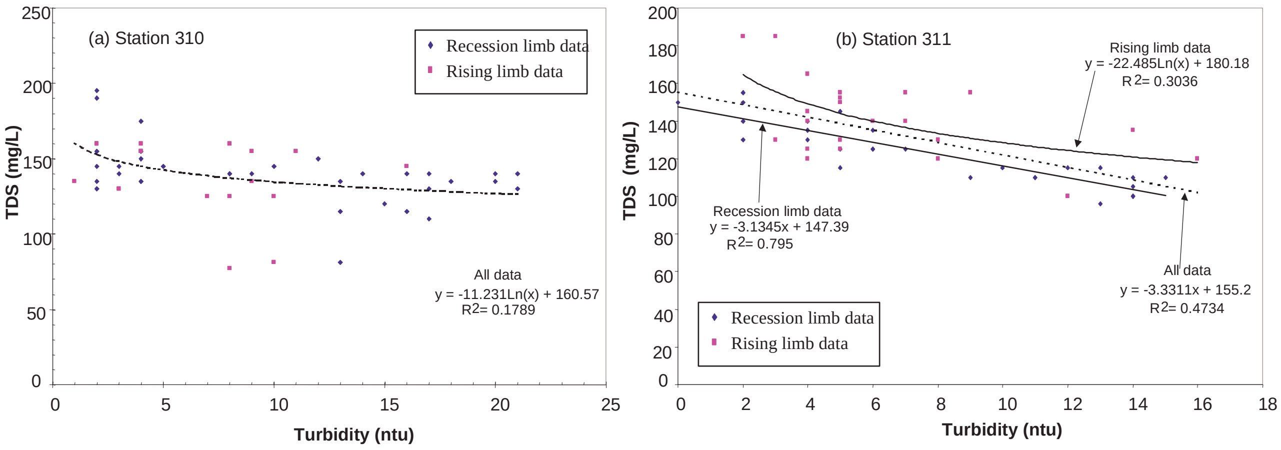


Figure 12. TDS data regressed against turbidity for a) control catchment b) treatment catchment.

3.5 Discussion - Turbidity, TSS and TDS

The cumulative probability plots (Figure 8) show that discharge event turbidities exceed the upper limit for drinking water (5 NTU) 80% of the time during the pre-treatment period and 70% of the time for the post-logging phase. The plots show that the control site NTU exceedence probabilities slightly increase from the pre-treatment monitoring phase to the post-logging monitoring phase. Data for 311 show increased turbidity during roading operations with respect to the control, however the roading phase turbidities for both catchments are below the pre-treatment values.

There was considerable variability in NTU data within treatment periods. The highest values in both catchments occurred during the logging phase, although these were levered by a single mean event NTU. However as no logging actually occurred in the control catchment it is unlikely that the higher NTU value at that time can be attributed to this process, but rather to rainfall induced natural hillslope and channel erosion within the catchment. The ability of varying rainfall intensities to generate different rates of sediment erosion in this region was outlined in Wilson *et al*. (1999). These authors further noted that the frequency of rainfall events also influences the amount of sediment supply.

The ANOVA results comparing flow weighted mean event NTU (Table 5) indicate that (with the exception of the roading period) there is no change in mean event NTU during the trial for the control catchment (within uncertainties). However the mean event NTU for the treatment catchment, while initially higher than the control in the pre-treatment phase, fails to sustain this increase. The logging and post logging NTU's are lower than the control for the same periods.

Further investigation of event mean turbidities with respect to event volumes showed that much of the discharge events during post-logging were orders of magnitude greater than pre-treatment discharge events. Post-logging discharge events of similar magnitude to pre-treatment events had mean NTU's much lower in the post-logging phase for both catchments, not just the treatment catchment as suggested by the ANOVA results. Consequently, analyses of event turbidities (based on the limited data available) indicates that harvesting operations have not increased mean event turbidities in the Gentle Annie trial.

TSS concentrations for the treatment station (Figure 10) are slightly higher (but within uncertainties) than the control station. Median, 75th and 90th percentile values suggest maximum concentrations during discharge events could be greater for the treatment catchment during the post-logging phase. Speculatively, this could be attributed to an impact from forestry operations. However, without pre-treatment data it is not possible to determine whether the elevated concentrations are due to other catchment factors. Langford *et al*. (1982) reported higher mean pre-treatment TSS concentrations (14 mg L^{-1}) which increased to 21 mg L^{-1} during road construction than compared with TSS measured for Gentle Annie treatment catchment. TSS measured in runoff from simulated rainfall events on hillslopes in Gentle Annie catchment resulted in concentration values orders of magnitude greater for both control and treatment sites (Wilson *et al*. 1999) than were measured in-stream during this trial.

TDS concentrations at the treatment station for the post-logging period are similar to the concentrations measured at the control site. However because pre-treatment data is not available it is not possible to determine the forestry operation impact on TDS concentrations. Furthermore, the dissolved solid fraction is primarily influenced by weathering of parent rock and is not expected to be significantly increased due to harvesting operations except for an initial flush of dissolved material (Langford *et al*. 1982). The TDS concentrations measured in Gentle Annie (110-200 mg L^{-1}) can be twice that of dacitic soils in Victoria (50-80 mg L^{-1}) (Langford *et al*. 1982).

The relationships between turbidity and TSS, as well as turbidity and TDS, were too poor to be used to predict TSS and TDS (Figure 11). It is therefore concluded that the length, timing and quality of the TSS and TDS data was insufficient to determine whether forestry operation effected solid concentrations in the Gentle Annie catchment.

3.6 Results - Total Kjeldahl Nitrogen and Total Phosphorus

Total Kjeldahl Nitrogen and Total Phosphorus data for the control (310) and treatment (311) stations for the post-logging period are presented as box plots (figure 13). TKN and TP data for the post-logging periods indicate that the control and treatment catchments have similar concentrations of nitrogen and phosphorus during discharge events. The median, 75th and 90th percentiles of TKN concentrations for the treatment catchment are marginally higher than for the control catchment indicating event maximum concentrations of TKN may be greater for the treatment site, although as above, the difference is minor. TP for the control and treatment sites are presented in Figure 13b show slight differences in the median and 90th percentile concentration level, otherwise the TP event concentration data appears to have a similar range between the stations.

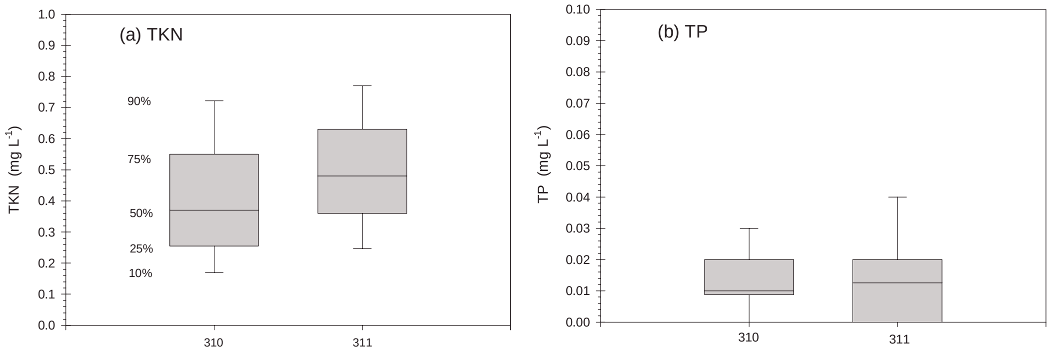


Figure 13. Box plots of TKN and TP for the post-treatment period. Note the change in scale between TKN and TP.

Plots of arithmetic event mean TKN and TP are presented in Figure 14. They show that for TKN and TP during the post-logging period, the control site generally has lower mean concentrations than the treatment site. Also evident is a convergence in TKN concentrations towards the end of the record.

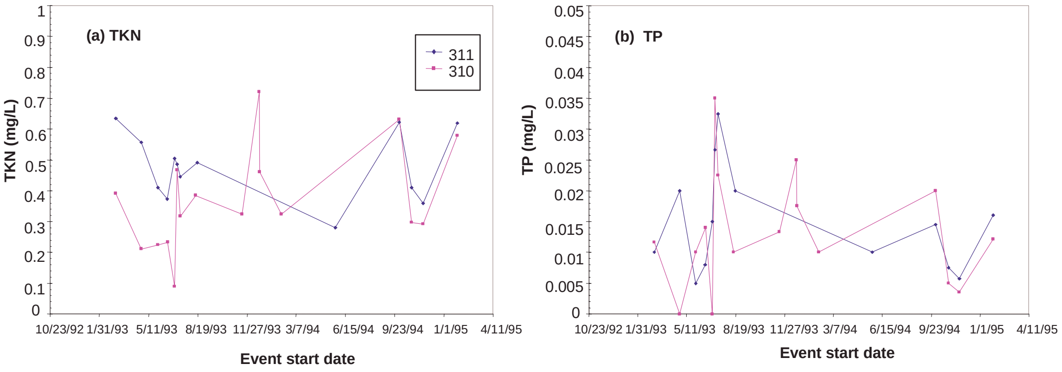


Figure 14. Mean event measures of a)Total Kjeldahl Nitrogen and b) Total Phosphorus for stations 310 and 311. Means are not flow weighted due to few samples per event taken (n=4).

3.7 Discussion - Total Kjeldahl Nitrogen and Total Phosphorus

Box plots of event concentrations of TKN and TP (Figure 13) exhibit similar range of values between the control and treatment sites however the median and 90th percentile concentrations are slightly higher for the treatment station. Unfortunately, no data are available to determine pre-treatment concentration levels or concentration levels for discharge events during forestry operations. Because no pre-treatment TKN and TP data are available to indicate background concentration levels for each sub-catchment, no conclusions regarding influence of forest harvesting operations on TKN and TP in-stream concentrations can be made.

Nonetheless, post logging event mean TKN and TP data plotted over time (Figure 14) provide some evidence that nutrient concentrations are lower for the control station and that concentrations for the treatment site are returning to the concentration levels of the control catchment, particularly for TKN. This implies that TKN concentrations may have been elevated in the treatment site as a result of harvesting and returned to control site concentrations 4 years after disturbance. However, as above, because there is no pre-treatment data, this hypothesis cannot be tested. Nonetheless, Swank *et al*. (2001) indicate that forest harvesting can induce significant changes in nitrogen cycling process leading to periodic increase in stream concentrations of nitrogen. Croke *et al*. (2000) observed relatively high nitrogen concentrations in overland flow after logging and burning of the general harvest area which was attributed to a solution process with ash and charcoal that was preferentially entrained by runoff. Slight elevations detected in the treatment catchment relative to the control site in nitrogen levels may be a result of the bush fire that occurred in the treatment site at the end of the logging period.

4.0 CONCLUSIONS

The pretreatment phase of the Gentle Annie trial, including roading and logging was undertaken during a period of below average rainfall, whereas the post logging phase occurred during a period of higher rainfall. About 45% of the treatment catchment (311) was harvested and a double mass analysis showed a significant change in the discharge relationship between the control and the treatment catchment. This change coincided with the logging phase in 1991, and was not related to increased rainfall. The change in the relationship was due to an increase in the rainfall-runoff ratio in the treatment catchment after logging. This was relative to the pre-treatment monitoring phase however, which was short (11 months).

The influence of the logging treatments on turbidity was more difficult to determine. This was partially due to the quality of the data and the timing of event sampling as well as the low rainfall during the pre-treatment phase compared to the high rainfall in the post-logging phase. Given these caveats, there appeared to be no change in mean event NTU for either the treatment or control catchment, both with treatment and over time. Although turbidity was found to be variable, there was no evidence to support an increase in turbidity due to harvesting and roading in the treatment catchment. An investigation of turbidity sampling and measuring techniques is warranted to ensure that inaccuracies in collated data have not been propagated to the analysis procedure present here. Gippel (1989) and RossRakesh (1999) outline problems and errors associated with measuring turbidity.

The TSS and TDS data was restricted to only the post-logging phase and as such, was not used to analyse changes due to logging. This data was of poor quality and no relationship with turbidity could be supported for either variable. TSS data had similar range of values for both the treatment and the control catchment in the post-logging period. This may imply that harvesting has not resulted in any prolonged increase in levels of suspended solids in the treatment catchment compared to the control. The TDS fraction was consistently higher than the TSS fraction.

The nitrogen (measured as total Kjeldahl nitrogen, TKN) and phosphorus (measured as total phosphorus, TP) data was also restricted to the post logging period and was of poor quality. TKN concentrations had similar range of values for both the control and treatment sites with slightly higher values observed in the treatment catchment. A temporal analysis showed that initial concentrations of TKN in particular, were higher in the treatment catchment than the control. However they appeared to converge with those of the control catchment over the post-logging monitoring phase of 4 years. This may indicate a possible elevation of concentrations due to the fire within the treatment catchment and harvesting, however the absence of pretreatment data did not allow this hypothesis to be tested. TP data showed a similar range of values for both the control and treatment sites.

In conclusion, the data from Gentle Annie support an increase in catchment water yield in the post harvesting phase. The 4 fold increase in runoff ratio persisted until the end of the trial in 1995. There was weaker evidence supporting an increase in TKN concentrations in the post-logging phase that may be associated with a fire in the treatment catchment. There was no firm evidence to support an increase in turbidity, TSS or TDS values, although conclusions are restricted by the quality of data.

SECTION II: DEACONS CREEK

5.0 INTRODUCTION

The aim of Deacons Creek trial was to assess the impact on water quality and flow of harvesting forest on highly erodible granite soils using cable logging equipment.

Deacons Creek catchment is located in Eastern Tasmania, approximately 10 Km south west of St. Helens. As with Gentle Annie, Deacons Creek is part of 'the granite erosion study' seeking to assess the effects of forest operations on highly erodible granitic soils. The vegetation is dry sclerophyll forest dominated by *Eucalyptus sieberi* and *E. obliqua* (Forestry Commission file).

6.0 METHODS

6.1 Experimental design

The Deacons Creek catchment was also set up as a simple nested design with an upper control site and lower treatment site in which the creek was instrumented with cut-throat flumes in 1990 (Figure 15). The treatment site (313) included 45 ha of harvested forest, 30 ha that was not harvested, as well as 30 ha of control (312) (Table 7). The experimental program began in April 1991 with the Pre-treatment monitoring phase. Forestry operations began with road infrastructure construction in March 1994. Road construction lasted for four months and was followed by three months of cable logging. The post-logging monitoring phase extended to the end of February 1996. Dates for these treatment periods are given in Table 8. A small area along the upper slope was harvested by ground based techniques as rocky outcrops prevented cable logging (Forestry Commission file). A road is located within the control catchment, running parallel to the major stream and intersects a smaller tributary (Figure 15).

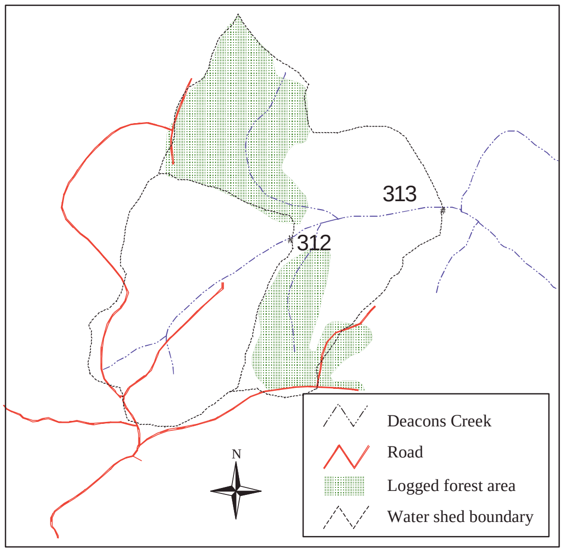


Figure 15. Deacons Creek with upper control catchment (station 312) and lower treatment catchment (station 313).

Table 7. Catchment areas

Site	**Station**	**Sub-catchment land-use**	**Area (ha)**
Control	312	unharvested	30
Treatment	313	45 ha of harvested (43%) + 60 ha unharvested (including Control)	105

Table 8. Treatments periods for Deacons Creek experimental catchment.

Periods	**Start**	**End**	**Months**
Pre-treatment, PT	1/01/90	14/03/94	51
Roading, R	15/03/94	21/07/94	4
Logging, L	27/07/94	13/10/94	3
Post-logging, PL	14/10/94	28/02/96	16

6.2 Data sampling

6.2.1 Rainfall Data

Daily rainfall was recorded at the stations 312 (6/01/90 – 21/09/95) and 313 (3/01/90 – 12/07/95). There were significant periods of missing data, these are shown in figure B1(a-g) in Appendix B. Rainfall records for St Helens were used to interpret periods of missing data.

6.2.2 Discharge Data

Discharge was recorded continuously from cut-throat flumes. Records commenced at both stations in early January 1990 and continued until the end of February 1996. There were many large periods of missing data which are indicated in Figure B1(a-g) in Appendix B. Data was supplied for analysis in cumecs.

6.2.3 Water Quality Data

Water quality variables assessed in Deacons Creek are the same as assessed in the Gentle Annie catchment trial which are:

- Turbidity (NTU),
- Total Suspended Solids (TSS),
- Total Dissolved Solids (TDS),
- Total Kjeldahl Nitrogen (TKN),
- Total Phosphorus (TP).

Weir stations were instrumented with automatic water samplers as in the Gentle Annie catchment. The same protocols were applied to Deacons Creek water quality sampling regime and similar data bias and missing periods of data were also present as in the Gentle Annie trial (Section 2.2.3). Time periods over which samples were taken are given in Table 9.

Table 9. Water quality records for Deacons Creek catchment trial.

Variable	**310**		**311**	
	Start	End	Start	End
Turbidity (ntu)	15-7-91	13-5-95	15-7-91	13-5-95
TSS (mg/L)	8-7-93	13-5-95	19-6-93	13-5-95
TDS (mg/L)	8-7-93	13-5-95	19-6-93	13-5-95
TKN (mg/L)	25-1-93	13-5-95	24-1-93	13-5-95
TP (mg/L)	25-1-93	13-5-95	24-1-93	13-5-95

6.3 Analysis methods

6.3.1 Rainfall and Discharge

Analysis methodologies applied to rainfall and discharge data from Deacons Creek catchment are the same as those applied in the Gentle Annie catchment (Section 2.3.1).

6.3.2 Turbidity

The methods employed to assess event turbidity were largely the same as for Gentle Annie in Section 2.3.2. However the ANOVA's were undertaken on the arithmetic mean turbidity for each event. This was because discharge was not available for the time that water samples were taken; preventing the calculation of flow weighting. Arithmetic means calculated in this way will be systematically higher than those using the flow weighted method. This is not a problem if they are compared to data calculated in the same way for both treatment and control catchments. However it will have an effect if the ANOVA data is compared to that from elsewhere (ie Gentle Annie), in which the flow weighting method has been used. Box plots of data can be used to compare data between Gentle Annie and Deacons Creek sites.

Single factor ANOVA's were conducted on arithmetic mean event turbidity to test for differences in means between treatment periods for each station and to test for differences between stations for each treatment period. Null hypotheses tested are as for Gentle Annie, where 312 denotes the control catchment and 313 denotes the treatment catchment. It should be noted that the symbol μ is the arithmetic mean event ntu, not flow weighted as is the case for Gentle Annie ANOVA's. The probability for determining if a significant difference existed between any of the means was $p< 0.05$. If significant differences were determined, a Tukey test (Zar 1984) was then applied to indicate which group(s) were statistically different.

6.3.3 Total Suspended Solids and Dissolved Solids

Box plots showing medians and percentile values were produced for TSS and TDS. These were used to compare the differences between logging and post-logging treatment periods and allow comparisons between stations. TSS and TDS were sampled considerably less frequently than turbidity, thus providing insufficient data to calculate event mean concentrations (EMC) and event fluxes of sediment (Olive and Rieger 1988).

6.3.4 Total Kjeldahl Nitrogen and Total Phosphorus

TKN and TP were also sampled less frequently than turbidity. Data for each station and treatment period are presented as box plots for total Kjeldahl nitrogen and total phosphorus. Percentiles are given to describe the spread of the data.

7.0 RESULTS, INTERPRETATION AND DISCUSSION

7.1 Results - Rainfall and Discharge

Time-series plots of daily rainfall and discharge data are presented in Figure B1(a-g) in Appendix B. Missing data for both rainfall and discharge records are indicated by arrows in the plots.

A cumulative double mass plot of rainfall for the control and treatment catchments is shown in figure 16. The initial section of the plot for 1990 and 1991 appears chaotic due to missing data records for most of 1990 and 1991 (see time-series plots Figure B1(a-g) in Appendix B). In the section of the plot from 1992 onward, rainfall is highly correlated between the treatment and control catchments. The control site receives approximately 15% more rain than the treatment site. Years 1990 and 1991 are not considered in further discussion due to the quality of the data.

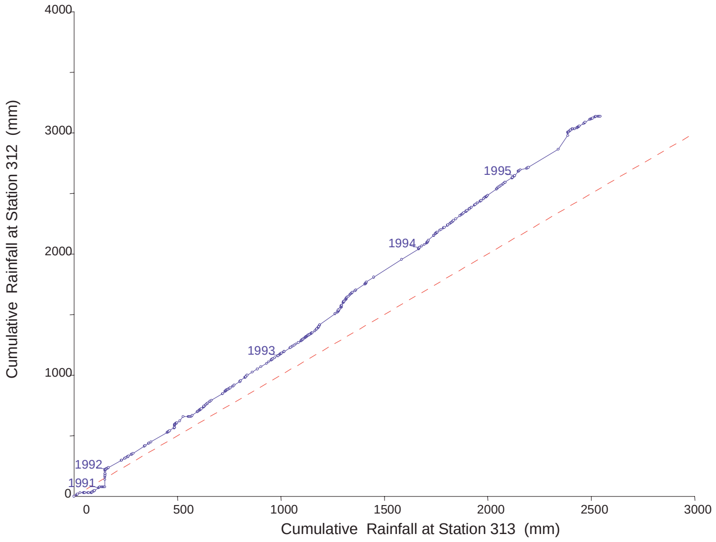


Figure 16. Double mass plot comparing rainfall records between station 312 and 313. The dashed line (red) indicates the 1:1 unit ratio.

It is apparent from Figure B1(a-g) that two major rainfall events occurred during the period of record. The first event occurred on the 22 and 23 December 1993 when 232.6mm and 216.6mm where recorded and the second event occurred on the 28 and 29 January 1995 when 261.2mm and 189.8mm where recorded at the control and treatment sites respectively. Both of these events would have lead to significant local flooding. The extended 1993 event was bigger than the 1995 event with 350mm of rain being recorded in a six day period. The cumulative rainfall data for both stations 312 and 313 was quite highly correlated with St Helens Post Office rainfall data. The control site rainfall was approximately 10% greater than St Helens (Figure 17a) and the treatment site rainfall was approximately 5% less than St Helens (Figure 17b).

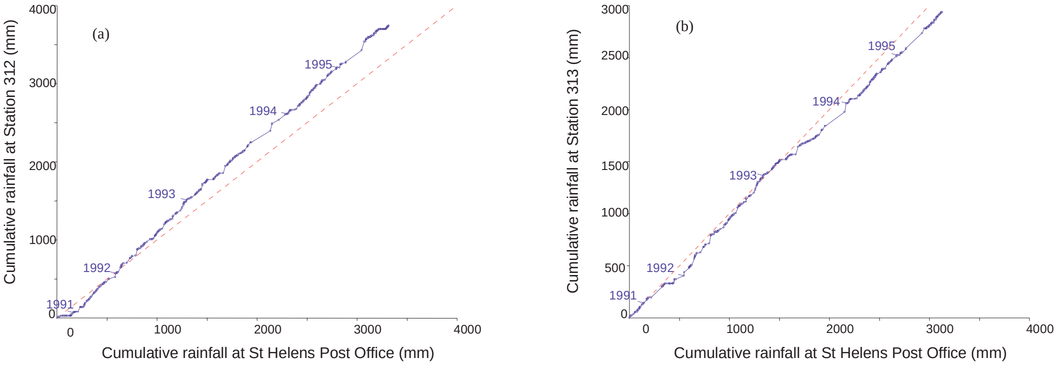


Figure 17. Double mass plots of daily rainfall comparing a) St Helens record to station 312 and b) St Helens records to station 313. The dashed line (red) indicates the 1:1 unit ratio.

The second feature of interest is that the slope of the rainfall-runoff plot for 1994 in both catchments is significantly steeper than for the other years (Figures 18 and 19). This is expected as 1994 was by far the driest year (Figure 20) so a lower rainfall-runoff ratio is expected. Although the shape of the rainfall-runoff plots for the control and treatment sites are quite similar (Figures 18 and 19), a double mass analysis of discharge (Figure 21) illustrates a significant change in the relationship between them. This occurs towards the end of the pre-treatment monitoring phase and coincides with the very large rainfall event in December 1993. The large rainfall event in January 1995 however, does not result in such an extreme change in runoff ratio. The forestry harvesting phase of the trial commenced in mid March in 1994, and continued until early October 1994, which was the driest year during the trial. The double mass curve analysis of discharge (Figure 21) illustrates a high correlation between the control and treatment catchment discharges throughout 1994 even though 43 % of the catchment was subjected to forestry operations.

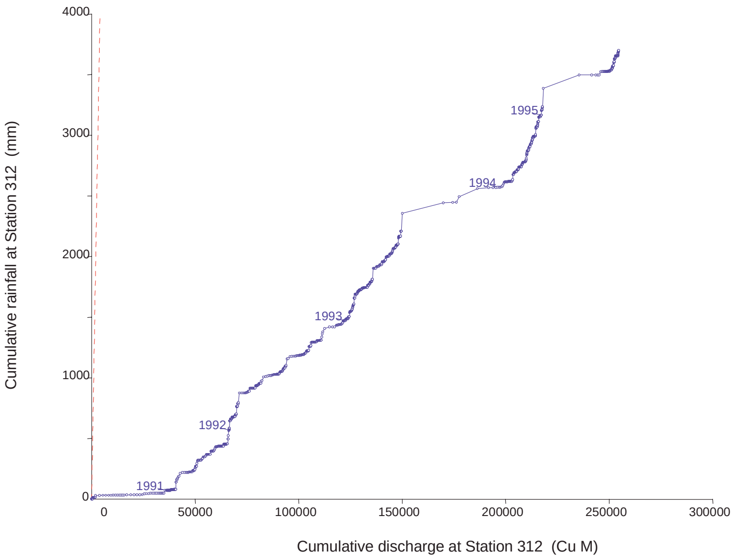


Figure 18. Double mass plot showing the rainfall-runoff ration for control catchment, 312.

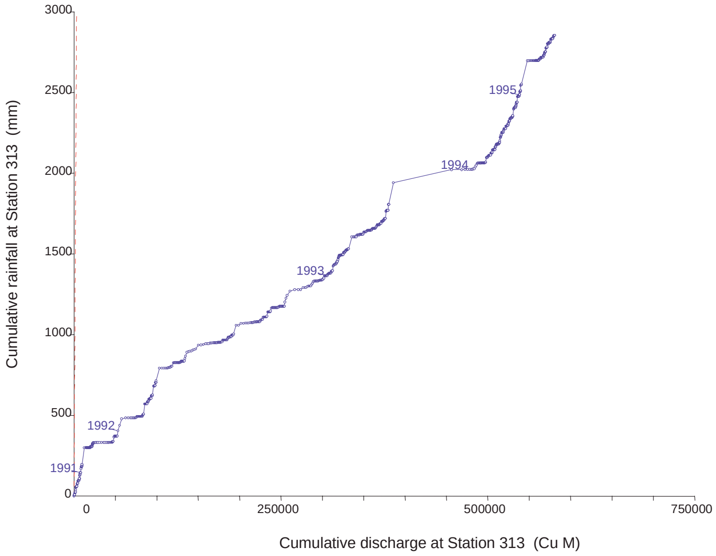


Figure 19. Double mass plot showing the rainfall-runoff ratio for the treatment catchment, 313.

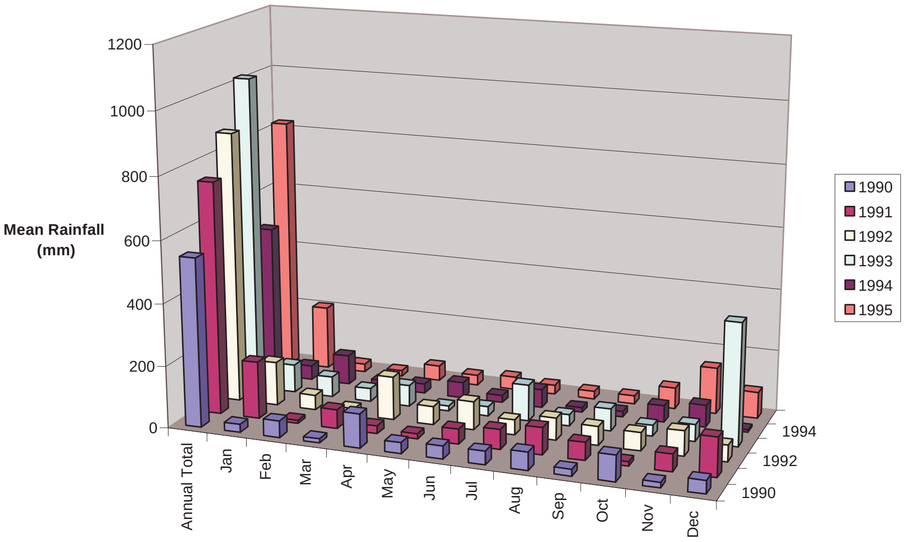


Figure 20. Mean monthly and annual rainfall for St Helens Post Office (092033).

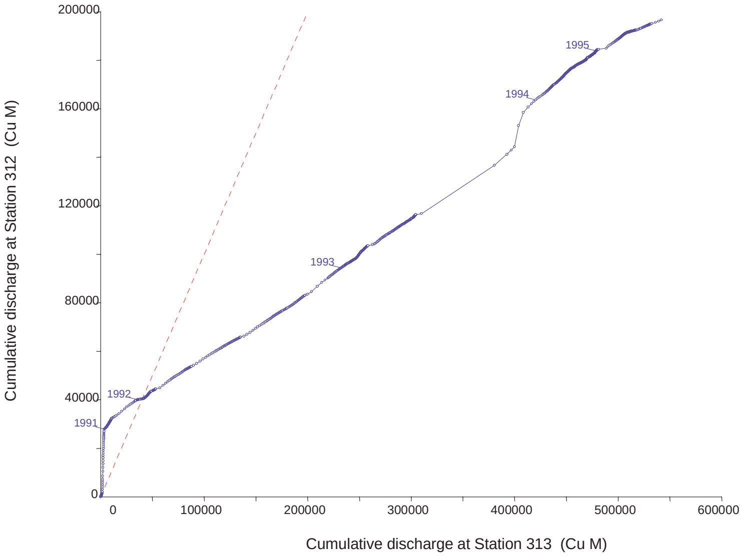


Figure 21. Double mass plot comparing discharge record of control catchment (312) to the discharge record of the treatment catchment (313). The dashed line (red) indicates the 1:1 unit ratio.

7.2 Discussion - Rainfall and Discharge

Forestry operations occurred during a very dry year compared with pre-treatment and post-logging monitoring phases. No change in the runoff ratio between the control and treatment is evident during roading or logging phases. Reasons for this are not apparent. The response of both catchments appears to be dominated by annual rainfall variations rather than treatment factors. The biggest change in the discharge relationship between the control and treatment occurred in the pre-treatment phase of the trial. This related to the large rainfall event that occurred over several days in December 1993. Close examination of the data (Figure B1d) reveal that the control catchment had a large discharge response to the rainfall over the entire event (in particular showing a second discharge peak correlating with rainfall on 23 December), whereas the treatment catchment did not. Reasons for this include the heterogeneity of rainfall across the study area at this time.

7.3 Results - Turbidity

Cumulative probability plots of turbidity data are presented in Figure 22 which also gives the 5ntu limit for drinking water, (NHMRC & ARMCANZ 1996). The data show that turbidity at the control site is exceeded by that at the treatment site for each monitoring phase. For the treatment station 313, 50% of the time turbidity equaled or exceeded 19 ntu during the pre-treatment phase; during roading, turbidity equaled or exceeded 31 ntu 50% of the time; during logging turbidity equaled or exceeded 23ntu 50% of the time; and for the post-logging monitoring phase turbidity equaled or exceeded 11ntu 50% of the time. For the control catchment, NTU measures equaled or exceeded 50% of the time but this decreased for successive treatment periods of the trial. The cumulative probability plots indicate that during forestry operations turbidity increased but then returned to pre-treatment levels in the post-logging monitoring phase.

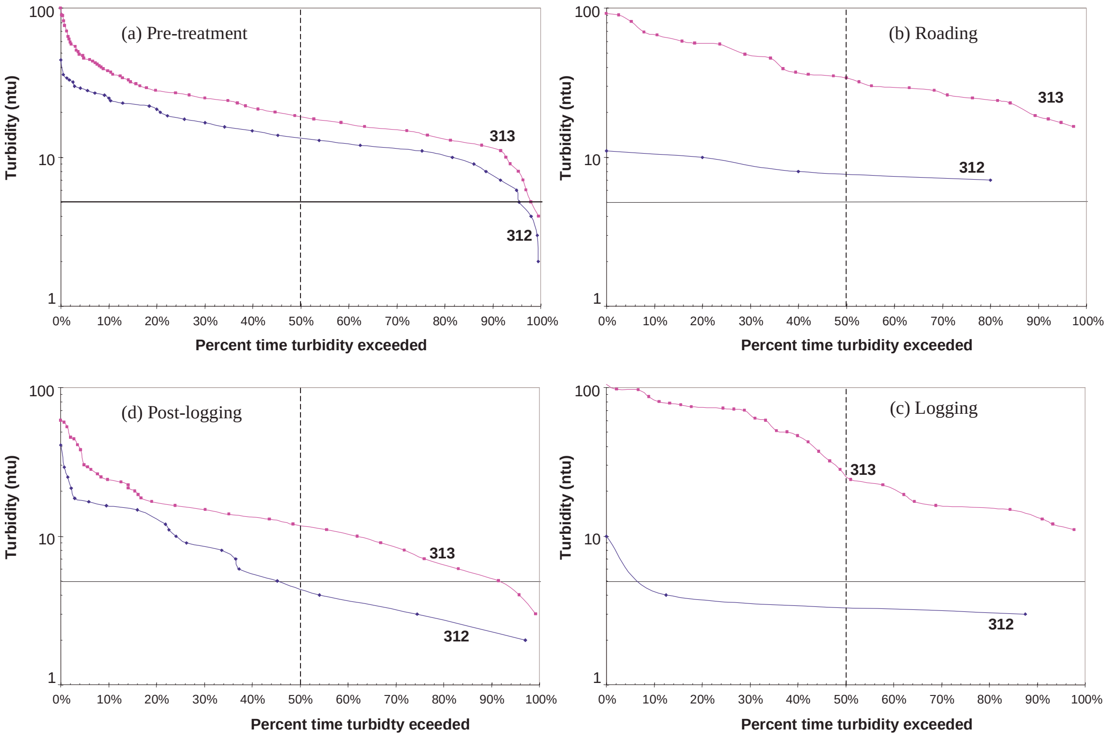


Figure 22. Cumulative probability plot of turbidity for each treatment period comparing the control (312) to treatment (313) catchments. 5 ntu (solid line) and 50% probability (dashed line) marks indicated.

Arithmetic mean event turbidity are calculated for events with at least three records occurring during a discrete time interval. The number of events analysed and the results of ANOVAs conducted on mean event turbidities comparing treatment phases for each station are presented in Table 10. At the control station only the pre-treatment and post-logging phases could be tested due to insufficient event data during the roading and logging time periods. Post-logging mean event turbidity at the control and treatment sites was lower than during the pre-treatment phase. At the treatment site both the roading and logging phases exhibited significantly higher mean event turbidities.

Table 10 ANOVA results comparing mean event turbidity between treatment phases for each station. Significant differences between groups are denoted by different letters. Like letters denote no significant difference between group(s).

Group	Number of Events	Mean Turbidity (ntu)	Standard deviation	Significant differences ($p<0.05$)
312 - Control				
Pre-treatment	22	13.36	5.40	A
Post-logging	7	7.02	3.69	B
Roading	1	8.80	0.00	Not analysed
Logging	1	4.63	0.00	Not analysed
313 - Treatment				
Post-logging	8	14.66	8.30	A
Pre-treatment	31	24.28	9.25	A
Roading	6	43.76	11.54	B
Logging	4	47.72	13.16	B

The Results of ANOVA's on mean event turbidity comparing stations for each treatment period are shown in table 11. Due to insufficient roading and logging event data at the control site only pre-treatment and post-logging phases were tested. During the pre-treatment and post-logging phases the treatment catchment showed about a factor of two higher turbidity than the control catchment. Overall however the mean turbidities of both catchments were approx. half that in the post-logging phase compared to that in the pre-treatment.

Table 11 ANOVA results comparing flow weighted mean event turbidity between stations for each treatment periods. Significant differences between groups are denoted by different letters. Like letters denote no significant difference between group(s).

Group	Number of Events	Mean Turbidity(ntu)	Standard deviation	Significant differences ($p<0.05$)
Pre-treatment				
312	22	13.36	5.40	A
313	31	24.28	9.25	B
Post-logging				
312	7	7.02	3.69	A
313	8	14.66	8.30	B

Figure 23 describes mean event turbidity for each station over time with treatment periods identified by dashed lines. During the pre-treatment monitoring phase station 313, while uniformly higher than station 312, generally follows the mean event turbidity trend at the control site. During the roading and logging phase however mean event turbidity for the treatment station diverges upward while the control catchment mean event turbidity decreases. During the post-logging monitoring phase the treatment site mean event turbidity converges to the control site turbidity levels.

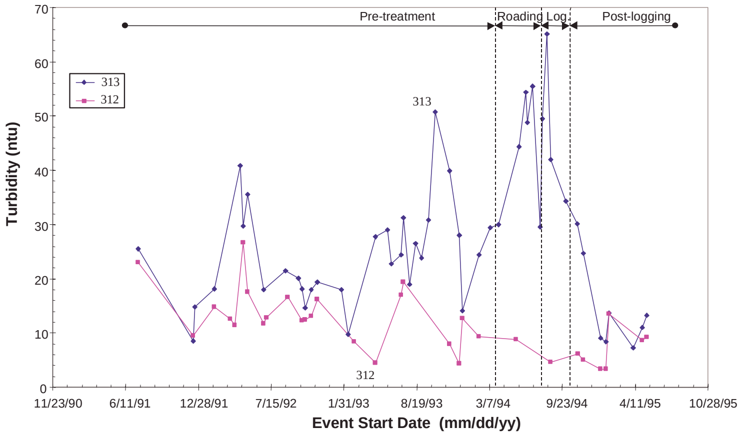


Figure 23. Mean event turbidity comparison between control station and treatment station. Dashed lines divide the plot into treatment periods.

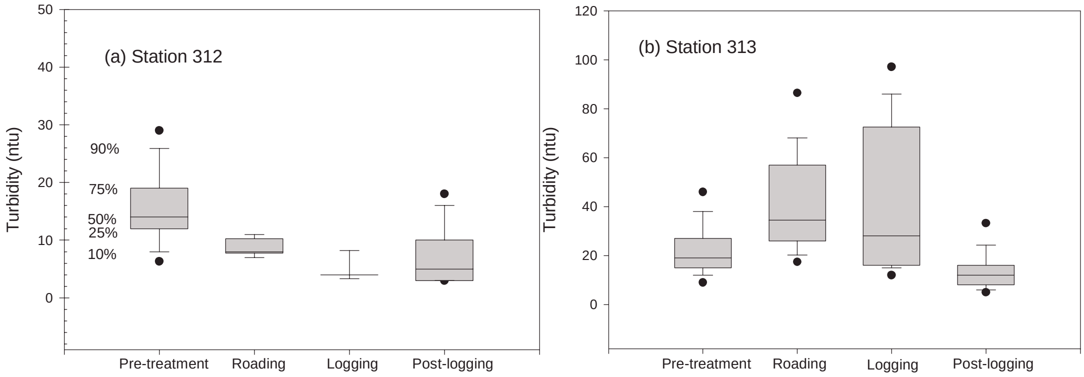


Figure 24. Box plot of turbidity comparing treatment periods for each station. Note the change in scale between plots.

Box plots comparing raw turbidity data for both stations are presented in Figure 24. They indicate that elevated turbidity levels occurred during events in the roading and logging phases in the treatment catchment, compared to the control and the pretreatment data.

7.4 Results - Total Suspended Solids and Total Dissolved Solids

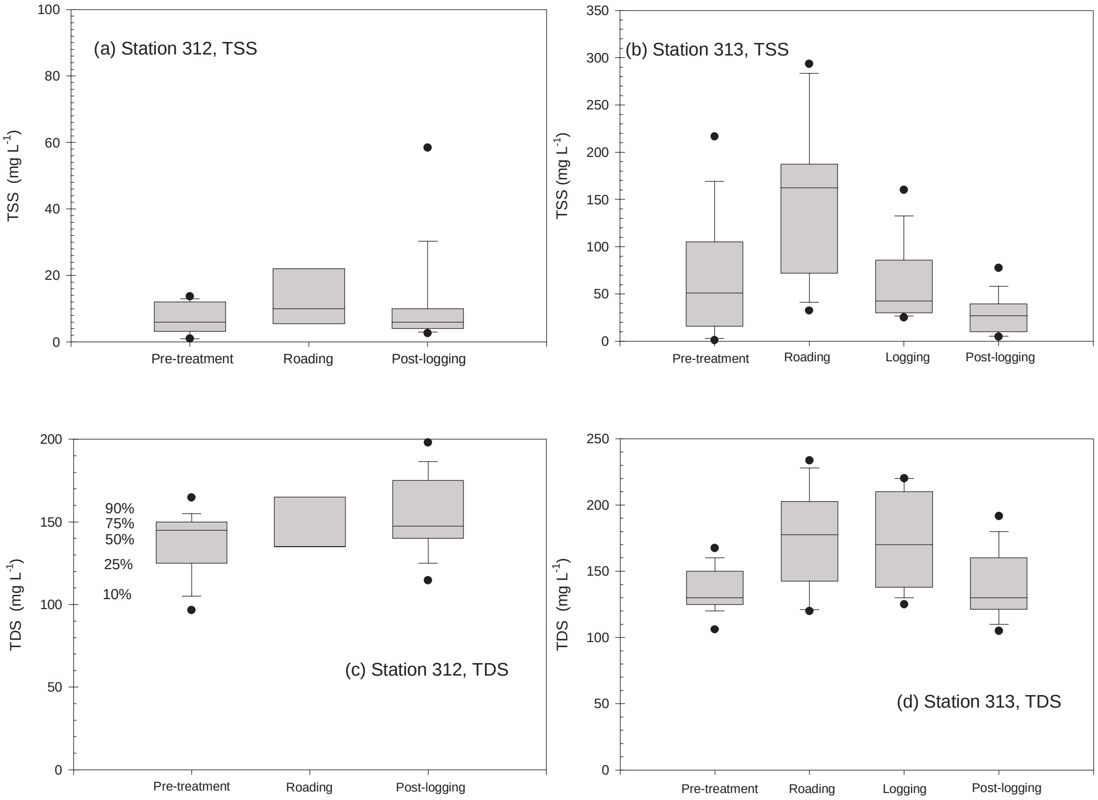


Figure 25. Box plots of TSS and TDS derived from raw data for each station. Note the significant change in scale for TSS plots (a) and (b).

Box plots comparing raw total suspended solids and total dissolved solids between treatment periods for each station are presented in figure 25 (Note differences in vertical scales). The spread of TSS data for station 312 is similar for both the pre-treatment and post-logging phases while the roading phase is slightly elevated. TSS data for the treatment catchment however shows that both pre-treatment and harvesting treatment concentrations are significantly higher than those of the control. Comparing treatment phases in the treatment catchment, the roading phase has median, 75th and 90th percentile concentration values a factor of 3 greater than any other phase. The TSS concentrations during the logging phase are similar to the pre-treatment phase concentrations and the post-logging monitoring phase has the lowest median, 70th and 90th percentile concentrations.

The TDS data for station 312 (Figure 25c) show similar median concentration values for the pre-treatment, roading and post-logging phases but the post-logging phase also exhibits higher concentrations at the 75th and 90th percentiles. TDS data for the treatment site (Figure 25d) shows similar pre-treatment concentrations to the control.

Pre-treatment TDS concentrations in the treatment catchment are similar to the post-logging concentrations, however both the roading and logging phases exhibit elevated median, 75th and 90th percentile concentration values.

7.5 Discussion - Turbidity, Total Suspended Solids and Dissolved Solids

The cumulative probability plots of turbidity data (Figure 22) indicate that NTU increased significantly during forestry operations in the treatment catchment. They returned to pre-disturbance levels during the post-logging monitoring phase.

ANOVA results comparing treatment phases and stations show that mean event NTU for the treatment catchment is systematically higher than NTU for the control during both pre-treatment and post-logging monitoring phases. The treatment catchment mean event NTU shows a decrease between the pre-treatment and post-logging phases. However there is a significantly higher mean event turbidity in the treatment catchment during the operational phases of roading and logging. Figure 23 shows mean event turbidity for the treatment catchment diverging from mean event turbidity for the control catchment. This is further illustrated in Figure 24 which shows that turbidity increases by about a factor of 2 during logging and roading phases but then returns to pre-disturbance levels once logging has ceased.

Box plots of TSS data (figure 25) also shows that concentrations measured at the treatment site (25 to 110 mg/L in the 25th to 75th percentile range for pre-treatment phase) are higher than concentrations of TSS in the control site (3 to 13 mg/L in the 25th to 75th percentile range for pre-treatment phase). This shows that the treatment catchment has systematically higher TSS concentrations than the control prior to the trial commencing, similar to turbidity. During the trial, the control station showed an increase in 75th percentile concentration during roading and slightly increased median value compared with pre-treatment TSS concentration levels (Figure 25). Post-logging levels of TSS within the control catchment have returned to pre-treatment levels. For the treatment site, the roading phase, however, had much higher percentile values compared with all other treatment phases. The median value was ~160 mg/L a factor of 3 higher than the pre-treatment median of ~50mg/L. This implies that sediments derived from the roading operation contribute more solids than did erosion from logging on the slopes themselves. The post-logging TSS concentrations were lower than the pre-treatment levels, suggesting that any influence of harvesting on stream turbidity and TSS was restricted to the harvesting period.

Box plots of TDS (Figure 25) show that concentrations measured during the pre-treatment period are similar for both stations, unlike TSS data. Median values for the pre-treatment and post-logging monitoring phases for both stations are similar. However much higher median and 75th percentile values were observed during roading and logging phases in the treatment catchment. Where TSS showed only roading affected concentration levels, both roading and logging operations result in increased TDS concentrations during discharge events.

7.6 Results - Total Kjeldahl Nitrogen and Total Phosphorus

Total Kjeldahl Nitrogen and Total Phosphorus data for the control (312) and treatment (313) stations comparing treatment phases are presented as box plots (Figure 26). TKN data for control catchment is only available for the pre-treatment and post-logging periods and exhibit same range of concentration values. TKN data for the treatment catchment includes the logging period. Median, 75th and 90th percentile TKN concentration values are higher for discharge events during the logging phase but appear to have returned to pre-treatment levels during the post-logging monitoring phase. TKN concentrations for the treatment catchment appear to be twice as high than the control catchment for both pre-treatment and post-logging phases (Figure 26).

TP data for the control is only available for the pre-treatment and post-logging phases. TP concentrations measured during the post-logging phase show lower median, 75th and 90th percentiles. TP data for the treatment catchment include data for the logging period which, as for TKN logging period, show higher median and 90th percentile concentration values. TP data for the post-logging period in the treatment catchment shows similar trend to the control in having lower median, 75th and 90th percentiles than during the pre-treatment monitoring phase.

7.7 Discussion - Total Kjeldahl Nitrogen and Total Phosphorus

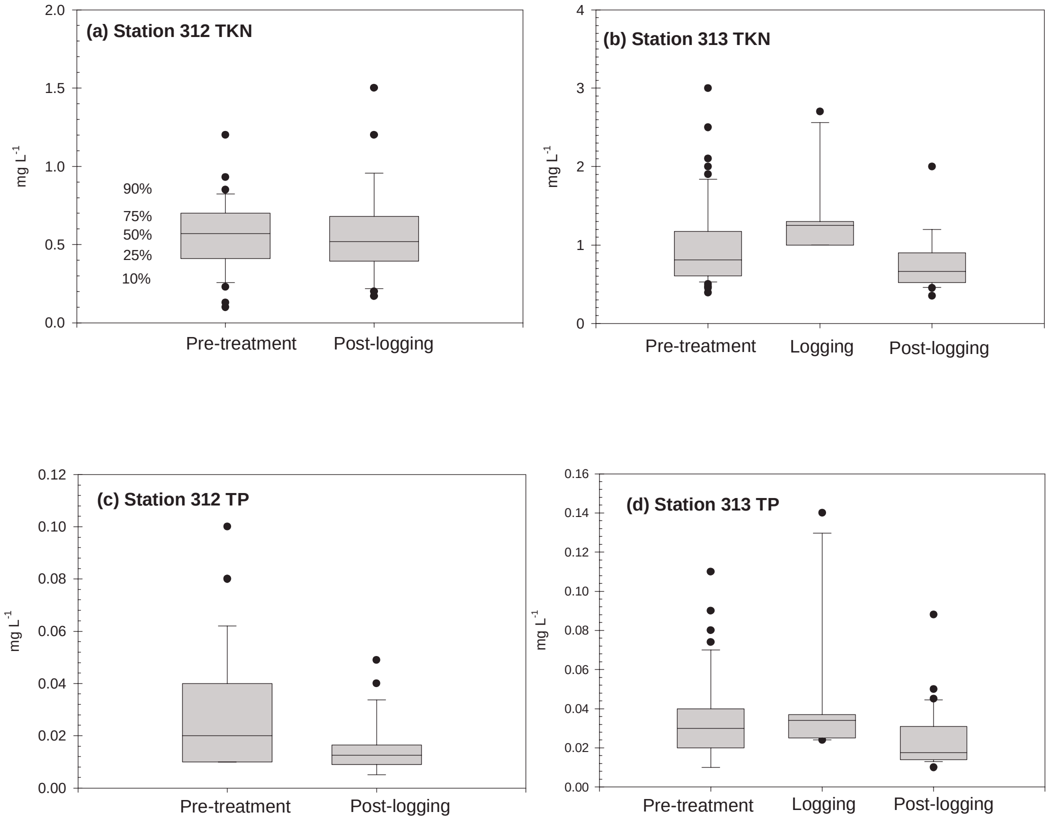


Figure 26. Box plots for TKN and TP at each station. Note the change in scale for TKN between stations.

Box plots of TKN and TP data for station 312 show similar or reduced median and 75th percentile values during the post-logging period compared with the pre-treatment values. The same trend is evident for station 313. Logging phase data available for station 313 shows higher median values of TKN and TP indicating an increase in concentration levels during logging operations which then return to pre-disturbance levels when the logging ceases.

8.0 CONCLUSIONS

There was considerable annual variability of rainfall throughout the study period, the roading and logging phases occurring during the driest year (1994). The double mass analysis of discharge showed no detectable influence of catchment treatment on discharge.

The turbidity data show that although the treatment catchment had systematically higher turbidity values then the control catchment, that roading and harvesting in the treatment catchment further increased mean NTU values during discharge events by about a factor of 2. However mean event turbidity returned to pre-treatment levels once logging had ceased. TSS data for the treatment catchment was also systematically higher than that of the control catchment during pre-treatment monitoring. The TSS data showed a factor of 3 increase in concentration for discharge events during the roading phase but not the logging phase in the treatment catchment.

TDS concentrations were higher than TSS concentrations in Deacons Creek except during the roading phase when similar concentration range were measured. The TDS data showed increases in concentration during both the roading and logging phases in the treatment catchment, although they returned to pre-treatment levels once harvesting had ceased. TKN and TP data also indicated slightly increased concentrations during logging (no roading data). These then returned to pre-treatment concentration levels once harvesting had ceased.

Overall the data show no influence of harvesting on discharge, yet the evidence supports up to a factor of three increase in NTU and TSS during harvesting operations. This increase in concentrations declined once logging had finished.

9.0 SYNTHESIS OF FINDINGS FROM GENTLE ANNIE AND DEACONS CREEK TRIALS

There were important similarities and differences in the response of Gentle Annie and Deacons Creek to harvesting operations. Both treatment catchments (311 and 313) were of approximately the same size, 164 and 105 ha respectively, and contained about the same relative area of harvested forest. However Gentle Annie showed a significant increase in water yield, whereas Deacons Creek did not. Conversely, Deacons Creek showed up to a factor of 3 increase in turbidity and solids concentrations during roading, while Gentle Annie had no discernable increase in measured sediment concentration. The reasons for this are not well understood. Clearly soil type and underlying geology had little effect as both were based on granitic soils. The effect of rainfall was shown to be minor. Some difference will arise because the Gentle Annie NTU and TSS data permitted computation on an event weighted basis, whereas at Deacons Creek these variables were calculated as an arithmetic mean, and the latter will be systematically higher. Nonetheless this will not affect any comparison of the box plot data on which our general observations have been made. The small numbers of events with turbidity data for Gentle Annie (2 events during roading; 2 events during logging) compared with Deacons Creek (4 events during roading; 6 events during logging) may not be representative and introduce bias.

The outcome is further intriguing because, in the absence of roading, cable operated systems should theoretically result in a minimal influence on stream turbidity due to less erosion on the slopes. We hypothesize that the cable logging system at Deacons Creek, although reducing total road length, may inadvertently cause disturbance and sediment generation via sawn log hauling pathways for instance if sawn logs were dragged through wet areas, or drainage lines. The furrows left behind from logs dragged upslope presumably become preferred pathways for water flow to drainage lines, the walls and base of the furrows themselves are significant sources of sediment. This combination of sediment supply and connectivity has been shown to be critical in delivery of sediments from slopes to drainage lines (Croke *et al*. 1999b).

Both catchments displayed similar range of concentration of TDS. The dissolved solid fraction is higher in both catchments than the suspended solid fraction. At Deacons Creek the TSS levels were elevated during the roading phase then reduced during the logging phase yet TDS also remained elevated during the logging phase. This data was not available for Gentle Annie. However both catchments appear to have returned to pre-treatment levels of TDS and TSS after logging had ceased, showing no influence of logging on TDS beyond the time period of harvesting operations themselves.

Both catchments showed some evidence of slightly elevated levels of TKN co-incident with roading and harvesting, although these had reduced to pre-treatment levels after a period of about 4 years. The TP data was less clear although both catchments showed no increases in concentrations after harvesting.

10.0 REFERENCES

National Health and Medical Research Council & Agriculture and Resource Management Council of Australia and New Zealand (1996). Australian drinking water guidelines.

Croke, J., Hairsine, P. and Fogarty, P. (2000). Nutrient movement due to overland flow in managed native Eucalyptus forests, southeastern Australia, *Water, Air and Soil Pollution* **122**, 17-35.

Croke, J., Wallbrink, P., Fogarty, P., Hairsine, P., Mockler, S., McCormack, B. & Brophy, J. (1999a). Managing sediment sources and movement in forests: the forest industry and water quality. Cooperative Research Centre for Catchment Hydrology Industry Report 99/11, November 1999.

Croke, J., Hairsine, P. and Fogarty, P. (1999b). Sediment transport, redistribution and storage on logged forest hillslopes in southeastern Australia, *Hydrological Processes*, **13**, 2705-2720.

Grayson, R. B., Argent, R. M., Nathan, R. J., McMahon, T. A. & Mein, R. G. (1996a). Hydrological Recipes, estimation techniques in Australian hydrology. CRC Catchment Hydrology

Grayson, R. B., Finlayson, B. L., Gippel, C. J. & Hart, B. T. (1996b). The potential of field turbidity measurements for the computation of total phosphorus and suspended solidss loads. *J Environmental Management* **47**:257-267.

Grayson, R. B., Haydon, S. R. Jayasuriya, M. D. A. & Finlayson, B. L. (1993). Water quality in mountain ash forests – separating impacts of roads from those of logging operations. *J Hydrology* **150**:459-480.

Langford, K. J., Moran, R. J. & O'Shaughnessy, P. J. (1982). The Coranderrk experiment – the effects of roading and harvesting in a mature mountain ash forest on streamflow yield and quality. The First National Symposium on Forest Hydrology, Melbourne, 11-13 May 1982.

Olive, L. J. and Rieger, W. A. (1988). An examination of the role of sampling strategies in the study of suspended sediment transport. In **Sediment Budgets**. Proceedings of the Porto Alegre Symposium, December 1988. IAHS Publ. No.174.

RossRakesh, S., Gippel, C., Chiew, F. & Breen, P. (1999). Blackburn Lake discharge and water quality monitoring program: data summary and interpretation. CRC Catchment Hydrology Technical Report 99/13

Sinclair Knight Mertz and CSIRO Land and Water (SKM/CSIRO; 1998). ESFM Project: Water quality and quantity for the Upper and Lower North East, Southern RFA regions. Aproject undertaken as part of the NSW Comprehensive Regional Assessments Project Number NA 61/ESFM, for the Resource and Conservation Division, Department of Urban Affairs and Planning.

Swank, W. T., Vose, J. M., Elliot, K. J. (2001). Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. *Forest Ecology and Management* **143**, 163-178.

Thompson, C. J., Wallbrink, P. J. & Crapper, P. (2002). Analysis of water quality and water yield in response to forest harvesting on doleritic soils in the Musselboro Creek catchment, Tasmania. CSIRO Land and Water Technical Report 01/02 January 2002.

Wallbrink, P. J. & Murray, A. S. (1996). Determining soil loss using ratio of excess Lead-210 to Cesium-137. *Soil Sci Soc of Am J*. **60**(4):1201-1208

Walling, D. E. (1977). Assessing the accuracy of suspended sediment rating curves for a small basin. *Water Resource Research* **13**(3):531-538.

Wilson, C., Wallbrink, P. & Murray, A. (1999). Minimum impact logging systems in forest erosion Part A: Impact of logging and fires on runoff and erosion on highly erodible granitic soils in Tasmania. CSIRO Technical Report 19/99 June 1999.

Zar, J. H. (1984). Biostatistical analysis. Second edition. Pub. Prentice and Hall Inc., New Jersey.

11.0 Appendix A

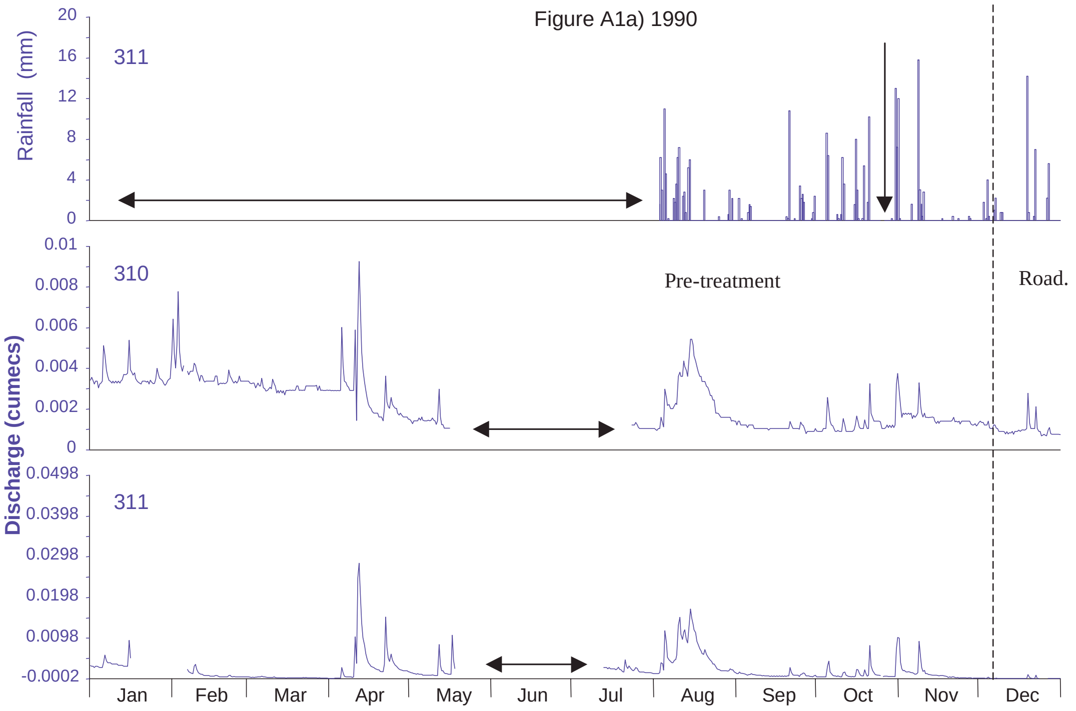


Figure A1a) 1990

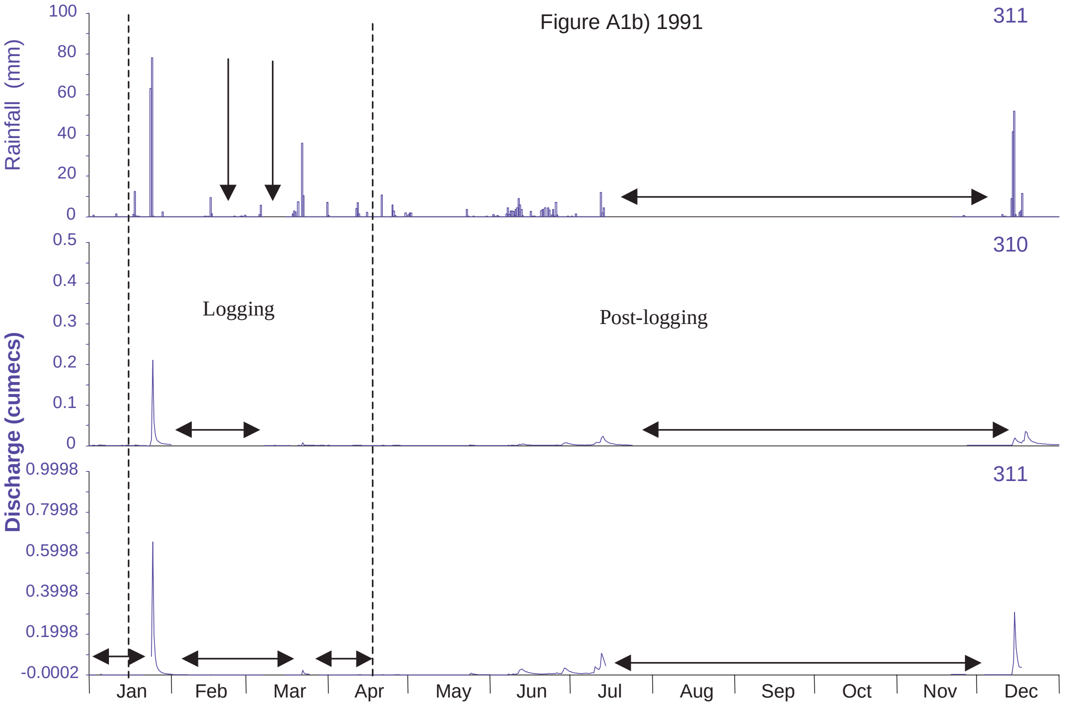


Figure A1b) 1991

Figure A1c) 1992

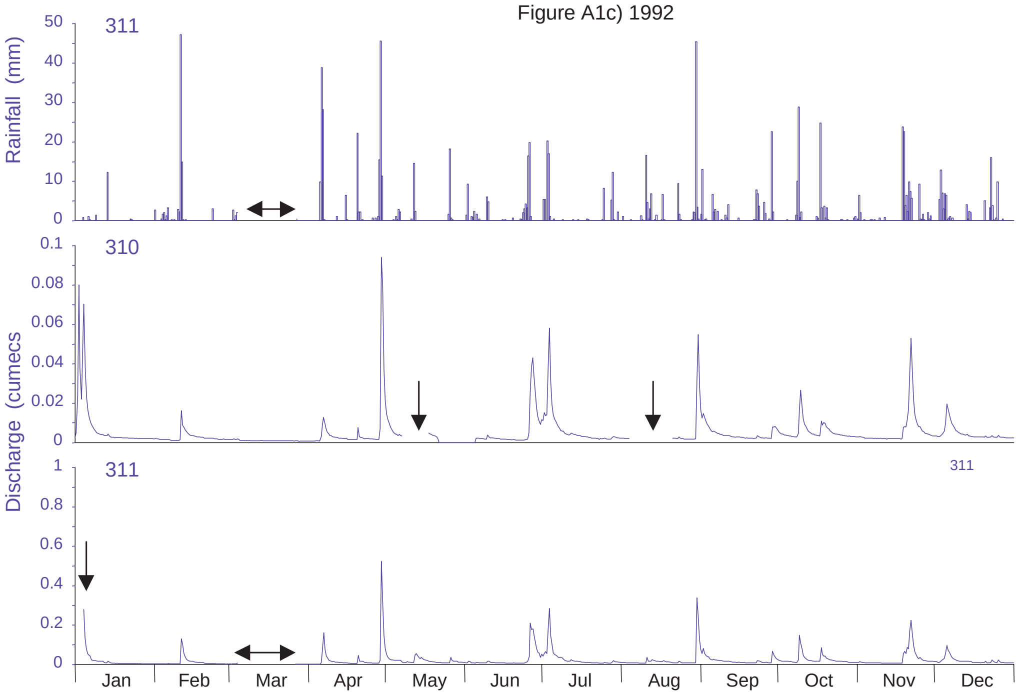
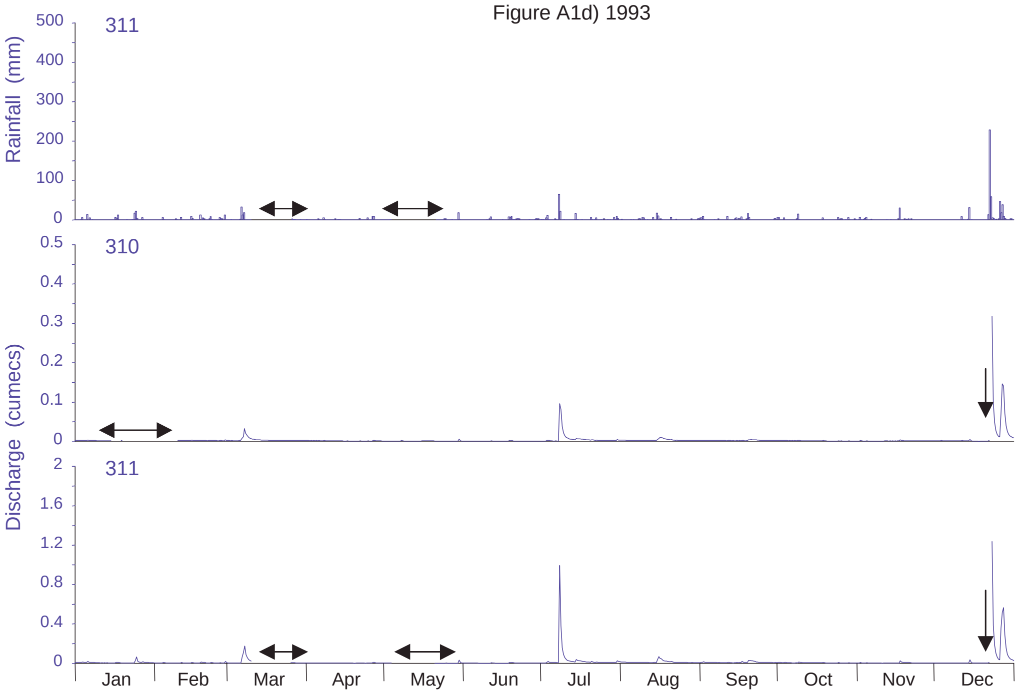
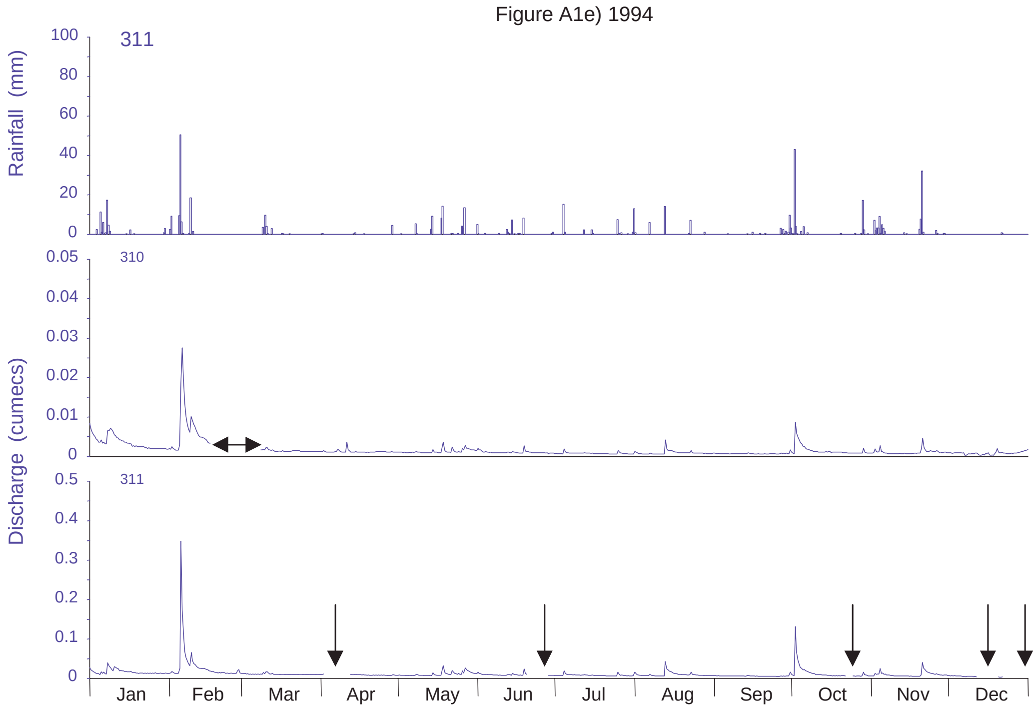


Figure A1d) 1993





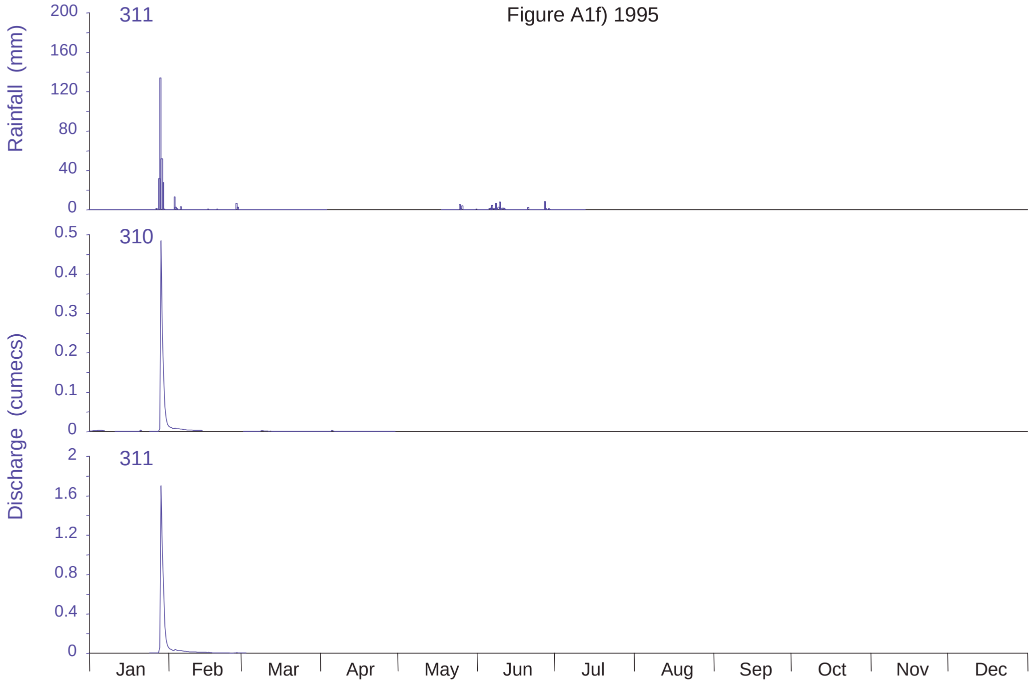
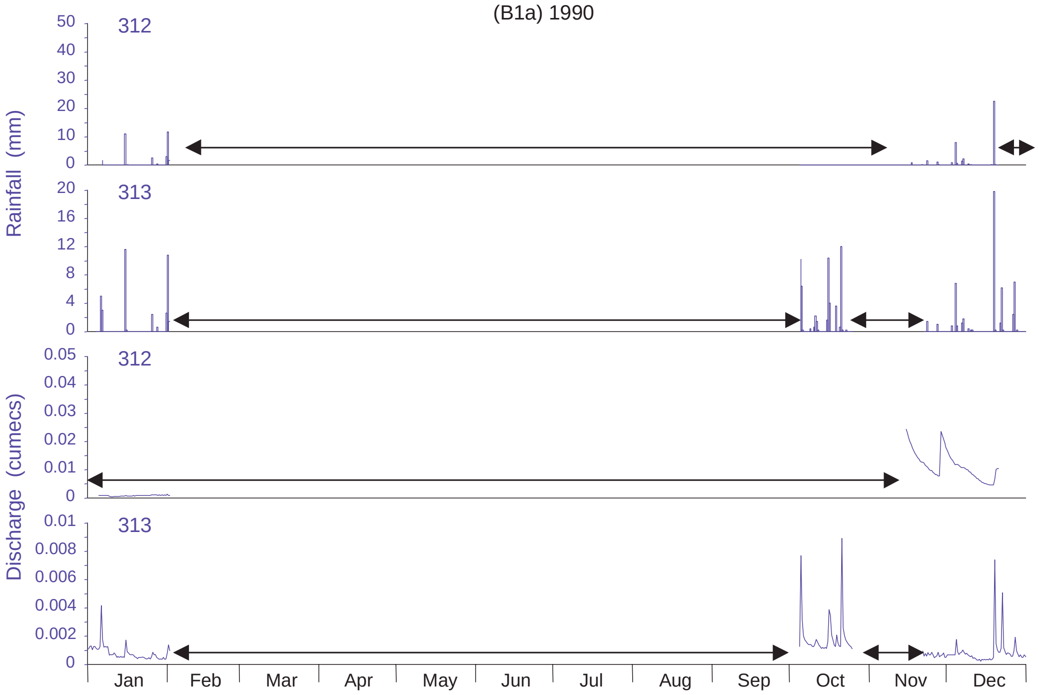
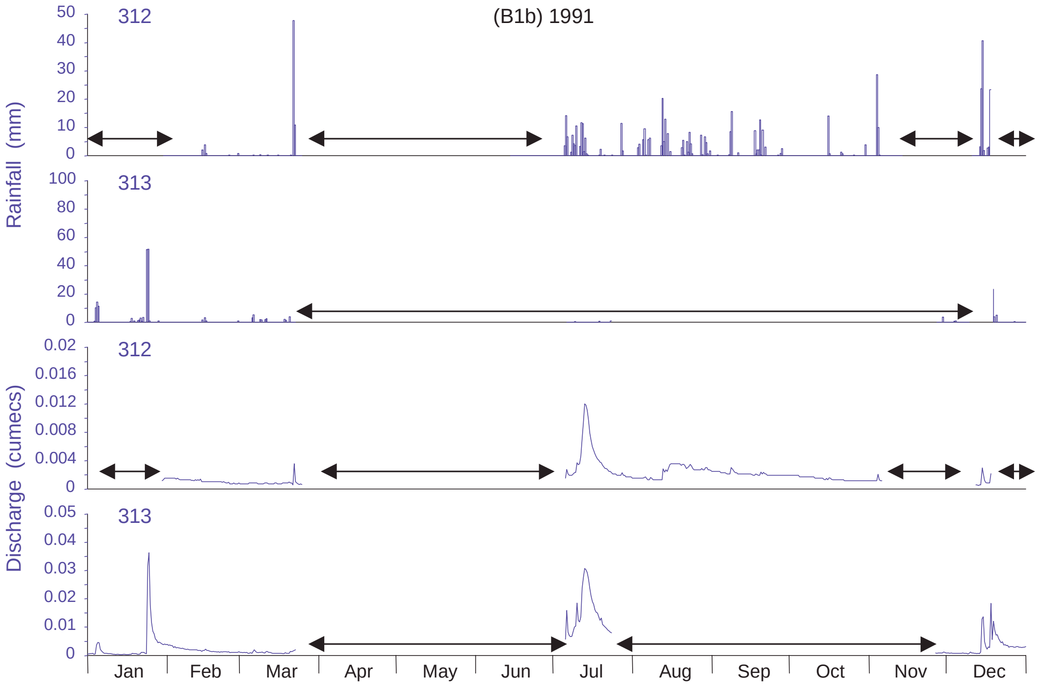
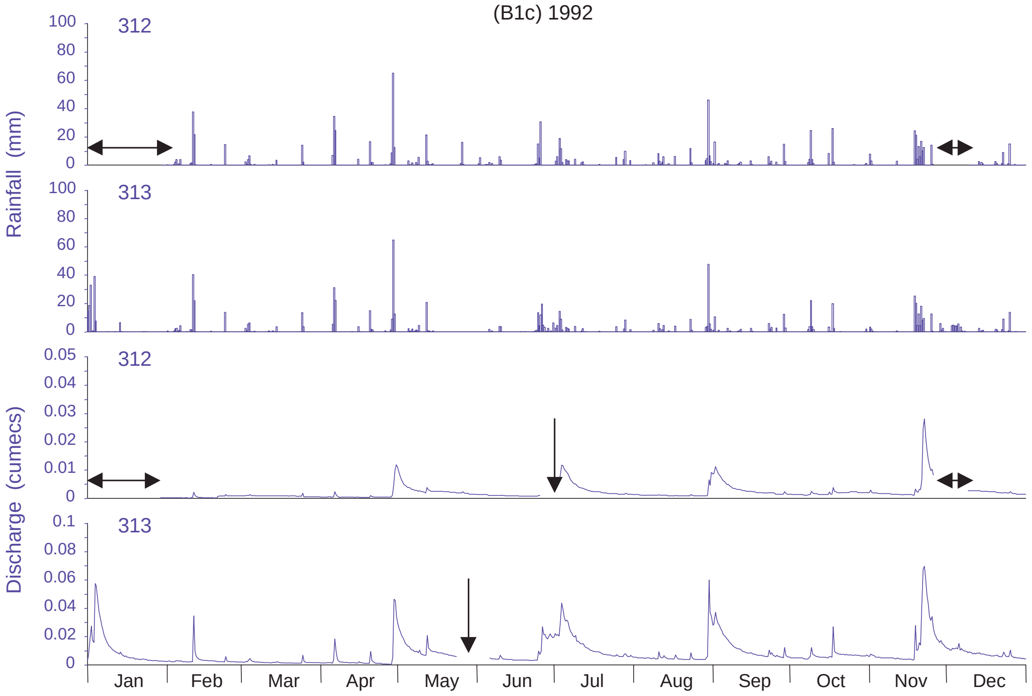


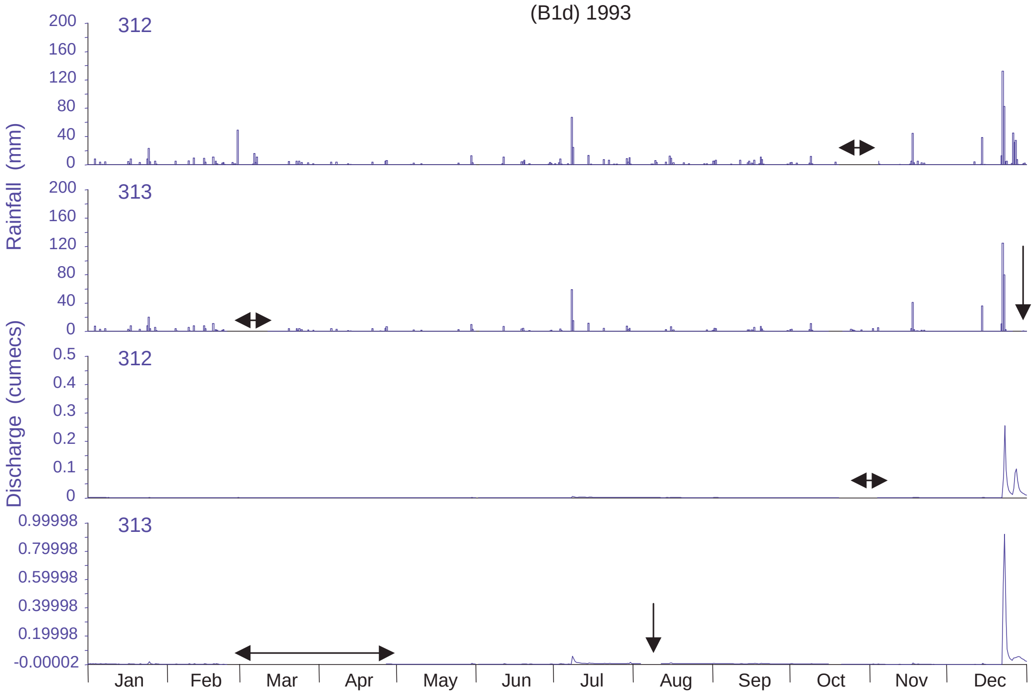
Figure A1. Daily rainfall (mm) at station 331 and discharge from the control and treatment catchments for the duration of the trial.

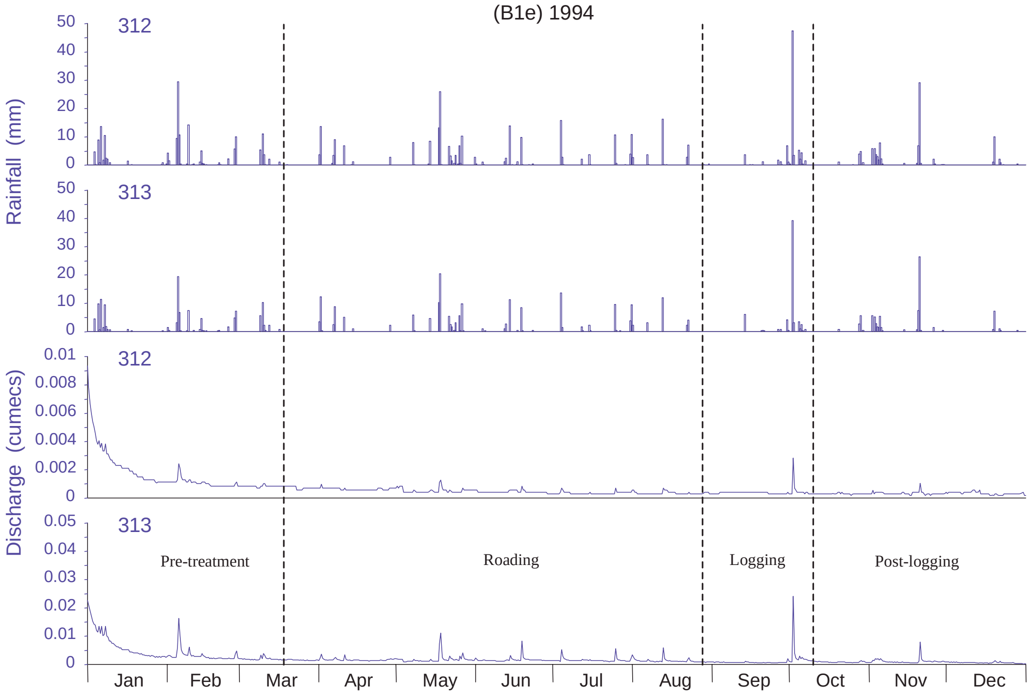
12.0 APPENDIX B.

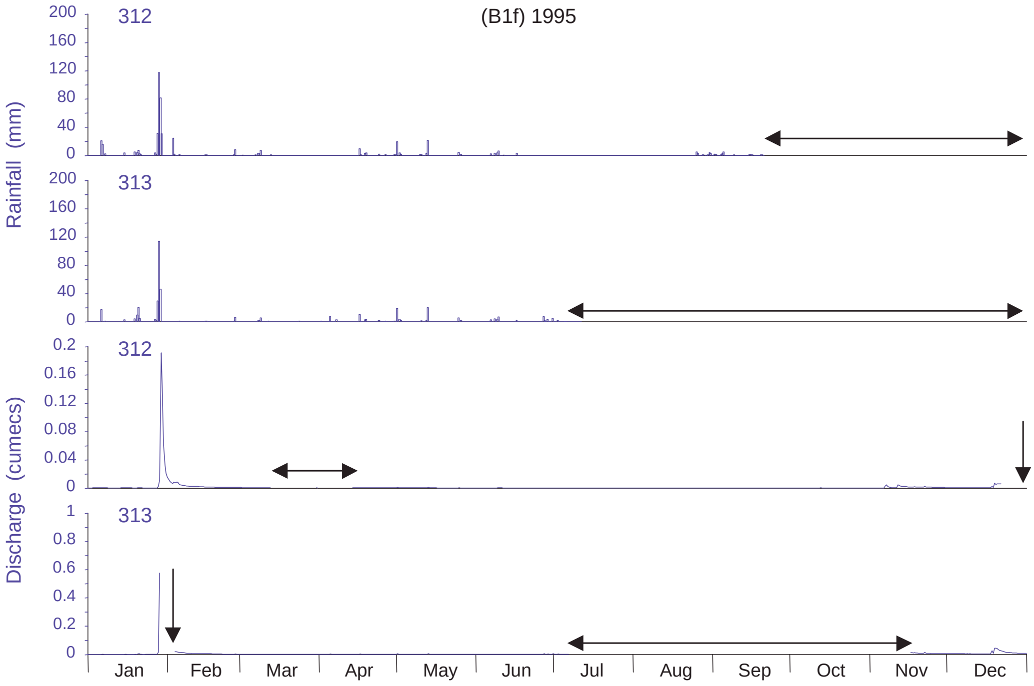

(B1a) 1990
Rainfall (mm)
312
0
10
20
30
40
50
313
0
4
8
12
16
20
Discharge (cumecs)
312
0
0.01
0.02
0.03
0.04
0.05
313
0
0.002
0.004
0.006
0.008
0.01
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


(B1b) 1991
Rainfall (mm)
312
0
10
20
30
40
50
313
0
20
40
60
80
100
Discharge (cumecs)
312
0
0.004
0.008
0.012
0.016
0.02
313
0
0.01
0.02
0.03
0.04
0.05
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


(B1c) 1992


(B1d) 1993


(B1e) 1994
Rainfall (mm)
312
50
40
30
20
10
0
313
50
40
30
20
10
0
Discharge (cumecs)
312
0.01
0.008
0.006
0.004
0.002
0
313
0.05
0.04
0.03
0.02
0.01
0
Pre-treatment
Roading
Logging
Post-logging
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


(B1f) 1995
Rainfall (mm)
312
200
160
120
80
40
0
313
200
160
120
80
40
0
Discharge (cumecs)
312
0.2
0.16
0.12
0.08
0.04
0
313
1
0.8
0.6
0.4
0.2
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

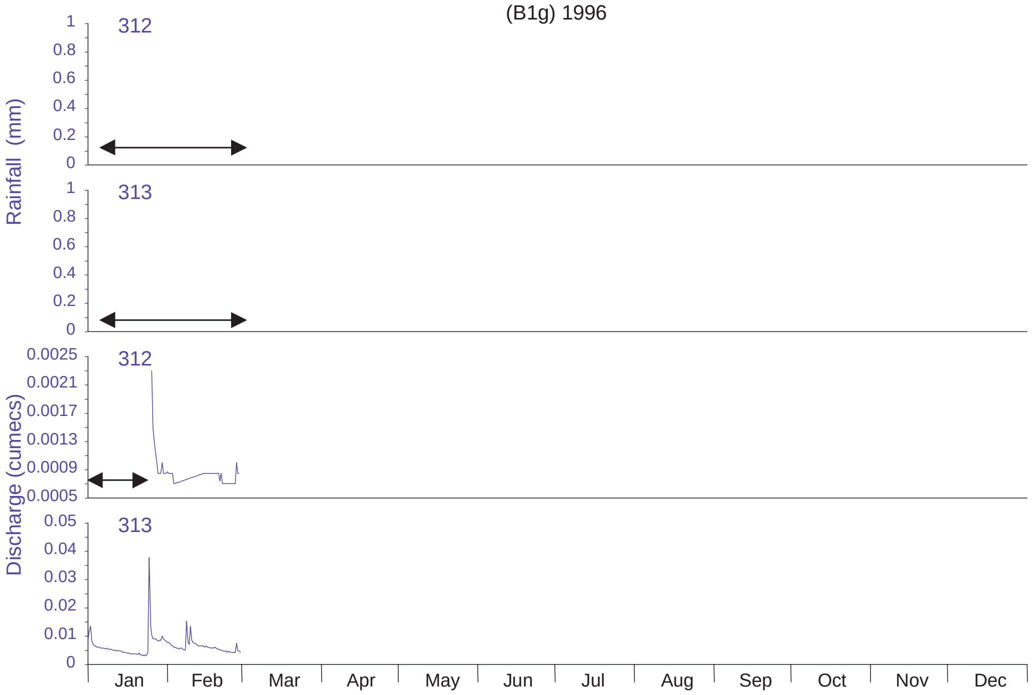


Figure B1. Time-series plots of Daily rainfall and discharge for the control catchment (312) and treatment catchment (313) for the duration of the trial. Arrows indicate periods of missing data in the record. Dashed lines (C1e) indicate the treatment periods.