Technical report 193

Water quality in the Warra Long-Term Ecological Research study area 1998–2006

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Summary

We measured turbidity, electrical conductivity (EC) and pH of water at fifteen sites in the Warra LTER study area on a fortnightly or monthly basis from 1998 to 2006. The catchment area of one stream was free of both harvesting and roading, harvesting area was negligible in six of the catchments, and the remaining catchments were partly harvested. Turbidity, pH and EC values for the streams were usually in the expected range for Tasmania's southern forests. All streams except one showed increased turbidity, decreased electrical conductivity and increased pH with time. Water quality differed between streams. Streams in the south of the Warra LTER site were usually more turbid than streams in the east, while the larger catchments at higher altitudes were least turbid. Continued monitoring of water quality is recommended, but this should be done in conjunction with collection of better rainfall data and better characterisation of the catchments and stream channels.

Introduction

In 1998, Forestry Tasmania started measuring water quality in a number of streams in the Warra Long-Term Ecological Research (LTER) study area (Bren, 1997). The Warra LTER site was established in 1995 as part of an international network of sites for multidisciplinary, long-term, site-based research at a range of scales, to help decision-making to ensure sustainable forest management (Brown et al 2001). Water quality studies are one component of the spectrum of Warra LTER projects.

The purpose of studying water quality in the Warra LTER site was to develop an understanding of the physical water quality of pristine[1] streams, and how this varies through space and time, as a basis for comparison to water quality of streams impacted by forest operations or natural disturbance.

The original water project aims were (Bren, 1997):

1. characterisation of the water yield and aspects of water quality in a pristine catchment with the aim of providing a data set for reference in the indefinite future

2. characterisation of the effects of logging under the Tasmanian Forest Practices Code using a multiple catchment study approach

3. broad-scale characterisation of the water quality over the Warra LTER area using periodic in-situ monitoring

4. development of sustainability indicators that meet Montreal criteria.

A number of studies were initiated to achieve these goals. These included:

a. regular collection of water samples for analysis from fifteen streams from 1998 (Ringrose and Meyer 2001; Meyer *et al.* 2002)

b. continuous monitoring of streamflow, turbidity and electrical conductivity for three streams from 1998 (Ringrose *et al.* 2001)

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[1] Pristine streams are defined as streams occurring in catchments where there has been no human disturbance such as road construction or forest harvesting and no recently recorded fire.

c. short-term targeted studies of biological and physical water quality parameters for a subset of these streams and elsewhere in the Warra LTER site (Davies and Cook 2002; Meyer *et al.* 2002; Ringrose and Meyer 2001; Clapcott 2007).

This report describes the results of study (a), which was established to address aim (3). This study involved the collection and analyses of water quality grab samples from fifteen locations in the Warra LTER site over a period of eight years from 1998 to 2006.

Site description and experimental methodology

The Warra LTER site

The Warra LTER site is located in the southern forests of Tasmania (Map 1). The LTER site covers an area of 15 900 ha at an altitude range of 37–1260 m, and includes tributaries of the Weld and Huon rivers (Brown *et al.* 2001).

Average annual rainfall at Warra Rd is estimated at 1922 mm (ranging from 1311 to 2706 mm/yr) since 1960 (see Appendix A). Rainfall is winter/spring-dominated, with maximum monthly rainfall occurring in August (201 mm on average).

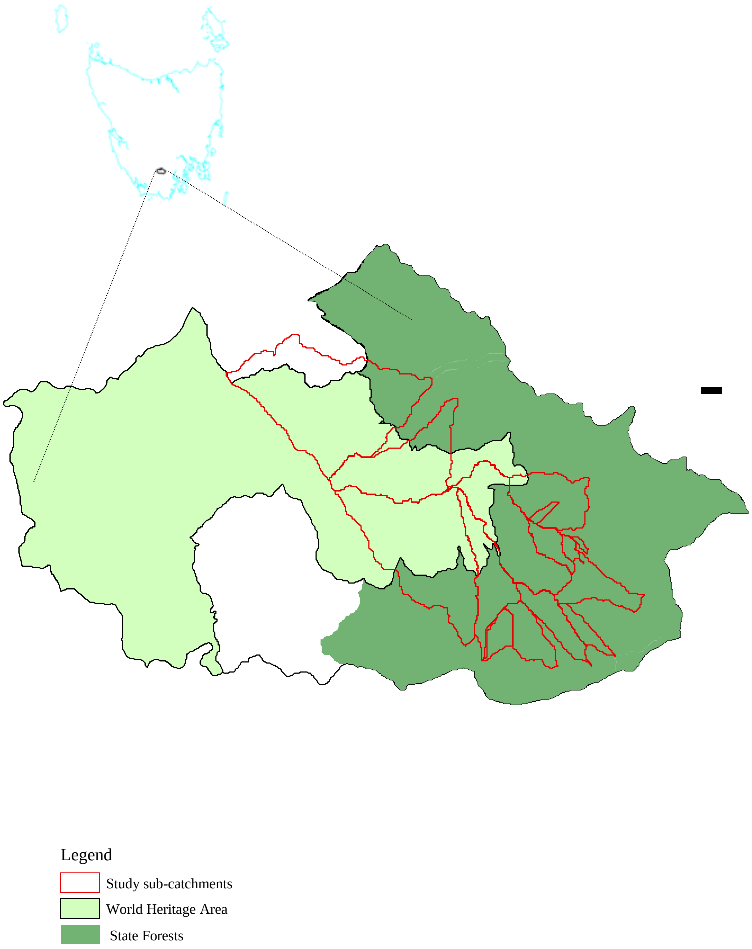
The Warra LTER site is geologically diverse, but is dominated by dolerite, with associated quaternary deposits and a variety of sedimentary rocks (Laffan 2001). Soil patterns are diverse and show strong links to geology and vegetation: organic soils are associated with heath and scrub; gradational soils are found under moist forest; and texture contrast soils occur on sandstone (Laffan 2001).

Corbett and Balmer (2001) describe the vegetation of the Warra LTER site. Common communities include wet and mixed *Eucalyptus obliqua* forests, temperate rainforest, buttongrass moorland, alpine moors and scrub.

Hickey *et al.* (1999) reconstructed fire history for the Warra LTER site tall wet eucalyptus forests by analysing ring counts, stand age and structure. They determined that major fires occurred in the Warra LTER site in 1898, 1906, 1914, 1934 and 1944. The fires influenced the age of forest and its structure, generating both mixed-aged and even-aged forests. Alcorn *et al.* (2001) found forest cohorts that were likely to have originated following fire in 1670, 1740, 1790 and 1873 and observed that the wet *E. obliqua* forest was usually multi-aged indicating that complete-stand-replacing fires are uncommon. Natural and silvicultural fires also burnt approximately 1000 ha of the Warra LTER site between 1972 and 1993.

Part of the Warra LTER site is state forest managed for multiple use including timber harvesting. The remainder is conserved within the World Heritage Area. Until recently most harvested coupes in the Warra LTER site were clearfelled, burnt and sown, although there have also been instances of salvage logging following wildfire.

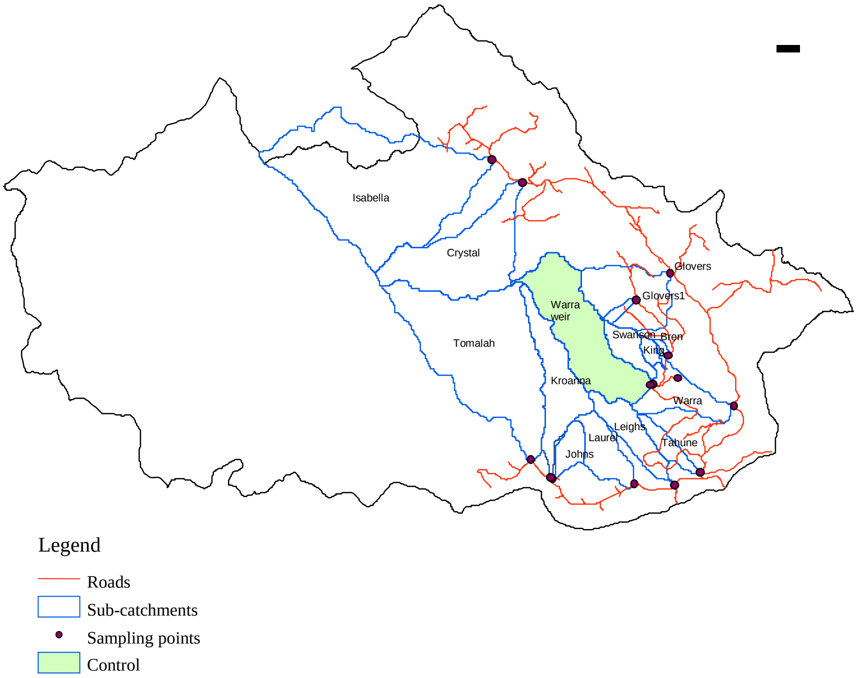
Harvesting alternatives such as aggregate retention, strip harvesting and selective harvesting were recently trialled in the Warra LTER site (Hickey and Neyland, 1999; Hickey and Neyland 2000; Hickey *et al.* 2001; Neyland *et al.* 2002; Neyland 2001; Neyland 2004).



Map 1. The Warra LTER site showing study catchments, world heritage area and state forest

Water sampling sites

The fifteen streams sampled in the Warra LTER site (Map 2) were selected to cover a range of stream classes (classes 1–4 as defined by the Forest Practices Code, Forest Practices Board 2000), geological types, vegetation types, elevations, levels of potential impact from forestry and roading, and colouration of stream water (Ringrose *et al.* 2001).



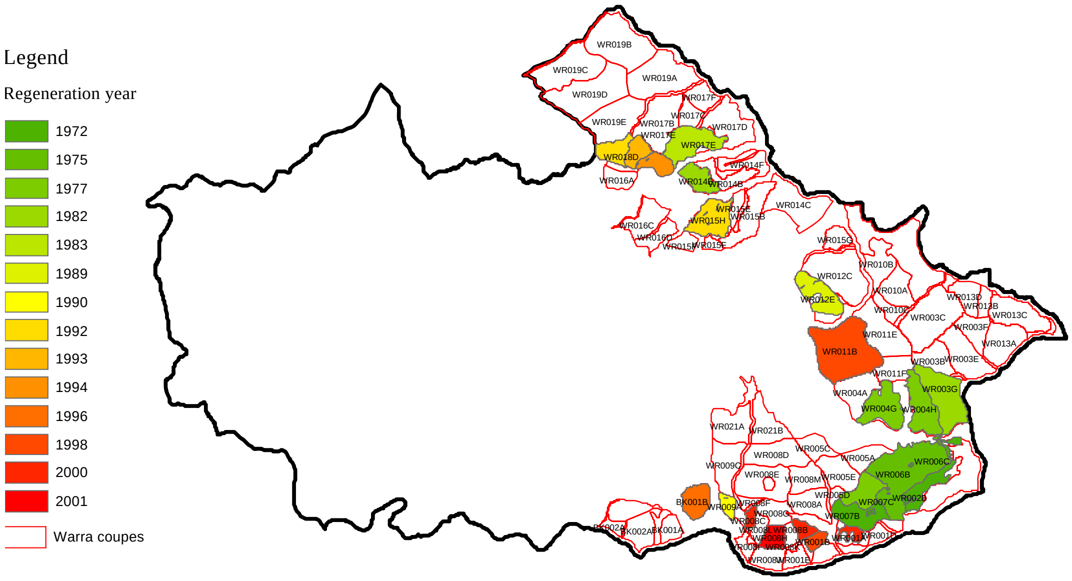
Map 2. The Warra LTER site showing catchment boundaries, roads and water quality sampling locations

Grid coordinates (GDA) of the water sample sites were captured by hand-held GPS (Original X, Y Table 1). The original grid coordinates were inconsistent with the position of streams and roads on maps, so, modelled grid coordinates (Modelled X, Y Table 1) were used to define catchment outlets and to calculate catchment areas for each of the water sample sites from digital elevation models. Calculated areas of vegetation, geology, soil, harvesting, road lengths and numbers of stream crossings were based on the modelled catchments.

The catchments range in size from 7 to 1164 hectares, are between 85 and 420 metres above sea level, with drainage direction varying from south-east to east and to north-east. Some catchment attributes are described in Table 1.

Table 1. Summary of the characteristics of each of the catchments sampled

Catchment name	Original X	Original Y	Modelled X	Modelled Y	Modelled catchment area (ha)	Forest Practices Code stream class	Min elevation	Max elevation	Road length (m)	Stream cross-ings	Drainage direction	% slopes greater than 30 degrees
Bren	476289	5231574	476453	5231870	7	4	420	482			SE	16.5
Crystal	472747	5235974	472850	5236145	495	1	289	1150	21.3		NE	32.1
Glovers 1	475605	5233027	475662	5233240	285	2	198	684	4086.9	10	NE	20.7
Glovers 2	476408	5233755	476501	5233918	16	4	389	577	160.6	2	NE	5.9
Isabella	472010	5236570	472106	5236722	1164	1	333	1226	89.0		E	26.9
Johns	473505	5228525	473601	5228822	70	3	163	570	120.0	1	S	48.6
King Weir	476250	5231240	476384	5231560	25	4	393	500			SE	0.0
Kroanna	473383	5228709	473553	5228851	270	1	165	780			S	15.5
Laurel	475521	5228530	475620	5228697	138	2	85	580	5.6		SE	42.1
Leighs	476335	5228386	476622	5228674	148	2	110	590	1209.2	2	SE	22.5
Swanson Weir	475972	5230940	476080	5231163	83	3	343	580			SE	5.5
Tahune	477124	5228772	477239	5228981	63	3	100	520	819.5	2	SE	17.0
Tomalah	472936	5229157	473069	5229295	907	1	182	1120	25.9	1	S	28.0
Warra 1	478011	5230511	478080	5230634	753	1	86	820	3188.3	6	SE	13.8
Warra Weir	475967	5230944	476022	5231147	462	2	345	820			SE	14.8



Map 3. Coupes and year of harvesting in Warra LTER site – white coupes have mature forest

Based on the current mapping of catchment and coupe boundaries, all catchments other than Warra Weir have experienced some harvesting since 1972 (Map 3, Table 2). Crystal, Isabella, Johns, Kroanna, Laurel, and Tomalah catchments have had less than 5% of their area harvested.

Table 2. Couped areas occurring within each catchment and year/s of regeneration following harvesting or fire

Catchment	Total % of catchment area harvested	Coupe ID	Area of harvested coupe in catchment (ha)	Regeneration year/s	Location of harvested coupes
Bren	42.9	WR011B	3.31	1998	upper catchment
		WR004A			
Crystal	2.8	WR016D			lower south catchment
		WR015H	14.42	1992	
		WR015F			
Glovers 1	44.9	WR012E	36.83	1989	mid- to upper catchment
		WR012C			
		WR011E			
		WR011B	91.34	1998	
		WR012B		current	
Glovers 2	37.5	WR011B	5.5	1998	lower catchment
Isabella	1.3	WR016A			lower northern part at boundary
		WR018D	7.98+3.37+3.75	1992,1993,1994	
		WR016C			
Johns	4.3	WR008C			lower south
		WR008F			
		WR008E			
		WR008D			
		WR008G	3.34	2000	
King	40	WR011B	9.94	1998	upper north
		WR004A			
Kroanna	0	WR008F			at western boundary
		WR008E			
		WR008D			
		WR021B			
		WR021A			
		WR009C			
		WR009A	0.01	1990	
Laurel	0	WR008B	0.03	2000	at southern boundary
		WR008A			
		WR008E			
		WR008G			
		WR008D			
Leighs	21.6	WR007C	15.77+16.10	1972,1977	lower catchment
		WR007B		1972,1977	
		WR005D			
		WR005E			
		WR008A			
		WR005C			
		WR008D			
		WR021B			
Swanson	22.9	WR011B	18.63	1998	north-east upper catchment
		WR004A			
Tahune	60.3	WR007C	2+12.62+22.74	1972, 1975, 1977	lower catchment
		WR005A			
		WR005E			
		WR005C			
Tomalah	0.2	BK001B	0.54	1996	south-west and south-east boundaries
		WR009A	0.92	1990	
		WR009C			
		WR021A			
Warra 1	11.2	WR011B	28.56	1998	mid and lower catchment
		WR004A			
		WR004G	32.72	1977	
		WR004H		1977	
		WR006C	22.16 + 0.04	1975, 1972	
		WR006B		1975	
		WR005C			
Warra Weir	0	WR005C			
		WR021B			

Historically, coupes in the Warra LTER site were clearfelled and then burnt. Aerial seeding facilitated regeneration when natural seed supply was insufficient. In some instances salvage logging occurred after wildfire (e.g. WR005A).

The Warra Silvicultural Systems Trial has introduced different silvicultural systems to the Warra LTER site in recent years (Neyland *et al.* 2002; Hickey *et al.*, 1999). For example, WR012E was harvested using dispersed retention, WR008B was clearfelled, burnt and sown with retention of understorey islands, WR005D had single-tree selection, and WR008G was harvested using small-group selection (80 m clearfell). Although areas of WR008G fall within several of the catchments, only unharvested portions of the coupe occur in the research catchments.

Crystal, Glovers 1 and 2, Isabella, Johns, Laurel, Leighs, Tahune, Tomalah and Warra 1 catchments contain mapped gravel roads. Road length ranges from 5 m to 4 km (Table 1). Roads cross streams in Glovers 1 and 2, Johns, Leighs, Tahune, Tomalah and Warra 1 (Table 1). Dam construction is reported to have occurred in Johns and Leighs creeks (Meyer *et al.* 2002).

Collection of water samples, field and laboratory measurements and analysis methods

Water samples were collected from the fifteen streams on a fortnightly basis from August 1998 until 2002, when sampling frequency was reduced to monthly. Water temperature was usually recorded, and stage height was usually determined from a stage board when water samples were collected.

Water samples were collected in clean polyethylene bottles for analysis of conductivity, pH and turbidity in the Forestry Tasmania (FT) laboratory. The bottles were rinsed in the stream before being filled. Samples were refrigerated and usually analysed within two days. Turbidity (NTU) of samples was measured with an Analite portable nephelometer (Model 156, McVan Instruments, Mulgrave) during the first years of the study. Later on, a portable turbidimeter (model DRT—15CE, HF Scientific Florida) was used. Conductivity was measured with a temperature-compensated EC meter (WTW, West Germany). The pH was measured with a WTW pH meter (model 325, Germany). Equipment was calibrated before samples were measured using the protocols outlined by the equipment manufacturers. The features of the instruments are described in Table 3.

Table 3. Water quality meter accuracy

Instrument	Measurement range	Resolution	Repeatability
156 nephelometer	1–199 NTU	0.1	± 2% of reading ± 1 digit
DRT–15CE turbidity meter	0–10 NTU	0.01	± 1% of reading
DRT–15CE turbidity meter	0–100 NTU	0.1	± 2% of reading
LF196 conductivity meter	0–1000 μS/cm	0.1	<0.5% of reading ± 1 digit
WTW pH 325	–2.00 – 16.00	0.01	0.01 ± 1 digit

Sources of error in water quality parameter measurement

Other than the errors inherent in the laboratory instruments, thermometers and stage boards, there are a number of other potential sources of error:

Laboratory and data management errors

a. The period of storage of water samples sometimes exceeded two days. In August 2007 we analysed pH, EC and NTU for water samples on each weekday for six water samples taken from Warra. One-third of each sample was kept in the coolroom, at room temperature or in the constant temperature room (20 ^{o}C) to see if measured values varied through time or were influenced by the temperature of storage. It was also a useful way to ensure that the analytical technique was consistent for all staff. The results are reported in Appendix 2. Date of analysis and method of storage did have a small but significant impact on analytical result, indicating that coolroom storage and rapid analysis (within two days) is best.

b. Repeatability of measurements was worse than reported by the manufacturers particularly with the DRT–15CE turbidimeter (Appendix 2).

c. The instruments were not listed on data sheets until recently—so we are uncertain of the instruments and, hence, the resolution and repeatability of early measurements.

d. Calibration of instruments was not reported until recently—so for older data we cannot verify that instruments were correctly calibrated at the time of use. Discussions with long-term staff indicate that calibrating instruments before use was standard practice.

e. Errors in data entry were observed in the electronic databases. Incorrect entries were identified using graphs and corrected by re-entering data from the original laboratory notes.

f. Multiple operators performed the water quality analyses so there is potential for differences in the way measurements were made. For example, during the August 2007 experiment (Appendix 2) it became apparent that there were differences in the ways in which staff were analysing water samples—e.g. length of period before reading was taken after insertion of sample in test well of DRT 15CE may influence settling of particles or presence of air bubbles.

g. Infrequent independent testing of samples (e.g. by AST) for comparison with Forestry Tasmania laboratory results.

Sample collection errors

a. Some stage boards are not set in the deepest part of streams. A stage height of zero does not necessarily indicate that there was no flow. Rocks in streambeds limit placement of stage boards.

b. Water temperature was not always measured at the time of sample collection.

c. Some samples were not collected. This was usually because of road closures.

d. The following errors are possible, although they were not reported as occurring: mislabelling of sample bottles, contamination of bottles during sample collection, disturbance of substrate during sample collection, bias in the timing of sample collection (towards peak or baseflow periods), bottles overfilled so that they could not be shaken before subsamples were decanted for analysis.

Results

Descriptive statistics

Descriptive statistics for turbidity, electrical conductivity and pH data collected at each of the fifteen sampling sites from 1998 to 2006 are reported in Table 4. Median turbidity values ranged from 1 NTU at Tomalah Creek to 5.7 NTU at Bren Creek. The largest turbidity value recorded during grab sampling was 113.4 NTU in Leighs Creek. Median EC values ranged from 38.5 uS/cm at Isabella Creek to 98.3 uS/cm at Leighs Creek. The highest EC value recorded during sampling was 194.2 uS/cm at Leighs Creek. Median pH values ranged from 5.45 at Warra Weir to 6.59 at Leighs Creek.

The distribution of values for each water quality parameter at each of the sites is skewed[2] which influences the statistical methods used to analyse the data. Turbidity data have a positively skewed distribution, EC data have small but variable skew, while pH tends to have a weak negatively skewed distribution. Skewness is illustrated in the Frequency histograms (Figures 1–3).

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[2] Skewness characterises the degree of asymmetry of a distribution around its mean. Positive skewness indicates a distribution with an asymmetric tail extending toward more positive values. Negative skewness indicates a distribution with an asymmetric tail extending toward more negative values.

Table 4. Descriptive statistics for turbidity (NTU), EC (uS/cm) and pH at fifteen sites in the Warra LTER site between August 1998 and November 2006

		Bren	Crystal	Glovers1	Glovers 2	Isabella	Johns	King	Kroanna
Turbidity	no. samples	139	139	137	136	139	141	141	142
	median	5.7	1.0	2.2	3.4	0.8	4.2	3.0	1.7
	mean	8.2	2.1	3.6	4.8	1.8	6.4	4.2	2.7
	minimum	0.5	0.0	0.0	0.3	0.0	0.0	0.0	0.0
	maximum	44.2	44.5	29.1	68.0	38.1	72.5	40.5	24.7
	1st quartile	4.4	0.4	1.4	2.4	0.2	2.2	2.3	1.0
	3rd quartile	9.5	2.1	3.8	4.8	1.9	7.2	4.6	2.8
	skewness	2.5	6.7	3.4	6.7	6.7	5.0	5.2	3.8
	kurtosis	7.5	48.5	12.9	55.6	49.3	35.2	33.7	16.3
Electrical conductivity	no. samples	140	140	138	137	140	142	142	143
	median	67.6	44.0	50.9	51.3	38.6	83.5	52.2	47.3
	mean	67.5	46.5	52.6	52.6	42.0	84.1	53.5	48.1
	minimum	40.3	28.7	29.7	32.4	23.9	56.5	34.5	35.3
	maximum	88.6	96.1	71.5	74.8	96.1	111.4	79.9	65.3
	1st quartile	60.0	38.2	47.6	45.5	33.3	76.2	48.0	44.1
	3rd quartile	74.6	53.0	57.5	59.3	47.0	91.4	59.4	50.4
	skewness	-0.1	1.2	0.4	0.4	1.6	0.2	0.4	0.8
	kurtosis	-0.5	2.2	0.1	-0.8	2.8	-0.3	-0.2	0.7
pH	no. samples	140	140	138	137	140	142	142	143
	median	6.1	6.5	6.3	5.8	6.6	6.4	6.0	5.9
	mean	6.1	6.5	6.3	5.8	6.5	6.3	6.0	5.9
	minimum	4.8	5.3	5.1	4.5	5.3	5.2	4.7	4.7
	maximum	7.1	7.7	7.2	7.3	7.3	7.1	7.1	7.1
	1st quartile	5.8	6.3	6.1	5.4	6.3	6.1	5.8	5.5
	3rd quartile	6.4	6.8	6.6	6.2	6.8	6.6	6.3	6.2
	skewness	-0.6	-0.4	-0.5	-0.2	-0.7	-0.6	-0.5	0.0
	kurtosis	0.5	0.5	0.2	-0.4	0.4	0.2	0.4	-0.2

		Laurel	Leighs	Swanson	Tahune	Tomalah	Warra 1	Warra 2 (Weir)
Turbidity	no. samples	142	142	141	141	143	141	141
	median	3.9	4.5	2.5	5.4	1.0	2.0	1.6
	mean	5.4	8.3	3.4	8.2	1.7	3.2	2.7
	minimum	0.9	0.0	0.0	0.0	0.0	0.0	0.0
	maximum	41.0	113.4	24.4	53.1	22.7	30.2	28.8
	1st quartile	2.5	2.2	1.6	3.4	0.2	1.2	1.0
	3rd quartile	6.2	9.8	3.8	9.2	1.7	3.6	3.0
	skewness	3.8	5.2	3.3	3.0	4.6	4.1	4.5
	kurtosis	19.0	36.1	13.5	11.5	23.4	20.4	24.4
Electrical conductivity	no. samples	143	143	142	142	144	142	142
	median	63.0	98.3	50.2	75.5	45.6	47.7	42.2
	mean	63.0	98.9	51.3	74.3	47.8	49.1	43.2
	minimum	42.7	51.8	34.5	29.1	31.5	33.1	33.1
	maximum	82.5	194.2	68.7	97.8	79.1	74.6	56.5
	1st quartile	57.3	85.3	47.0	67.5	40.5	43.6	40.0
	3rd quartile	67.6	111.6	55.4	81.2	52.4	51.9	45.4
	skewness	0.3	0.7	0.6	-0.8	1.0	1.0	0.8
	kurtosis	0.0	2.3	0.1	1.7	0.5	0.9	0.5
pH	no. samples	143	143	142	142	144	142	142
	median	6.5	6.6	5.8	6.2	6.2	6.2	5.5
	mean	6.4	6.5	5.7	6.2	6.2	6.1	5.4
	minimum	4.5	5.4	4.4	5.0	4.9	4.6	4.1
	maximum	7.0	7.2	6.9	7.1	7.4	7.4	6.9
	1st quartile	6.2	6.3	5.5	6.0	5.9	5.8	5.0
	3rd quartile	6.7	6.8	6.1	6.4	6.5	6.5	5.9
	skewness	-1.2	-0.7	-0.4	-0.8	-0.1	-0.6	-0.1
	kurtosis	3.1	0.1	-0.1	0.9	0.2	0.3	-0.6

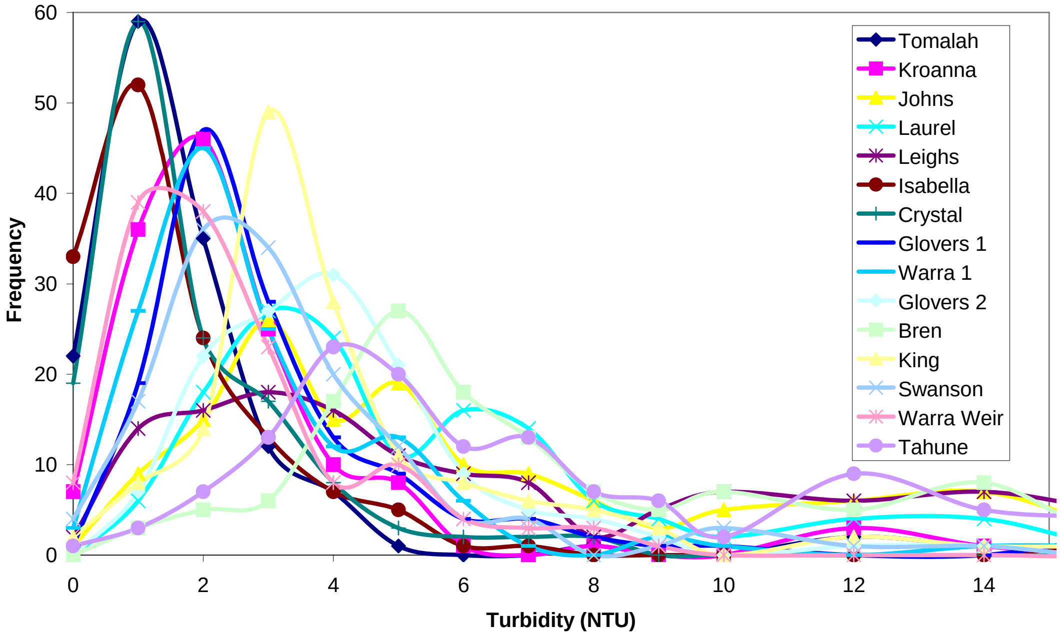


Figure 1. Frequency histogram for turbidity in each of the streams

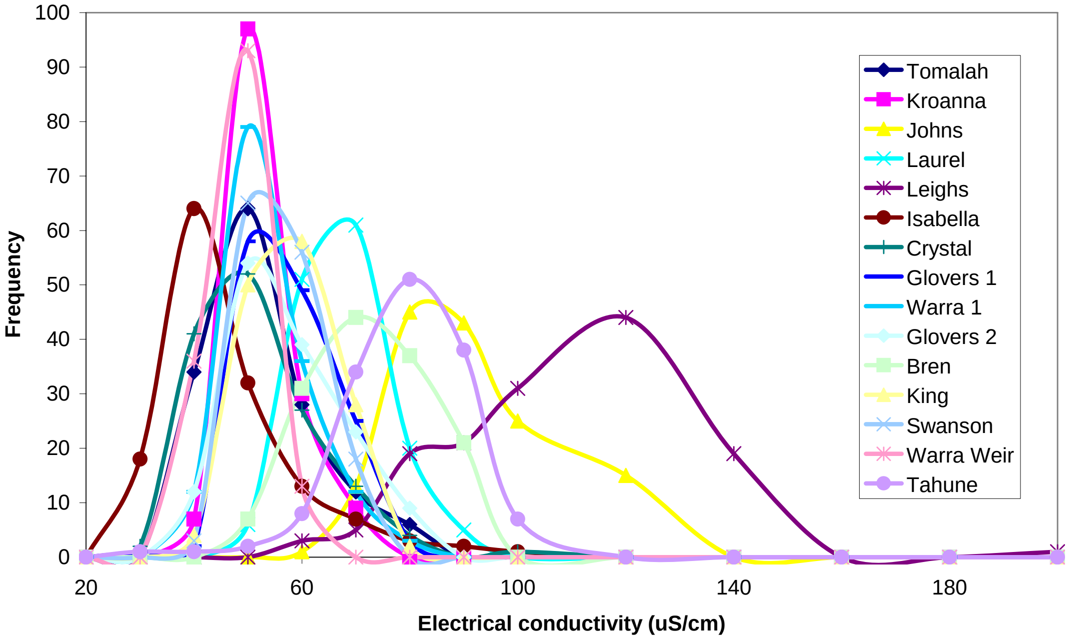


Figure 2. Frequency histogram for electrical conductivity in each of the streams

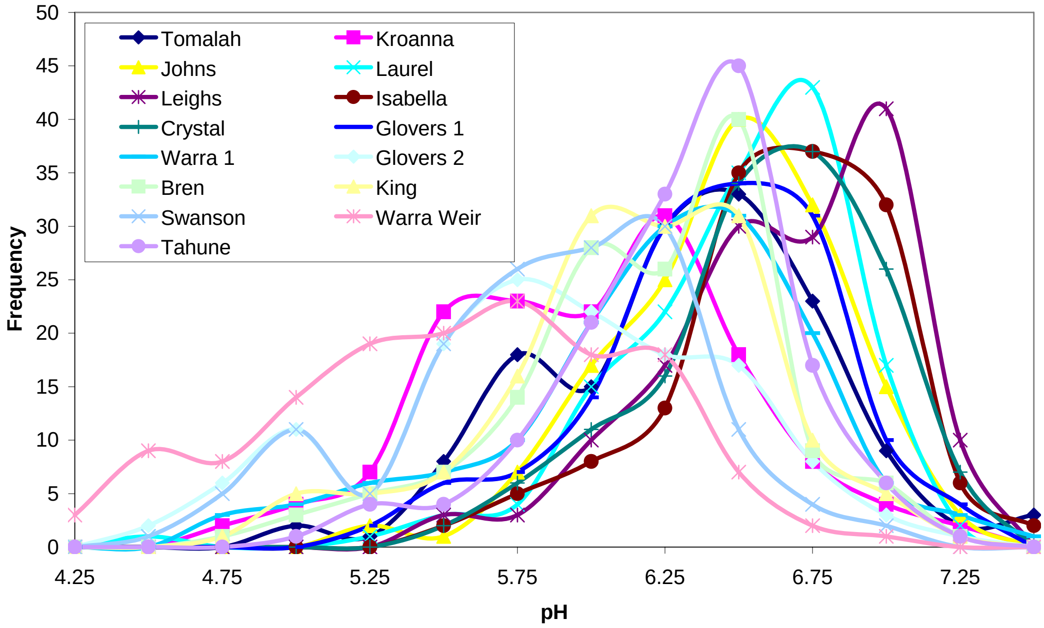


Figure 3. Frequency histogram for pH in each of the streams

Looking for change in water quality through time

A major goal of long-term ecological research is to gather data that will identify and quantify changes that are occurring in landscapes over long periods of time. To see how pH, EC and turbidity change through time, data were log transformed after adding 1 to accommodate zero values in the data sets, then average annual turbidity, EC and pH were calculated. Average annual turbidity, EC and pH were analysed for change through time using ANOVA and linear regression models for each sample site. An exponential transformation was applied using a bias correction and 1 was subtracted to untransform data.

When the data were grouped by year, analysis of variance showed significant differences in average annual turbidity (σ=0.000), pH (σ=0.01) and EC (σ=0.000) through time at the 95% confidence level (Table 5).

When the data were grouped by site, analysis of variance showed significant differences in the average annual turbidity (σ=0.003) and EC (σ=0.024) of the different sites. The pH was not significantly different between the sites (σ=0.98) at the 95% confidence level.

The significant site*year findings for EC (σ=0.026) and turbidity (σ=0.005) indicate that the rate of change of average annual turbidity and EC was variable among sites.

Table 5. ANOVAs for average annual turbidity, EC and pH of water samples in the Warra LTER site

Dependent variable:
ln turbidity

Source	df	Sum of squares	Mean square	F	σ
Year	1	2.765873	2.765873	131.372	0.000
SiteName	14	0.78567	0.056119	2.66553	0.003
SiteName * Year	15	0.783837	0.052256	2.48203	0.005
Error	80	1.68429	0.021054		

Dependent variable:
ln pH

Source	df	Sum of squares	Mean square	F	σ
Year	1	0.264826	0.264826	6.56445	0.01
SiteName	14	0.206255	0.014732	0.36518	0.98
SiteName * Year	15	0.207363	0.013824	0.34267	0.99
Error	80	3.227397	0.040342		

Dependent variable:
ln conductivity

Source	df	Sum of squares	Mean square	F	σ
Year	1	838.215	838.215	105.916	0.000
SiteName	14	227.1462	16.22473	2.05015	0.024
SiteName * Year	15	235.8202	15.72135	1.98654	0.026
Error	80	633.1127	7.913909		

To investigate the rate of change through time, plots of average annual EC, pH and NTU were created (figures 4–6) for each site.

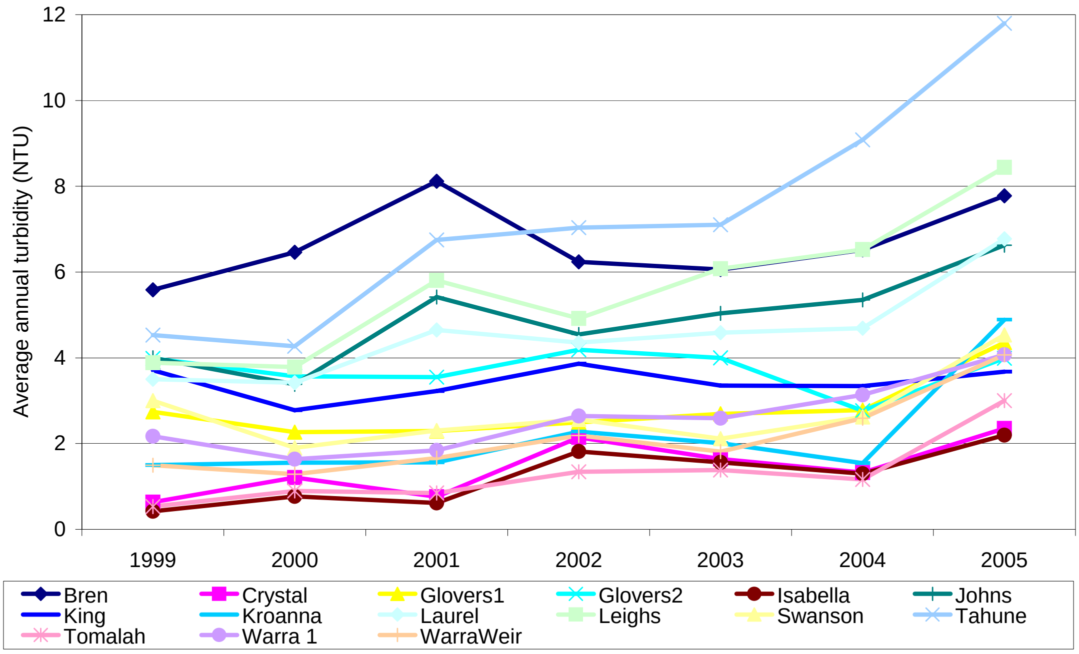


Figure 4. Average annual turbidity (NTU) through time for each stream

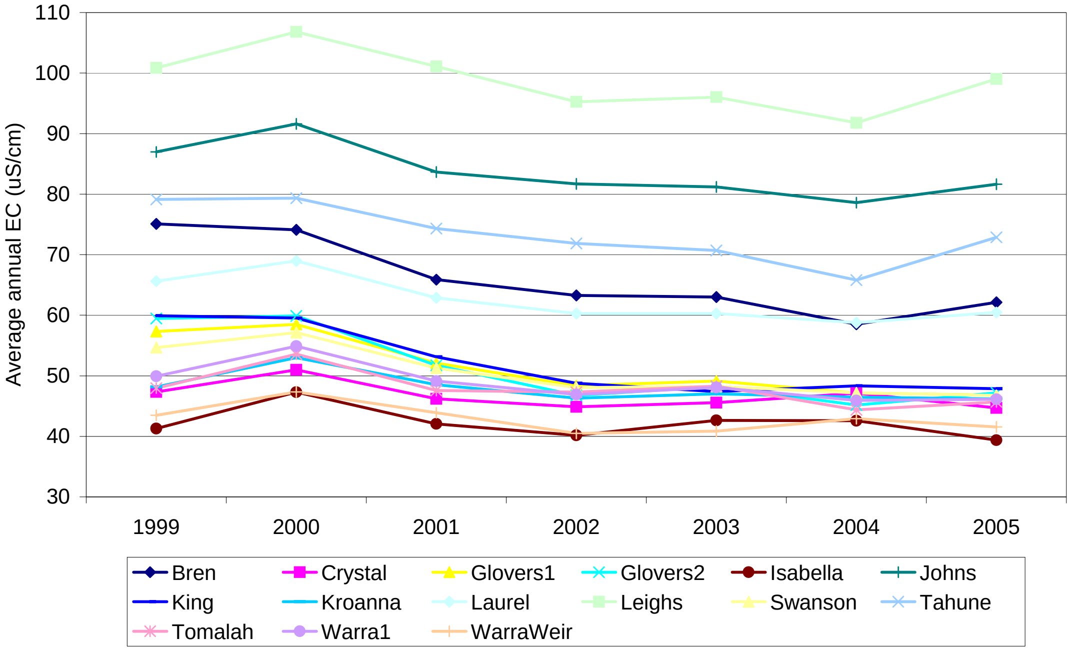


Figure 5. Average annual EC (uS/cm) through time for each stream

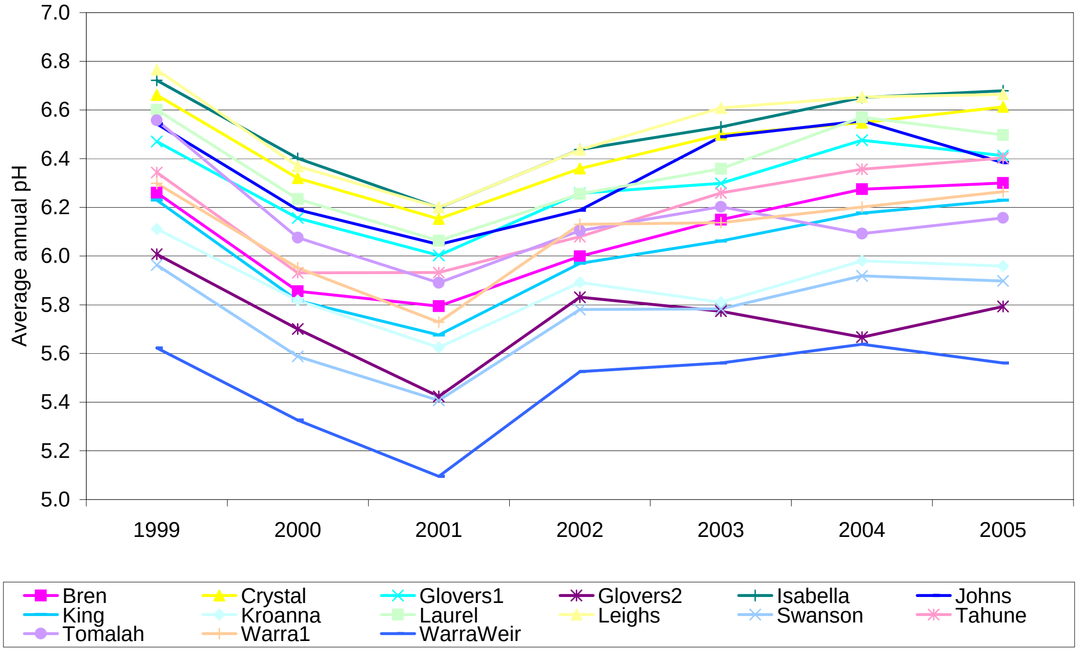


Figure 6. Average annual pH through time for each stream

A linear regression was fitted to each plot of average annual EC and NTU to identify systematic change in average annual water quality through time (this method assumes that there is a constant rate of change per year and that any other variation is random).

Table 6 lists the slope and intercept for each of the fitted equations. The slope is the best estimate of the rate of change through time. For turbidity the percentage change predicted each year is shown. For EC and pH a prediction of the absolute change per year is shown.

Table 6 shows that streams have become more turbid through time (1% to 15% per year) with the exception of Glovers 2, EC has decreased in all streams by (0.2–2.0 uS/cm each year) while pH has increased at an average of 0.02 units per year.

Table 6. Change through time in turbidity, EC and pH

Turbidity

	Intercept	Rate of change/year	% change per year
Tahune	–273.9	0.1379	15%
Isabella	–243.0	0.1218	13%
Tomalah	–242.6	0.1216	13%
Warra Weir	–219.4	0.1101	12%
Leighs	–207.1	0.1044	11%
Kroanna	–194.0	0.0975	10%
Crystal	–189.4	0.0950	10%
Warra 1	–180.6	0.0908	10%
Laurel	–150.8	0.0762	8%
Johns	–137.5	0.0696	7%
Glovers 1	–104.8	0.0530	5%
Swanson	–95.8	0.0485	5%
Bren	–42.4	0.0222	2%
King	–18.8	0.0101	1%
Glovers 2	22.2	–0.0103	–1%

Electrical conductivity

	Intercept	Rate of change (decrease)/year
Bren	5281	–2.60
Glovers 2	5037	–2.49
King	4648	–2.30
Glovers 1	4137	–2.04
Tahune	3608	–1.77
Swanson	3386	–1.67
Johns	3266	–1.59
Leighs	2999	–1.45
Laurel	2822	–1.38
Warra 1	2220	–1.08
Tomalah	1797	–0.87
Kroanna	1518	–0.73
Warra Weir	1298	–0.63
Crystal	1209	–0.58
Isabella	1092	–0.52

pH

	Intercept	Rate of change/year
Tahune	–91	0.05
Bren	–88	0.05
King	–73	0.04
Warra Weir	–59	0.03
Swanson	–54	0.03
Warra 1	–51	0.03
Glovers 1	–48	0.03
Isabella	–44	0.03
Johns	–43	0.02
Leighs	–42	0.02
Crystal	–40	0.02
Laurel	–41	0.02
Kroanna	2	0.00
Glovers 2	31	–0.01
Tomalah	67	–0.03

This analysis doesn't consider differences in the timing of and number of sample collection days in each year, does not compensate for flow rates at the time of sampling, and does not test to see if there are non-linear trends.

Correlation between the parameters

Log-transformed average annual turbidity, EC and pH were weakly correlated at each site. Turbidity was positively correlated with pH, turbidity was negatively correlated with EC, while pH and EC were negatively correlated (Table 7).

Table 7. Within-site correlation between water quality parameters

Parameter	Turbidity	EC
pH	0.27	–0.25
EC	–0.40	

Looking for differences between sites

One goal of the water quality study is to identify the biophysical factors that have the greatest influence on the quality of water in forests. Substantial differences in pH, EC and NTU between streams provide a basis for studying the catchments for factors that may generate these differences.

The ANOVA in the 'differences through time' section of this report identified significant differences in the average annual EC and turbidity of streams. The Kruskal-Wallis Rank Test (StatGraphics) confirmed that there are significant differences in the median EC and NTU of at least some of the sites at the 95% confidence level. The multiple range test (StatGraphics) identified the homogenous groups with regard to mean turbidity (Table 8) and EC (Table 9). Multiple range tests were conducted on a common dataset (only records from days when data were collected from all sites). The multiple range tests show seven homogenous turbidity groups and nine homogenous EC groups. Theoretically, streams with similar water quality features are more likely to have similar catchment attributes.

Table 8. Multiple range test results for turbidity showing groups with homogenous means

Catchment	Mean NTU	Homogenous groups						
Tomalah	1.73	X						
Isabella	1.8	X						
Crystal	2.14	X	X					
Kroanna	2.66	X	X					
Warra Weir	2.79	X	X					
Warra 1	3.24	X	X	X				
Swanson	3.41		X	X	X			
Glovers 1	3.54		X	X	X			
King	4.34			X	X	X		
Glovers 2	4.93				X	X	X	
Laurel	5.34					X	X	
Johns	6.30						X	
Bren	8.27							X
Tahune	8.33							X
Leighs	8.35							X

Table 9. Multiple range test for EC of streams in Warra LTER site showing groups with homogenous means

Catchment	Mean EC	Homogenous groups								
Isabella	41.71	X								
Warra Weir	42.84	X								
Crystal	45.92		X							
Tomalah	47.10		X							
Kroanna	47.62		X							
Warra 1	48.52		X	X						
Swanson	50.94			X	X					
Glovers 1	52.19				X					
Glovers 2	52.31				X					
King	53.22				X					
Laurel	62.41					X				
Bren	67.03						X			
Tahune	73.56							X		
Johns	83.26								X	
Leighs	97.91									X

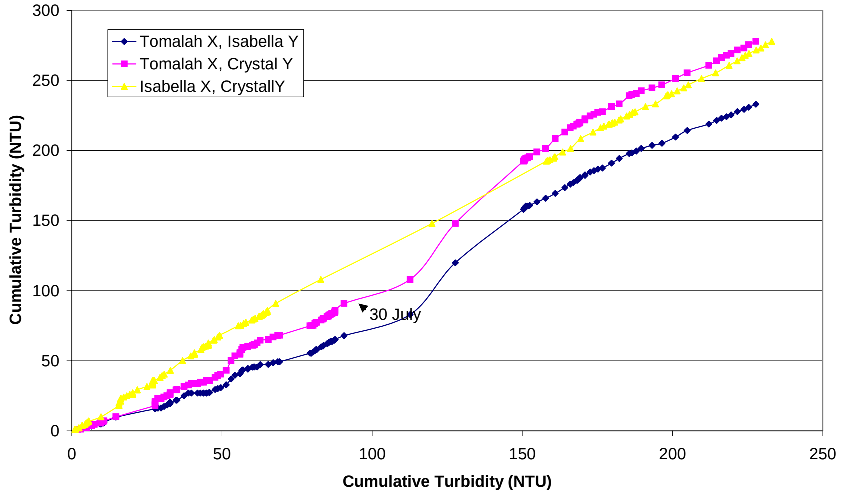
Relationship between median water quality and landscape attributes

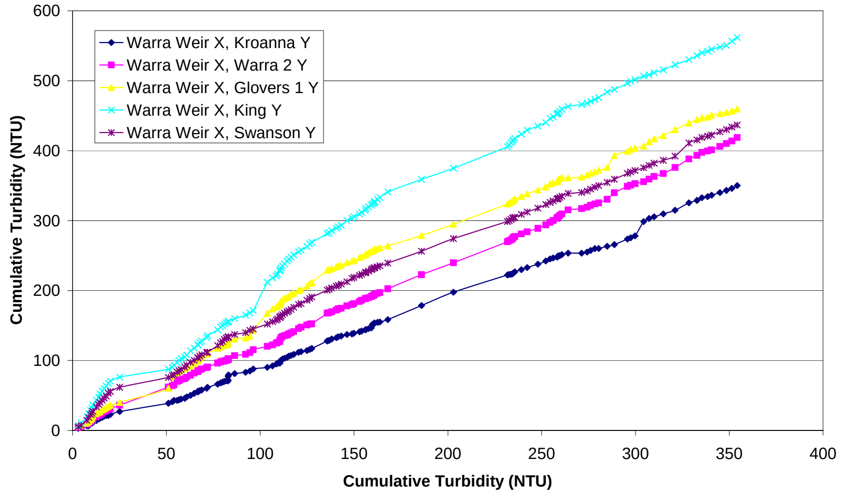
Reasons for the stream groupings in tables 8 and 9 may be identified by correlating water quality with biophysical features of the catchment and with the disturbance history. However, descriptions of the catchments are not sufficiently detailed to allow this at present.

Effects of harvesting on turbidity

Double mass plots show the cumulative turbidity of one site plotted against the cumulative turbidity of another site. The slope of the double mass plot changes when there are changes in the water quality of one stream relative to another. Changes in slope can be investigated to see if they relate to management activities or natural events or are simply part of the natural range of variation.

The double mass plots (Figure 7) show that for the most part there are no obvious trends towards higher NTU at individual sites. There are occasional single incidents of poorer water quality in some catchments compared with others—these mostly occur when samples were collected during high flow. In storms or periods of peakflow, relative turbidity of streams is less predictable. There is one period of sustained increase in turbidity in Bren Creek from 06/09/2000–12/07/2001 compared with other catchments, followed by a return to normal levels. This cannot be explained at present.





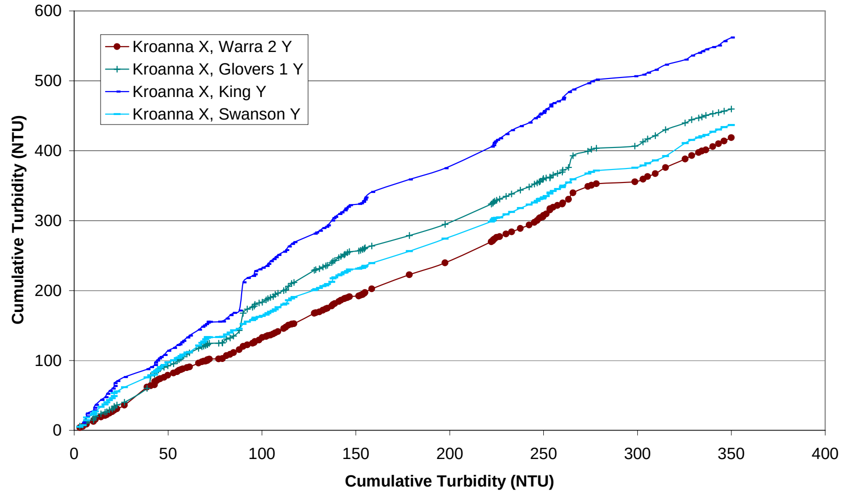
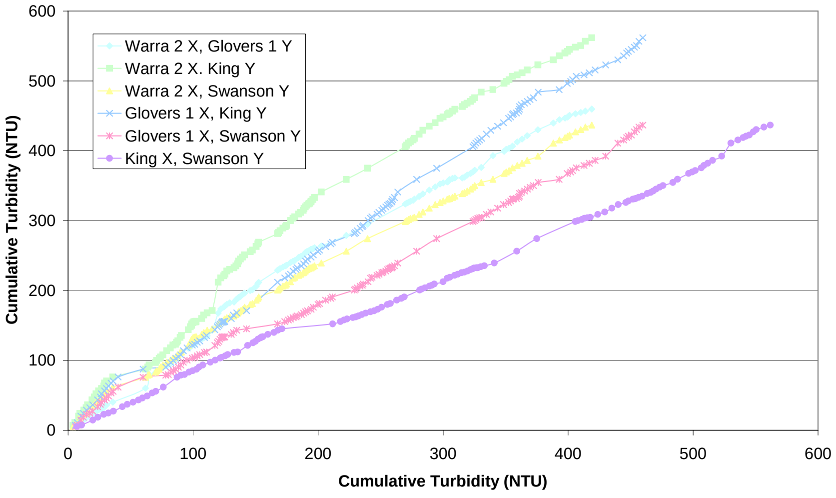
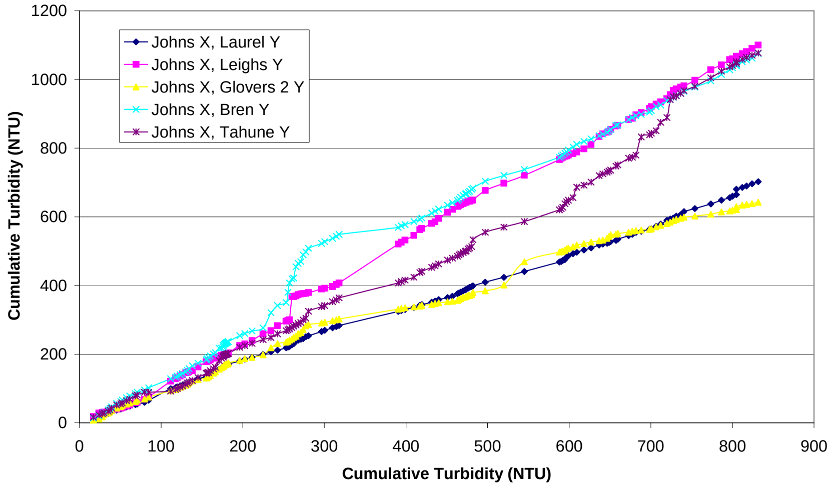


Figure 7. Double mass plots for turbidity in Warra LTER site streams





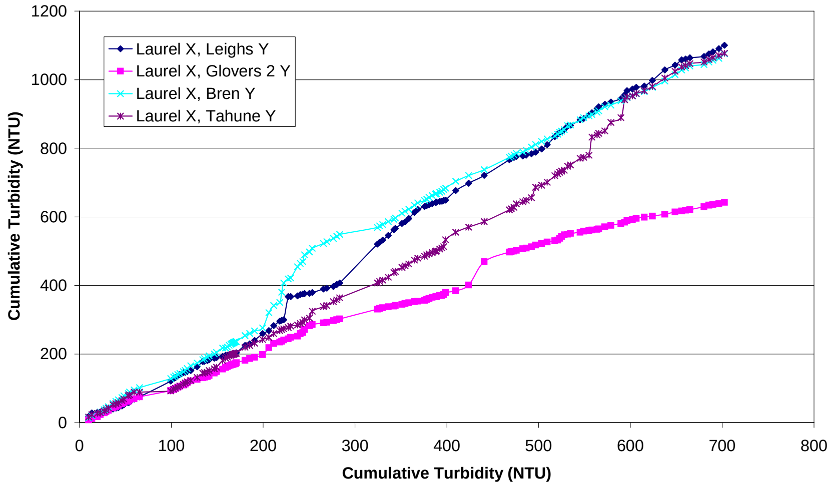


Figure 7cont. Double mass plots for turbidity in Warra LTER site streams

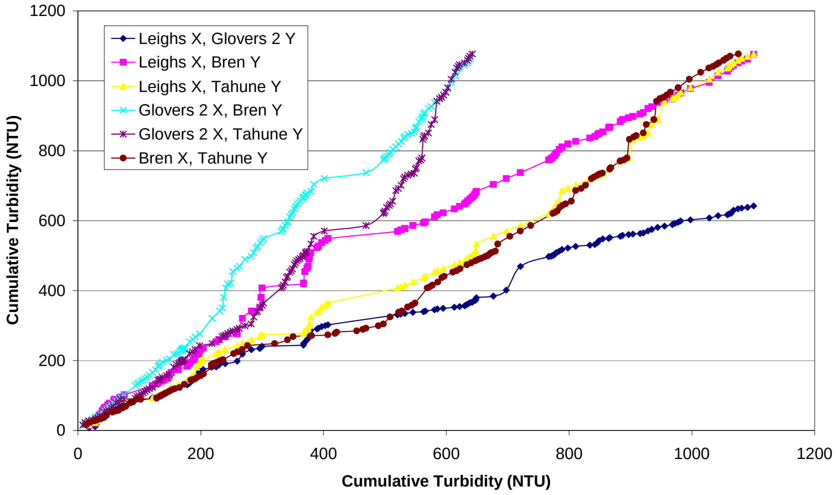


Figure 7cont. Double mass plots for turbidity in Warra LTER site streams

Testing for a harvesting impact on turbidity

Small amounts of harvesting occurred in Johns and Laurel catchments during this study. Less than 1 hectare of Laurel was harvested in Jan/Feb 2006 and 3.34 ha (4%) of Johns catchment was harvested using dispersed retention in 2000. The double mass plots do not show changes in slope that would indicate a significant change in sediment production in Johns or Laurel creeks after harvesting.

Mann-Whitney tests (Statgraphics) for differences in turbidity in Johns and Laurel creeks after harvesting showed that median turbidity was 1 NTU greater in Johns Creek and 1.6 NTU greater in Laurel Creek after harvesting (Table 10).

Mann-Whitney tests showed that the median stage height of Laurel and Johns creeks at the time of sampling was not higher after harvesting (Table 10), so it is unlikely that sampling during higher flows after harvesting is the explanation for the difference. This leads to the potential hypotheses that increased turbidity is a direct result of:

- harvesting
- increased traffic associated with harvesting and regeneration
- unknown factors such as trees overturning in the stream channel
- the use of different instruments for measurement of turbidity in the laboratory
- or simply due to whatever is causing a general increase in turbidity across all catchments.

Table 10. Results of Mann-Whitney tests for differences in median turbidity and stage height values before and after harvesting for Johns and Laurel creeks

Johns catchment	Median turbidity	No. samples	Turbidity range	Average rank
After	4.5	92	0–72.5	70.93
Before	3.5	39	0–27	54.36

Single-sided test with 95% confidence level W=1340 p=0.0112. Since p<0.05 there is a statistically significant increase in median turbidity in the 'after' sample.

Laurel catchment	Median turbidity	No. samples	Turbidity range	Average rank
After	5.2	7	4.3–15.5	90.5
Before	3.6	124	0.9–41	64.62

Single-sided test with 95% confidence level W= 262.5 p = 0.04. Since p<0.05 there is a statistically significant increase in median turbidity in the 'after' sample.

Johns catchment	Median stage height	No. samples	Stage height range	Average rank
After	0.3	91	0–0.6	66.63
Before	0.3	39	0.12–0.46	62.84

Single-sided test with 95% confidence level W=1671 p=0.2988. Since p>0.05 there is no statistically significant increase in median stage height in the 'after' sample.

Laurel catchment	Median stage height	No. samples	Stage height range	Average rank
After	0.12	7	0–0.18	45.93
Before	0.16	123	0–0.36	66.62

Single-sided test with 95% confidence level W= 567.5 p = 0.157. Since p>0.05 there is no statistically significant increase in median stage height in the 'after' sample.

Meyer and Nielsen (unpublished) described turbidity as a sensitive indicator of harvesting disturbance at Warra. They observed a general trend of reduced turbidity with time since logging, with streams surrounded by advanced regeneration showing little difference to unlogged streams. They concluded that short-term changes to river health were caused by forest harvesting and associated works. However, their analytical technique involved classifying catchments as either unlogged, advanced regeneration, recent logging or young regeneration based on the time since last harvesting—with no reference to the area harvested in a catchment, its proximity to the stream channel or consideration of differences in catchment size, location, shape, vegetation type, geology or soils. They used data from catchments within and external to the Warra LTER site and did not consider if differences could be attributed to factors other than harvesting.

Relationship between turbidity and stage height

Streamflow and turbidity are frequently linked (Meyer *et al.* 2002; Hopmans and Bren 2007). Figures 8 and 9 illustrate the relationship between turbidity and stage height for Laurel and Johns catchments respectively. The absence of a solid linear relationship between turbidity and streamflow is probably caused by hysteresis (e.g. Hopmans and Bren 2007).

Hysteresis is a lag in response to change. In hydrology, the maximum turbidity is frequently achieved before the maximum flow. As a consequence, during the rising limb of a storm hydrograph turbidity can be greater than for the same level of flow on the falling limb of the storm hydrograph. This occurs because the sources of particles responsible for the turbidity have been exhausted (Hopmans and Bren 2007). A better understanding of the link between flow and turbidity at Warra can probably be achieved through analysis of streamflow and turbidity data collected at fifteen-minute intervals in the three gauged catchments (Warra, Swanson and King). This will be the subject of a later report.

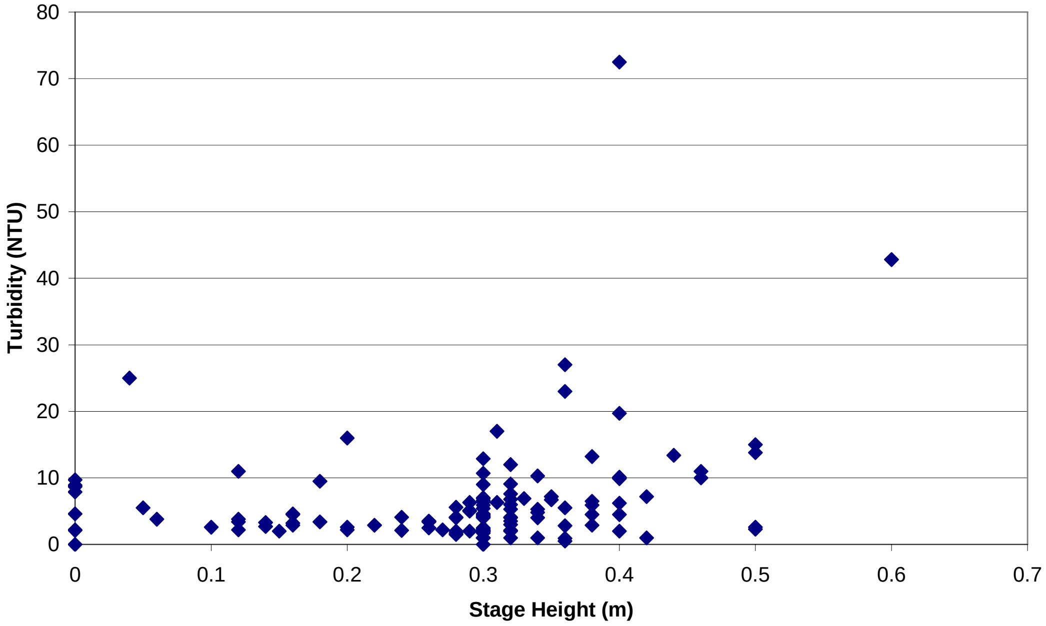


Figure 8. Comparison of turbidity to stage height in Johns Creek

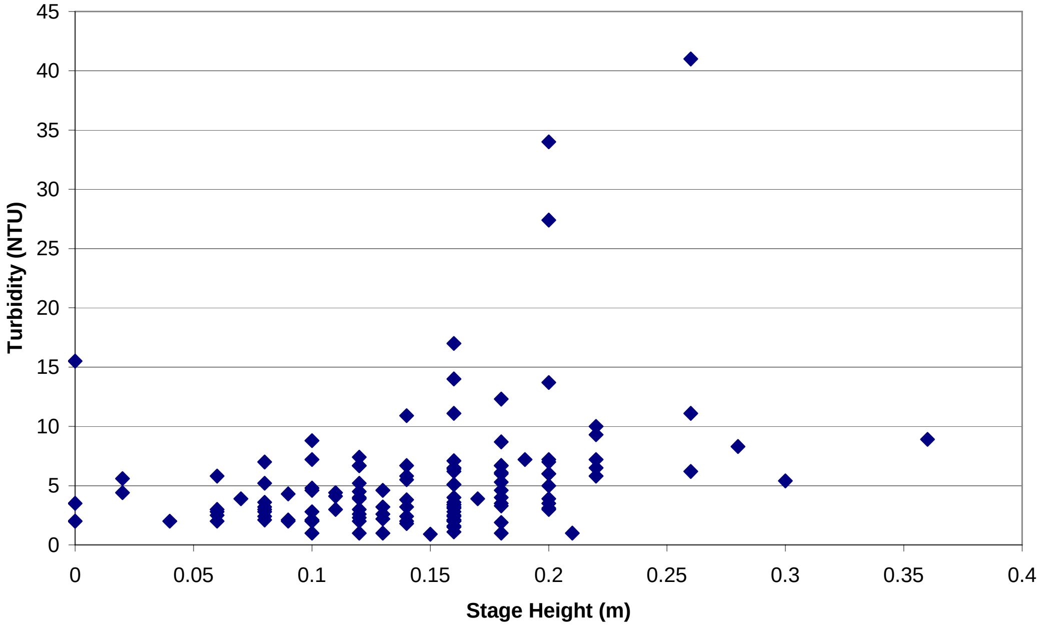


Figure 9. Comparison of turbidity to stage height in Laurel Creek

Relationship between mean turbidity and colour

Turbidity is a measure of the density of particles of both organic and inorganic origin suspended in the water column. Organic particles come from sources in and around streams such as algae and leaf litter. Inorganic particles come from erosion in the catchment and stream channel (Madej 2004). Inorganic particles tend to be increased by harvesting (Meyer *et al.* 2002), while organic particles tend to be diminished by harvesting (Davies *et al.* 2005). Colour in water is usually the result of particles and solutes such as iron and humic substances that originate in soils in the catchment (Meili, 1992). Tannins are frequently a source of colour in Tasmanian forest streams.

Colour and turbidity were measured each fortnight in the fifteen streams during 2001 (Meyer *et al.* 2002). Figure 10 is a scatter plot of mean turbidity versus mean colour. Mean turbidity increases as mean colour increases.

The ovals on the plot indicate what appear to be natural groupings of data. Group 1 includes Tomalah, Isabella and Crystal creeks. They are pale in colour and have little suspended sediment. Group 2 includes Bren, Tahune, Leighs, Johns and Laurel creeks. For a given colour they have higher turbidity than groups 1 and 3. This suggests that inorganic sediments may be an important source of suspended sediments in these catchments. In the remaining catchments (group 3) turbidity is low and colour is dark. This suggests that there is greater input of organic matter to these streams and a greater probability that suspended sediments are of organic origin.

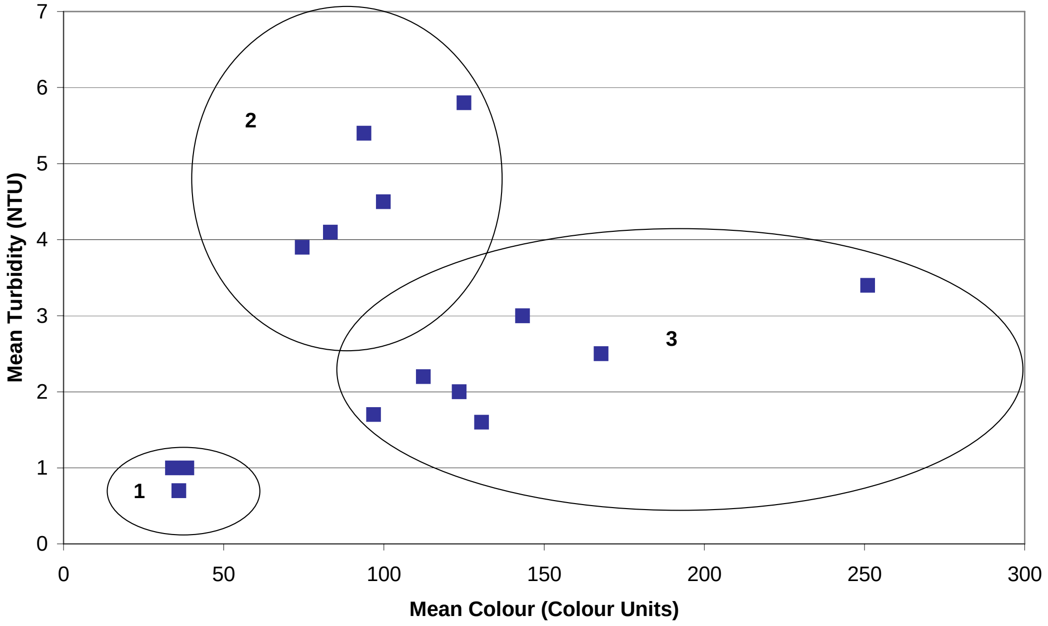


Figure 10. Scatter plots of mean colour and mean turbidity

Discussion

Turbidity and suspended sediments

The ANZECC and ARMCANZ (2000) guidelines for aquatic ecosystems suggest that turbidity of upland rivers in Tasmania should fall within a range of 2 to 25 NTU and that most upland streams in good condition will have low turbidity although high values may be observed during high flow events. Drinking water guidelines are for < 5NTU (NHMRC and ARMCANZ, 1996).

The mean turbidity of streams in the Warra LTER site falls within the ANZECC guideline range. Less than 2% (37 out of 1894) of samples from streams in the Warra LTER site exceeded the upper guideline value of 25 NTU. The drinking water guideline value of 5 NTU was exceeded approximately 24% of the time (458 out of 1894 samples).

There was significant variation in turbidity in both time and space in the Warra LTER site. Some streams exhibited low turbidity levels virtually all of the time (e.g. Tomalah, Isabella and Crystal creeks), while others streams exhibited higher levels of turbidity (e.g. Leighs, Bren and Tahune). High turbidity readings typically occurred during periods of high flow, although the relationship between flow and turbidity was not easily identified—possibly due to hysteresis.

All creeks showed increasing turbidity through time. Johns and Laurel creeks both showed small increases in turbidity following harvesting. It was not possible to demonstrate if this increase was solely attributable to increased disturbance—this actually seems unlikely given the very small areas harvested. The fact that larger changes in turbidity were measured in undisturbed streams suggests that multiple factors influence turbidity.

There were almost twice as many days with rainfall over 10 mm in 2005–2006 as there were in 1998 and 1999. In 1998 and 1999 rainfall was low. Further investigation of rainfall and streamflow patterns in conjunction with water quality may show that changes in average annual turbidity, pH and EC were an artefact of the timing of sample collection (with a greater proportion collected during high flow periods) or the result of a varying rainfall and streamflow regime. Examination of the disturbance history of the catchments may also show that disturbance, and its effect on runoff production, contributed to the changes.

The streams fall into several groups with similar mean or median turbidity. The multiple range test identified seven homogenous groups of streams. The least turbid streams (Tomalah, Isabella and Crystal) have larger catchments, at higher altitude, adjacent to each other, predominantly on dolerite or talus, have approximately 30% of catchment area steeper than 30 degree slopes, less than 3% of area harvested, and have very little colour. I hypothesise that the catchments of the least turbid streams are better drained, have higher rainfall, are relatively undisturbed by human activity, with smaller areas of poorly drained organic soils than the catchments of the streams with higher mean turbidity. This cannot be verified without more detailed assessment of the catchments.

Warra Weir, Kroanna, Warra 1, Glovers 1, King and Swanson creeks occur in the eastern section of the experimental area. The predominant geology is dolerite apart from Glovers 1 where mudstone is present. These catchments are mid-sized, draining to the north-east, south-east and south of the experimental area. Even though Warra Weir and Kroanna catchments have not been harvested or roaded, these streams display higher mean turbidity than Crystal, Tomalah and Isabella. The remainder of catchments in this group have experienced some human impacts. This group tends to have between 0 and 21% of their catchment area with slopes steeper than 30 degrees, and have a higher apparent colour (classes 1 and 2, Meyer *et al.* 2002). I hypothesise that these streams are naturally higher in turbidity than the first group because the catchments are less well drained, have greater areas of organic soils than for the first groups and/or different vegetation types. Further catchment assessment is warranted to test this hypothesis.

The most turbid streams were Glovers 2, Bren, Laurel, Tahune, Leighs and Johns. They either have small catchments or are located in the southern portion of the research area on a mix of talus and dolerite. They have variable slopes and 4 to 60% of their area is regrowth forest following harvest. Water is moderately or highly coloured. Disturbances such as in-stream dams (Leighs and Johns), roads parallel to streams (Leighs), and inappropriately located log landings (Leighs) were identified in some catchments (Meyer *et al.* 2002). Leigh Edwards (pers. comm.) has followed the channel of some of these streams and found overturned trees and underground stream channels. I hypothesise that these catchments have larger areas of poorly drained organic soils, poorly defined stream channels that partly occur below ground, and larger areas of non-eucalypt vegetation and that these factors are contributing to their poor water quality. Again this cannot be determined without more detailed surveys of the catchments.

Turbidity of each stream was quite strongly correlated to turbidity of at least some of the other streams (R^2 of greater than 0.74 for all except Bren Creek (R^2=0.68)). Correlation and the lack of significant slope changes in the double mass plots supports the hypothesis that turbidity is mostly varying in each stream in response to events that occurred in multiple catchments (such as rainfall and increased/decreased flows) rather than events that occurred in individual catchments.

Small turbidity increases were detected after harvesting of parts of Laurel and Johns catchments; however, increases in turbidity through time were detected in all streams—even those that had not been disturbed by harvesting. The harvested areas in Laurel and Johns catchments were so small and located so close to the catchment boundary that it is difficult to believe that harvesting could be responsible for this small increase. Estimated changes in turbidity through time were greater in some streams that had not been disturbed than in the creeks that had been disturbed by harvesting.

pH

The default trigger values of pH of upland rivers for aquatic ecosystems in south-eastern Australia are 6.5 (lower limit) and 7.5 (upper limit) (ANZECC and ARMCANZ 2000). For humic-rich Tasmanian lakes and rivers they are 4.0 to 6.5. The Australian Drinking Water Guidelines (NHMRC and ARMCANZ, 1996) recommend that pH falls in the range of 6.5–8.5 as values of less than 6.5 may be corrosive, and values greater than 8 decrease efficiency of chlorination and cause scale and taste problems.

The median pH of streams in the Warra LTER site ranged from 5.4 to 6.56. Water from thirteen out of the fifteen streams was more acid than recommended by drinking water guidelines. The pH values of the streams fell within the range that is considered acceptable for aquatic ecosystems in humic-rich rivers or lakes in Tasmania.

The pH showed some variance within streams. There was no significant difference in average annual pH of different streams. The most neutral streams were Crystal, Isabella and Leighs creeks.

Vegetation leachate reduces pH through release of humic acids (Gallagher, 1996). It is likely that pH indicates the presence of humic acids in Tasmanian streams and that where pH is low, unless geology consists of acid rocks, it is highly probable that organic matter is decomposing to produce humic and fulvic acids in the catchment.

Meyer (2002) found a strong negative correlation between pH and discharge (r^2=0.834) and pH and rainfall (r^2=0.59) in Warra Creek. Increased winter flow decreased pH. A possible explanation for the decreased pH is that humic acid was diluted by stormflow, reducing pH. Meyer (2002) observed similar trends at Crystal Creek (r^2 of 0.8 for discharge and 0.76 for rainfall). The pH was positively correlated with conductivity at Warra Creek (0.45) and at Crystal Creek (0.75) and weakly negatively correlated with turbidity at Warra Creek (0.46).

Electrical conductivity (EC)

The NHMRC and ARMCANZ (1996) drinking water guidelines suggest an ideal total concentration of dissolved solids of less than 500 mg/L. The default trigger conductivity values of EC in upland rivers for aquatic ecosystems are 30–350uS/cm. Tasmanian rivers are typically mid-range (90 uS/cm) (ANZECC and ARMCANZ 2000), or less than 150 uS/cm (Fuller and Katona, 1993).

EC was measured in uS/cm in this study. There are a number of different published conversion factors for EC (uS/cm) and total dissolved solids (TDS) (mg/L). Figure 11 shows the relationship between TDS and EC for multiple samples taken from each of six stream sites in the vicinity of the Southwood Mill (to the east of Warra LTER site). Samples were analysed for TDS by Analytical Services Tasmania and for EC by Forestry

Tasmania. There is a weak positive correlation between EC and TDS (R^2=0.37). At Southwood, the EC value that approximates the NHMRC and ARMCANZ (1996) guideline value of 500 mg/L TDS is 712 uS/cm.

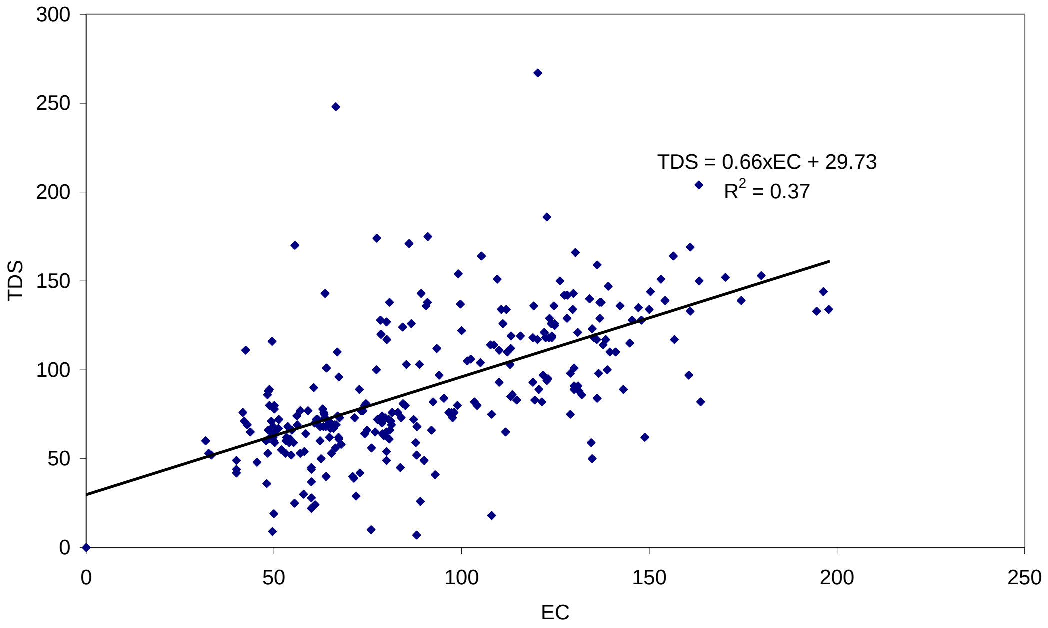


Figure 11. Relationship between EC (uS/cm) and TDS (mg/L) for six stream sites with approximately 45 samples from each site

The EC values measured at Warra are well within the drinking water guidelines and the range for aquatic ecosystems. They represent very low levels of total dissolved solids. For such low TDS to occur in the Warra LTER site, the rock and soil types must be resistant to dissolution. Low TDS probably indicates low soil erosion rates as soil can carry particles to streams that dissolve and release ions.

The geology of the Warra LTER site is dominated by Jurassic dolerite and derived Quaternary Slope Deposits (two-thirds of the Warra LTER site). Sedimentary and metamorphic rocks comprising precambrian quartzite, dolomite, slate and phyllite, and Parmeener Supergroup mudstone, siltstone, sandstone, tillite and conglomerate predominate in the west. Cambrian volcanic ultramafic rocks and Quaternary alluvium and morainal deposits cover minor areas (Laffan 2001).

If sedimentary rocks are less resistant to weathering than dolerite and its derivatives, then higher EC should occur in streams where sedimentary rocks are more prevalent in the catchment. This hypothesis is not supported by Figure 12, which shows the poor relationship between percentage area of sedimentary rock in a catchment and mean EC.

This suggests a number of possibilities:

- that the assumption that sedimentary rocks are less resistant to weathering is incorrect
- that mapping of geology at 1:25 000 is not sufficiently detailed for this comparison—e.g. Laffan (2001) assessed soils in coupes near Manuka Rd (near Leighs, John, Laurel, Tomalah, Tahune) and noted that slope deposits in this area (derived from dolerite) were underlain by sedimentary rocks, usually at depths greater than 1.5 m
- that some ions originate from sources other than the parent material, such as sediments added to streams by erosion, from areas of disturbance (e.g. road crossings)
- that an interaction between other factors, such as humic and fulvic acids, influences the supply of ions to the streams—e.g. some rock types may be more readily decomposed by acid water
- if rainfall/runoff ratios differ in the catchments, it is possible that flow and dilution rates influence mean EC.

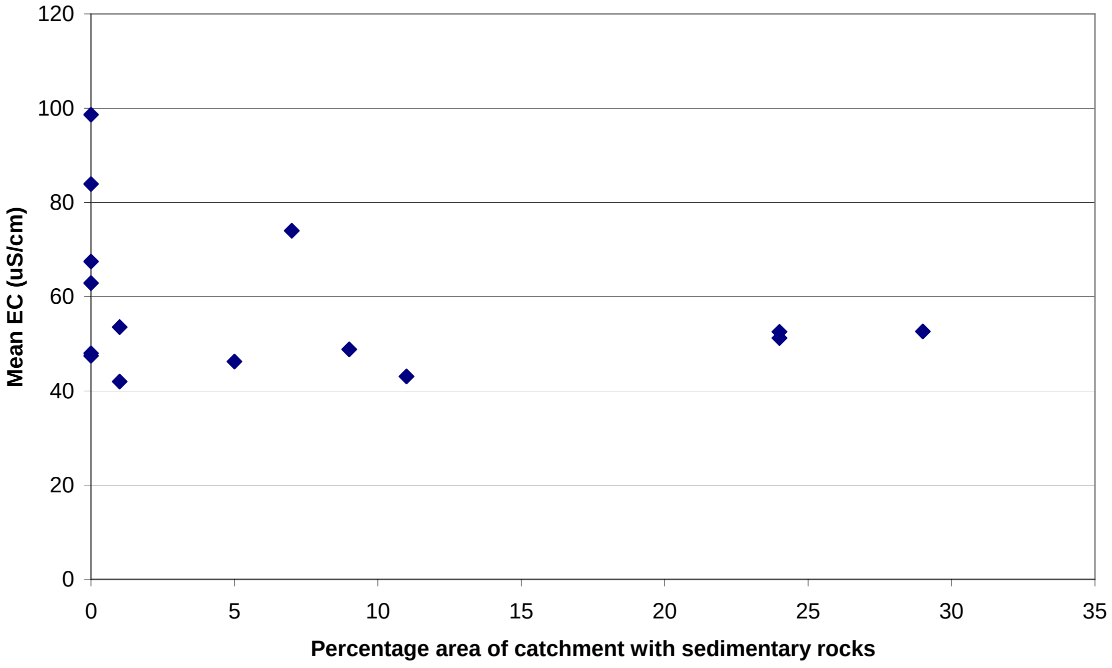


Figure 12. Mean EC (uS/cm) versus percentage area of catchment mapped with sedimentary rock

Table 11. Geology of catchments in the Warra LTER site from analysis of 1:25 000 mapping

Site	Parent Material	Area (ha)	Percentage
Bren	Dolerite (tholeiitic) with locally developed granophyre.	7	100
Crystal	Dolerite (tholeiitic) with locally developed granophyre.	196	40
	Talus, vegetated and active.	275	55
	Undifferentiated Late Carboniferous-Permian glacial, glaciomarine and non-marine sedimentary rocks.	24	5
Glovers 1	Dolerite (tholeiitic) with locally developed granophyre.	218	76
	Upper glaciomarine sequences of pebbly mudstone, pebbly sandstone and limestone.	67	24
Glovers 2	Dolerite (tholeiitic) with locally developed granophyre.	11	71
	Upper glaciomarine sequences of pebbly mudstone, pebbly sandstone and limestone.	5	29
Isabella	Dolerite (tholeiitic) with locally developed granophyre.	49	4
	Pleistocene glacial and glacigene deposits.	41	4
	Talus, vegetated and active.	1,054	91
	Upper glaciomarine sequences of pebbly mudstone, pebbly sandstone and limestone.	8	1
	Water	12	1
Johns	Dolerite (tholeiitic) with locally developed granophyre.	23	33
	Talus, vegetated and active.	47	67
King Weir	Dolerite (tholeiitic) with locally developed granophyre.	25	99
	Upper glaciomarine sequences of pebbly mudstone, pebbly sandstone and limestone.	0	1
Kroanna	Dolerite (tholeiitic) with locally developed granophyre.	251	93
	Talus, vegetated and active.	19	7
	Undifferentiated Late Carboniferous-Permian glacial, glaciomarine and non-marine sedimentary rocks.	0	0
Laurel	Dolerite (tholeiitic) with locally developed granophyre.	43	31
	Talus, vegetated and active.	95	69
Leighs	Dolerite (tholeiitic) with locally developed granophyre.	87	59
	Talus, vegetated and active.	61	41
	Upper glaciomarine sequences of pebbly mudstone, pebbly sandstone and limestone.	0	0
Swanson Weir	Dolerite (tholeiitic) with locally developed granophyre.	62	76
	Upper glaciomarine sequences of pebbly mudstone, pebbly sandstone and limestone.	20	24
Tahune	Dolerite (tholeiitic) with locally developed granophyre.	17	27
	Talus, vegetated and active.	41	66
	Upper glaciomarine sequences of pebbly mudstone, pebbly sandstone and limestone.	4	7
Tomalah	Dolerite (tholeiitic) with locally developed granophyre.	697	77
	Talus, vegetated and active.	211	23
Warra 2	Dolerite (tholeiitic) with locally developed granophyre.	660	88
	Talus, vegetated and active.	23	3
	Upper glaciomarine sequences of pebbly mudstone, pebbly sandstone and limestone.	70	9
Warra Weir	Dolerite (tholeiitic) with locally developed granophyre.	413	89
	Upper glaciomarine sequences of pebbly mudstone, pebbly sandstone and limestone.	50	11

There is little detailed information about soils and geology in the catchments. Some surveys were completed by Laffan (2001), Meyer (2002 and unpublished) and Jaskerniak (2005). Geology was mapped by Mineral Resources Tasmania (1997).

Previous publications on Warra water quality

A subset of the water quality data described in this report was analysed in 2001–02. To evaluate the relationship between biodiversity, stream habitat, water quality and hydrology, and to provide data for long-term assessment of forestry impacts, Ringrose and Meyer (2001) described the turbidity, EC and pH data that was collected from various streams during 1999–2001 and summarised results. Meyer *et al.* (2002) provided greater interpretation of these results and, in particular, they looked at the relationships between the water quality parameters and levels of disturbance in the catchments.

In addition to measurements of turbidity, electrical conductivity and pH, some measurements of water chemistry were made from 2001 to 2002 (Meyer *et al.* 2002; Ringrose and Meyer 2001) as were AUSRIVAS macroinvertebrate bioassessments (Davies *et al.* 2001; Davies and Cook 2002), and stream sediments (Risdon, 1998).

Davies and Cook sampled macroinvertebrates at more than 60 sites in 1999–2000 in the southern forests to see if observation of the range of species could identify impacts of disturbance. Twenty-nine of the sites were located in the Warra LTER research area. Warra, southern forests and Tasmanian models of expected taxa were developed and used to detect changes in taxon associated with impacts. Regional models and those based on genus/species rather than family, using live pick rather than lab sorting and using rank abundance rather than presence/absence data, were able to detect changes in community composition at relatively low levels of disturbance in the Warra LTER site. Mean water quality parameter values collected by Meyer *et al.* (2002) and Observed/Expected Davies and Cook scores have not been directly compared.

Analyses of chemical and physical water quality did not detect differences in water quality due to roads crossing streams (Meyer *et al.* 2002). Turbidity of streams in recently logged catchments was generally higher than in streams in catchments where forest was greater than three years old and tended to decrease with time since logging. The exceptions were Leighs and Johns creeks where, fire, fire-line construction, in-stream dams, bridge construction, landings close to streams and roads parallel to streams were hypothesised to have caused increased turbidity (Meyer *et al.* 2002).

Analysis of water quality data showed the link between apparent colour of streams and physical and chemical water quality (Meyer *et al.* 2002, Meyer 2002). Strongly coloured streams occurred in catchments with large areas of saturated organic soils. Meyer hypothesised that where water drains through organic soils rather than mineral earth, greater colouration of the water occurs. Strongly coloured streams tended to have higher levels of nutrients and higher turbidity during baseflow. Streams that were clear during baseflow tended to become coloured during peakflow, but colour was rapidly flushed and followed by a return to clear water. Meyer (2002) concluded that apparent colour and the presence of organic soils in combination with drainage patterns are key factors in understanding the quality of water in Tasmania’s southern forests. Meyer (unpublished and 2002) determined that nutrient-rich soils on waterlogged south-facing slopes were the main contributor of colour, turbidity and nutrients to Warra Creek.

Meyer and Nielsen (unpublished) analysed turbidity, conductivity, pH and stream temperature data for 27 sites in the Warra LTER site for 2001, plus data on apparent colour and chemical composition for base and stormflow events. They found significant differences in the turbidity of streams impacted by harvesting, although the statistical methods used to reach this conclusion were not well explained and did not check for changes in turbidity that were independent of harvesting.

Summary and conclusions

Turbidity, pH and EC of streams in the Warra LTER site are generally well within the range expected for streams in southern Tasmanian forests, and—except for periods with high flow rates—are within the range that is acceptable for drinking water.

Over the eight years of this study, turbidity increased in all except one stream, EC decreased, and pH mostly increased—regardless of levels of harvesting activity in catchments. The rate of change in water quality parameters through time varied among catchments.

Small increases in turbidity were observed in streams where the catchment was partly harvested during the study period; however, the rate of increase in turbidity was low and the area of harvesting was less than 4% of the catchment, so it is difficult to believe that these changes are solely due to harvesting—especially when increases in turbidity were seen in all streams.

There were significant differences in turbidity and EC of different streams. The pH did not vary markedly between catchments.

There were interesting interactions between stream colour and turbidity that warrant further investigation.

Recommendations for future research

Future research and monitoring is recommended in the Warra LTER site streams and catchments.

The difference in the average annual turbidity and EC of the streams highlights the importance of biophysical factors for water quality. At this stage, catchment descriptions do not allow for assessment of the influence on water quality of catchment size, catchment shape, elevation, drainage patterns, stream morphology, soil type, vegetation community and aspect. To better understand the important biophysical factors for water quality, far more detailed catchment assessment is required including:

- catchment area, and elevation mapping
- stream morphology surveys
- soil type mapping
- vegetation mapping
- runoff generation process studies
- disturbance history—including roading, harvesting and fire
- analysis of the links between each of these factors and metabolism, decomposition and sediment-generation processes.

Spatial data analysis, air photo interpretation, a study of coupe files and Forest Practices Plans, further analysis of the fire history, and field surveys could be used to collect this information, followed by statistical analyses.

Very little is known about the sources of sediments in streams. Particles in streams can be organic or inorganic in origin and derived within the stream or from the broader catchment. No tests have been conducted at Warra to identify the ratios of inorganic and organic solids in water samples. The relationship between colour and turbidity in streams in the Warra LTER site demonstrates the potential importance of organic particles in turbidity measurements. Colour is hypothesised to occur when water drains through organic rather than mineral soils to streams (Meyer 2002). Humic acid and other products of vegetation decomposition are dissolved and transported to streams creating the characteristic colour.

A study of the sources of particles in streams in the Warra LTER site will help to explain if their presence is due to natural processes or human activity. Analysis of a set of samples for turbidity, total suspended solids, organic suspended solids, inorganic suspended solids and colour collected at a range of flow rates and locations would increase this understanding. Simultaneous measurement of TSS and NTU will identify the relationship between turbidity and total suspended solids. This may ultimately allow estimation of sediment loads for the three sites where flow and turbidity are continuously gauged (Warra Weir, Swanson and King).

Another way to improve our understanding of the interaction of turbidity and streamflow is closer analysis of the time-series streamflow and turbidity data for the three gauged catchments at Warra.

The optimal long-term water-sampling regime for the Warra LTER site needs consideration, as does the collection of additional rainfall data. It seems that long-term monitoring can identify unexpected changes in water quality parameters that may be connected to processes not previously considered. For this reason, continued monitoring of at least a subset of the streams is recommended. Additional bulk or tipping-bucket rain gauges could be installed in the catchments to address the lack of quality rainfall data.

At this stage there are no recommendations for harvesting treatments in the experimental catchments or for additional environmental protection during harvesting. It would be very interesting to impose different silvicultural systems on catchments to see if there are significant differences in water quality impacts.

Ongoing research

Hydrological research in the Warra LTER site is ongoing. The University of Tasmania and the Tasmanian Forest Practices Authority continue to study the impacts of harvesting in the Warra LTER and surrounding areas on macroinvertebrate diversity and community structure, stream habitat and ecosystem processes (Clapcott 2007). These studies offer an opportunity to incorporate measurements of physical water quality to assess pH, EC and turbidity response to harvesting, and to examine the relationships between physical water quality, macroinvertebrates, habitat and processes.

Forestry Tasmania continues to monitor water quality (EC and turbidity) and flow in the three gauged catchments and continues to collect water samples in each of the streams described in this report each month. Forestry Tasmania has also commenced gathering additional data on catchment attributes to facilitate an understanding of the reasons for differences in water quality among the Warra LTER streams. This program includes:

- purchase of LiDAR data for the fifteen catchments to enable descriptions of catchment size, shape, drainage pattern, digital elevation, vegetation density and other features

- compilation of historical information on human activities and fires

- assessment of stream morphology, soil, geology and vegetation.

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Appendices

Appendix A. Rainfall estimation

Rainfall records were obtained from a Forestry Tasmania (FT) automatic weather station, a Bureau of Meteorology (BoM) weather station and SILO data drill (Department of Natural Resources QLD) for the top of Warra Rd within the LTER site. Rainfall data from the three sources were compared using scatter plots. The linear relationship between the short-term BoM data and long-term SILO data was used to correct the SILO data to allow long-term estimates of rainfall to be made at the site.

Rainfall was collected by FT at Lat. 43.1, Long. 146.7, Altitude 495 m from 16/3/2002 to 25/4/2004 using an Environdata Automatic Weather Station (AWS) with 0.2 mm tipping-bucket rain gauge. Of a total of 776 days of deployment of the AWS, data were collected on 269 days or 35% of the time. Comparison of rainfall data with rainfall predicted by SILO data drill for this location shows a very poor correlation (Figure A1). This either suggests that SILO is a poor predictor of rainfall in an area where there is a low density of climate stations to provide data for interpolation, or suggests that the FT AWS was dysfunctional even when data were being recorded.

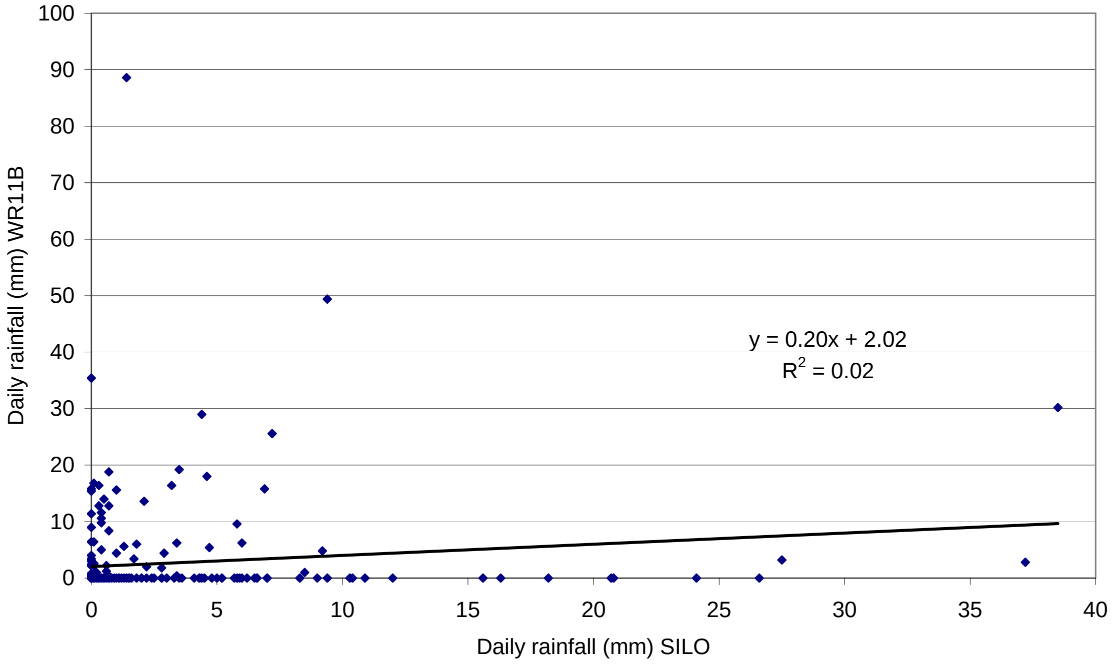

Figure A1. Scatter plot of SILO and FT rainfall data

On 28 September 2004 the Bureau of Meteorology installed an AWS at Warra Rd. It is still in service at the site. Rainfall data from this AWS was compared with SILO. Seven outliers were observed that had a large impact on the regression relationship—they all indicated low rainfall at BoM when SILO predicted larger events. This either suggests that some large storms are localised and while they may have been experienced at locations utilised by SILO for data interpolation they did not occur at Warra, or that there were measurement errors at Warra. I suspect the former is the case due to the strong relationship between the datasets during the common period. A double mass plot and descriptive statistics show that SILO typically underestimates the rainfall when compared with the BoM AWS so the equation in Figure 2 was used to correct SILO to create longer term estimates of rainfall. Even though the dataset shows some non-normality, attempts at transforming the data to correct this did not markedly improve the predictions, so the simple linear relationship was used. Because the rainfall data in this paper is being used to show when rainfall events occurred and when higher streamflow could be anticipated, this shouldn't matter.

Meyer (unpublished) cites rainfall of the Warra LTER site in 2001 at 1335 mm with median rainfall of 41.5 mm per fortnight. Meyer (2002) explains that the origin of this rainfall estimate is the stand gauge that was near Warra Creek, which was checked on a fortnightly basis. This is approximately 600 mm lower than the amount estimated by this method. The difference is possibly due to the rain gauge being at a lower altitude than the automatic weather station. Correlation cannot be drawn between the two sites as they did not coexist.

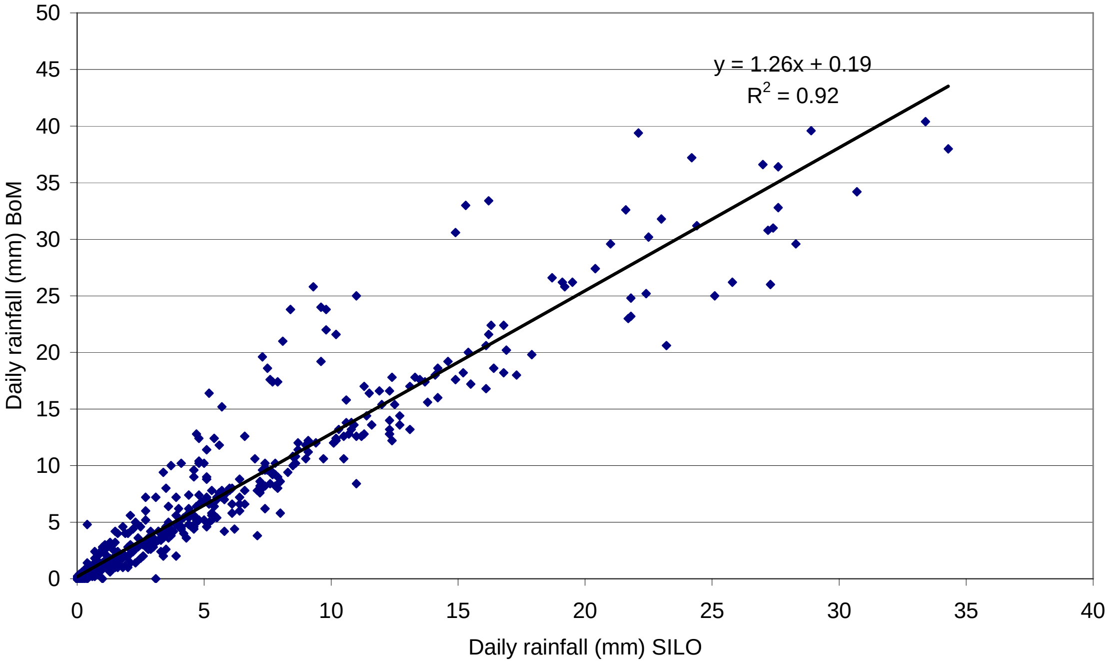

Figure A2. Scatter plot of SILO and BoM rainfall data

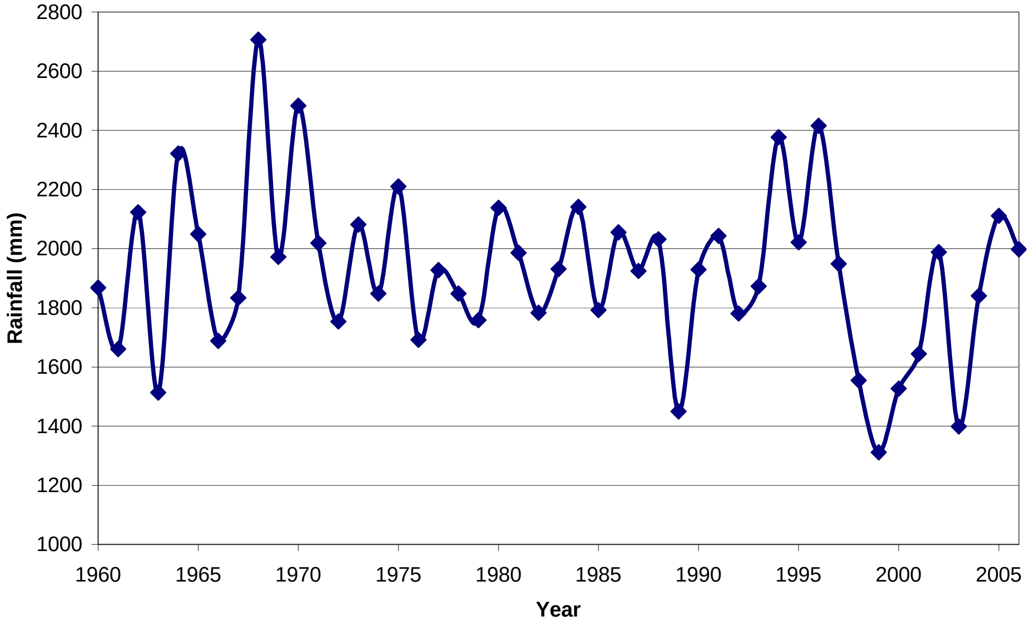

Figure A3. Annual rainfall total predicted from SILO data since 1960

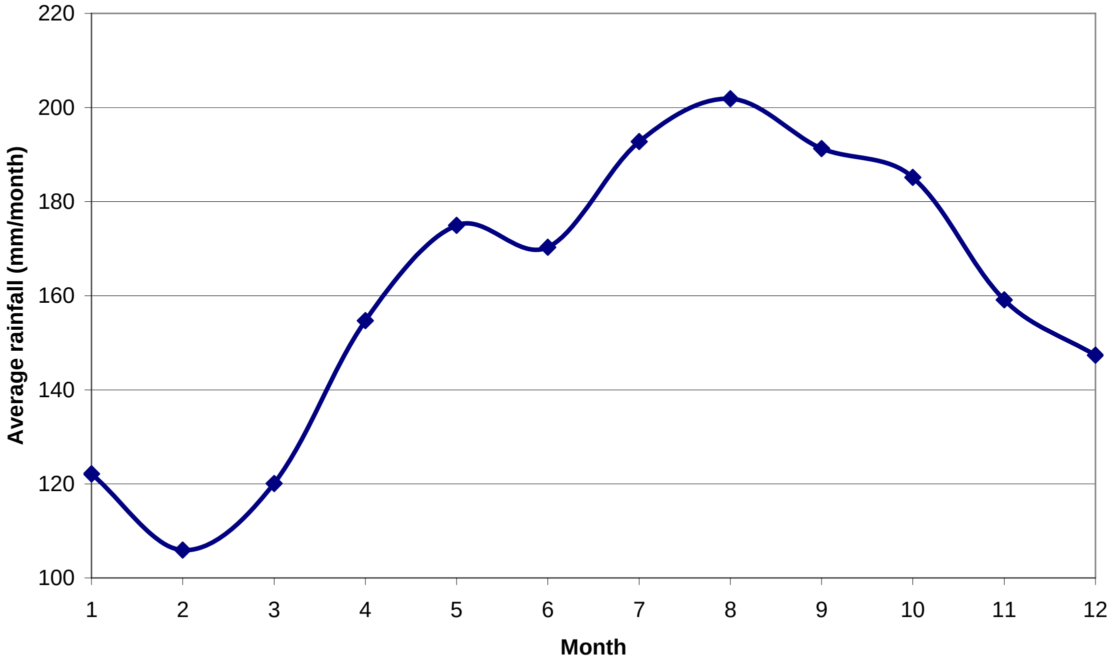

Figure A4. Mean monthly rainfall since 1960 showing seasonal variation (SILO)

Figures A3 and A4 show the annual totals since 1960 and the seasonal trend in rainfall respectively. Average annual rainfall is 1922mm, with peak rainfall typically occurring in August.

Appendix B: Water quality time series experiment—August 2007

Aim

- to assess the effect of length and temperature of storage of water samples on measured water quality parameters
- to measure the variation in water quality measurements repeated in the same samples.

Methods

a. 3 x 1 L bottles of water were collected for Warra Weir on 8/8/2007.

b. Samples were transported to FT laboratory within two hours of collection.

c. One sample was placed in the coolroom, one was kept on the laboratory bench and one was placed in the constant temperature room at 20 °C.

d. On each weekday (days 1, 2, 5, 6, 7, 8, 9, 12, 13, 14 after collection), pH, EC and NTU were measured using instruments described above; six times in each sample.

e. The pH meter was calibrated each day, the autoread function was used to give a stable reading, and between each reading the pH meter was rinsed with deionised water.

f. The EC probe was removed from the water sample between each reading.

g. The sample bottle was inverted serveral times before decanting a sample for NTU analysis. The same subsample was used for each of the six readings. Between each reading the sample bottle was removed from the meter and inverted three times and the meter recalibrated with a reference sample. The first value displayed was recorded to one decimal place.

h. After taking all measurements, the samples were returned to their designated storage conditions.

Table B1. Raw data

Sample	Date	Test	1st	2nd	3rd	4th	5th	6th	Average
Coolroom	9/08/2007	pH	4.88	4.63	4.57	4.61	4.60	4.60	4.65
Coolroom	9/08/2007	EC	35.9	35.6	35.7	35.7	35.6	35.8	35.7
Coolroom	9/08/2007	Turb	5.2	6.3	6.2	7.9	7.5	5.3	6.4
Room Temp	9/08/2007	pH	4.57	4.57	4.57	4.58	4.58	4.56	4.57
Room Temp	9/08/2007	EC	36.0	36.1	36.1	36.2	36.2	36.1	36.1
Room Temp	9/08/2007	Turb	5.2	6.3	7.6	8.2	7.1	7.2	6.9
20^{0}C	9/08/2007	pH	4.56	4.56	4.54	4.57	4.57	4.56	4.56
20^{0}C	9/08/2007	EC	36.1	36.2	36.3	36.3	36.4	36.3	36.3
20^{0}C	9/08/2007	Turb	5.3	7.1	9.8	5.4	7.8	7.6	7.2
Coolroom	10/08/2007	pH	4.6	4.61	4.64	4.61	4.67	4.57	4.62
Coolroom	10/08/2007	EC	35.7	35.8	35.9	36.1	36.0	36.1	35.9
Coolroom	10/08/2007	Turb	4.5	4.4	4.6	4.7	4.8	4.8	4.6
Room Temp	10/08/2007	pH	4.38	4.46	4.48	4.47	4.46	4.46	4.45
Room Temp	10/08/2007	EC	36.3	36.3	36.1	36.2	36.3	36.3	36.3
Room Temp	10/08/2007	Turb	4.1	4.4	4.4	4.5	4.6	4.4	4.4
20^{0}C	10/08/2007	pH	4.48	4.51	4.53	4.53	4.55	4.55	4.53
20^{0}C	10/08/2007	EC	36.4	36.4	36.3	36.4	36.4	36.4	36.4
20^{0}C	10/08/2007	Turb	4.6	5.0	4.5	4.3	4.4	4.4	4.5
Coolroom	13/08/2007	pH	4.51	4.54	4.54	4.55	4.55	4.56	4.54
Coolroom	13/08/2007	EC	35.9	36.1	36.0	35.9	36.1	36.0	36.0
Coolroom	13/08/2007	Turb	7.1	6.7	8.6	7.8	7.4	7.5	7.5
Room Temp	13/08/2007	pH	4.38	4.41	4.42	4.43	4.46	4.47	4.43
Room Temp	13/08/2007	EC	36.2	36.0	36.0	36.0	36.2	36.2	36.1
Room Temp	13/08/2007	Turb	4.4	4.1	5.2	5.4	4.6	5.1	4.8
20^{0}C	13/08/2007	pH	4.48	4.50	4.50	4.52	4.53	4.52	4.51
20^{0}C	13/08/2007	EC	36.3	36.3	36.3	36.3	36.3	36.2	36.3
20^{0}C	13/08/2007	Turb	4.3	5.3	4.7	5.4	5.0	4.9	4.9
Coolroom	14/08/2007	pH	4.48	4.51	4.51	4.53	4.54	4.53	4.52
Coolroom	14/08/2007	EC	36.9	35.9	35.9	35.9	36.0	35.9	36.1
Coolroom	14/08/2007	Turb	4.9	7.4	8.0	7.7	7.5	6.4	7.0
Room Temp	14/08/2007	pH	4.58	4.59	4.6	4.62	4.62	4.62	4.61
Room Temp	14/08/2007	EC	36.2	36.1	36.1	36.1	36.2	36.2	36.2
Room Temp	14/08/2007	Turb	7.7	10.1	7.1	8.5	9.4	8.9	8.6
20^{0}C	14/08/2007	pH	4.62	4.62	4.64	4.65	4.63	4.62	4.63
20^{0}C	14/08/2007	EC	36.2	36.4	36.5	36.4	36.3	36.3	36.4
20^{0}C	14/08/2007	Turb	7.2	8.6	8.1	7.3	9.2	7.2	7.9
Coolroom	15/08/2007	pH	4.62	4.64	4.65	4.63	4.62	4.65	4.64
Coolroom	15/08/2007	EC	35.5	35.8	35.8	35.8	35.9	35.8	35.8
Coolroom	15/08/2007	Turb	5.6	4.8	4.9	4.9	4.6	4.4	4.9
Room Temp	15/08/2007	pH	4.38	4.47	4.54	4.56	4.56	4.58	4.52
Room Temp	15/08/2007	EC	36.1	36.0	36.0	36.1	36.0	36.0	36.0
Room Temp	15/08/2007	Turb	4.1	4.3	5.2	5.2	4.7	5.0	4.8
20^{0}C	15/08/2007	pH	4.59	4.64	4.61	4.63	4.65	4.64	4.63
20^{0}C	15/08/2007	EC	36.0	36.1	36.2	36.0	36.2	36.2	36.1
20^{0}C	15/08/2007	Turb	6.5	4.8	6.3	4.7	5.2	5.8	5.6
Coolroom	16/08/2007	pH	4.62	4.60	4.59	4.63	4.60	4.61	4.61
Coolroom	16/08/2007	EC	35.6	35.8	35.6	35.6	35.8	35.8	35.7
Coolroom	16/08/2007	Turb	4.6	5.1	4.8	5.0	4.4	4.2	4.7
Room Temp	16/08/2007	pH	4.42	4.50	4.52	4.53	4.54	4.55	4.51
Room Temp	16/08/2007	EC	35.9	35.9	35.8	35.9	35.9	36.0	35.9
Room Temp	16/08/2007	Turb	4.6	5.1	4.9	5.2	4.8	4.8	4.9
20^{0}C	16/08/2007	pH	4.57	4.57	4.57	4.59	4.63	4.62	4.59
20^{0}C	16/08/2007	EC	36.1	36.1	36.1	36.1	36.1	36.1	36.1
20^{0}C	16/08/2007	Turb	4.0	4.3	3.7	3.7	3.7	3.9	3.9
Coolroom	17/08/2007	pH	4.68	4.63	4.67	4.71	4.68	4.70	4.68
Coolroom	17/08/2007	EC	35.9	35.9	35.7	35.8	35.8	35.8	35.8
Coolroom	17/08/2007	Turb	5.3	4.6	4.2	4.5	4.4	4.6	4.6
Room Temp	17/08/2007	pH	4.73	4.63	4.60	4.60	4.63	4.70	4.65
Room Temp	17/08/2007	EC	36.0	35.9	36.0	36.0	36.0	36.0	36.0
Room Temp	17/08/2007	Turb	4.5	4.9	4.7	4.8	4.9	5.4	4.9
20^{0}C	17/08/2007	pH	4.66	4.63	4.68	4.64	4.65	4.71	4.66
20^{0}C	17/08/2007	EC	36.0	36.1	36.0	36.0	36.0	36.0	36.0
20^{0}C	17/08/2007	Turb	5.1	5.2	4.9	4.5	4.5	5.2	4.9
Coolroom	20/08/2007	pH	4.63	4.64	4.63	4.59	4.63	4.64	4.63
Coolroom	20/08/2007	EC	35.7	35.7	35.7	35.8	35.7	35.5	35.7

S-plus analysis of variance, two-way model with replicates was used to identify significant interactions between water quality, storage method and the date of analysis.

Table B2. Turbidity Analysis of Variance

	Df	Sum Sq	Mean Sq	F Value	Pr(F)
Storage	2	0.1663	0.08313	0.16603	0.8472
Date	7	179.64	25.66	51.25	0
Storage.Date	14	50.27	3.59	7.17	0
Residuals	120	60.08	0.5		

Table B3. PH Analysis of Variance

	Df	Sum Sq	Mean Sq	F Value	Pr(F)
Storage	2	0.098	0.049	27.63	$1.34 * 10^{-10}$
Date	7	0.39	0.055	31.48	0
Storage.Date	14	0.1887	0.0134	7.59	$3.24 * 10^{-11}$
Residuals	120	0.21	0.0017		

Table B4. EC Analysis of Variance

	Df	Sum Sq	Mean Sq	F Value	Pr(F)
Storage	2	3.022	1.511	104.83	0
Date	7	2.17	0.31	21.53	0
Storage.Date	14	0.39	0.028	1.95	0.027
Residuals	120	1.73	0.014		

Did the method of storage affect the results?

Low *p* values indicate a significant difference for pH and EC measurements from samples stored in different locations; however, turbidity was not significantly different based on storage location. This may be a function of the greater variation in measurement of turbidity than of the other parameters. Differences in values were very small relative to precision of instruments.

Did the date of the measurement affect the result?

Yes, for all parameters there were some significant differences in measurements made at different times.

Table B5. Average EC, Turbidity and pH by storage location and time

Sample	Date	Test	Average	StDev
Coolroom	9/08/2007	EC	35.72	0.12
Room Tem	9/08/2007	EC	36.12	0.08
20^{0}C	9/08/2007	EC	36.27	0.10
Coolroom	10/08/2007	EC	35.93	0.16
Room Tem	10/08/2007	EC	36.25	0.08
20^{0}C	10/08/2007	EC	36.38	0.04
Coolroom	13/08/2007	EC	36.00	0.09
Room Tem	13/08/2007	EC	36.10	0.11
20^{0}C	13/08/2007	EC	36.28	0.04
Coolroom	14/08/2007	EC	36.08	0.40
Room Tem	14/08/2007	EC	36.15	0.05
20^{0}C	14/08/2007	EC	36.35	0.10
Coolroom	15/08/2007	EC	35.77	0.14
Room Tem	15/08/2007	EC	36.03	0.05
20^{0}C	15/08/2007	EC	36.12	0.10
Coolroom	16/08/2007	EC	35.70	0.11
Room Tem	16/08/2007	EC	35.90	0.06
20^{0}C	16/08/2007	EC	36.10	0.00
Coolroom	17/08/2007	EC	35.82	0.08
Room Tem	17/08/2007	EC	35.98	0.04
20^{0}C	17/08/2007	EC	36.02	0.04
Coolroom	20/08/2007	EC	35.68	0.10
Room Tem	20/08/2007	EC	35.88	0.13
20^{0}C	20/08/2007	EC	36.00	0.00
Coolroom	9/08/2007	pH	4.65	0.12
Room Tem	9/08/2007	pH	4.57	0.01
20^{0}C	9/08/2007	pH	4.56	0.01
Coolroom	10/08/2007	pH	4.62	0.03
Room Tem	10/08/2007	pH	4.45	0.04
20^{0}C	10/08/2007	pH	4.53	0.03
Coolroom	13/08/2007	pH	4.54	0.02
Room Tem	13/08/2007	pH	4.43	0.03
20^{0}C	13/08/2007	pH	4.51	0.02
Coolroom	14/08/2007	pH	4.52	0.02
Room Tem	14/08/2007	pH	4.61	0.02
20^{0}C	14/08/2007	pH	4.63	0.01
Coolroom	15/08/2007	pH	4.64	0.01
Room Tem	15/08/2007	pH	4.52	0.08
20^{0}C	15/08/2007	pH	4.63	0.02
Coolroom	16/08/2007	pH	4.61	0.01
Room Tem	16/08/2007	pH	4.51	0.05
20^{0}C	16/08/2007	pH	4.59	0.03
Coolroom	17/08/2007	pH	4.68	0.03
Room Tem	17/08/2007	pH	4.65	0.05
20^{0}C	17/08/2007	pH	4.66	0.03
Coolroom	20/08/2007	pH	4.63	0.02
Room Tem	20/08/2007	pH	4.66	0.09
20^{0}C	20/08/2007	pH	4.66	0.02
Coolroom	9/08/2007	Turb	6.40	1.11
Room Tem	9/08/2007	Turb	6.93	1.05
20^{0}C	9/08/2007	Turb	7.17	1.68
Coolroom	10/08/2007	Turb	4.63	0.16
Room Tem	10/08/2007	Turb	4.40	0.17
20^{0}C	10/08/2007	Turb	4.53	0.25
Coolroom	13/08/2007	Turb	7.52	0.65
Room Tem	13/08/2007	Turb	4.80	0.51
20^{0}C	13/08/2007	Turb	4.93	0.40
Coolroom	14/08/2007	Turb	6.98	1.15
Room Tem	14/08/2007	Turb	8.62	1.10
20^{0}C	14/08/2007	Turb	7.93	0.84
Coolroom	15/08/2007	Turb	4.87	0.41
Room Tem	15/08/2007	Turb	4.75	0.47
20^{0}C	15/08/2007	Turb	5.55	0.77
Coolroom	16/08/2007	Turb	4.68	0.35
Room Tem	16/08/2007	Turb	4.90	0.22
20^{0}C	16/08/2007	Turb	3.88	0.24
Coolroom	17/08/2007	Turb	4.60	0.37
Room Tem	17/08/2007	Turb	4.87	0.30
20^{0}C	17/08/2007	Turb	4.90	0.33
Coolroom	20/08/2007	Turb	5.17	0.48
Room Tem	20/08/2007	Turb	5.78	0.40
20^{0}C	20/08/2007	Turb	6.60	0.84

How variable were measurements made for the same sample on the same day?

The experiment showed that there is considerable instability in the measurement of turbidity. Table B5 lists the mean value (taken from six readings) and standard deviation for each of the water quality parameters, from each storage location on each date. Mean turbidity measurements ranged from 3.88 to 8.62 NTU depending on sample storage location and date, with standard deviation in the range of 0.22 to 1.15 NTU. This creates doubt in the ability of the DRT-15CE to reliably measure NTU.

EC and pH analytical results were more consistent. Average EC ranged from 35.7 to 36.38 us/cm with standard deviation in the range of 0 to 0.4 us/cm. Average pH ranged from 4.43 to 4.68 with standard deviation of between 0.01 and 0.12.

Repeatability was assessed for each parameter/storage/date. By taking the difference between the mean of the six readings and the actual readings (square and square root to make all differences positive) the average difference was calculated, then divided by the mean value for the parameter/storage/date and multiplied by 100 to give a percentage. The average repeatability of EC is 0.19%, pH is 0.52% and NTU 7.52% although for individual repeated samples they ranged from 0 to 0.27 for EC, 0.12 to 1.66 for pH and 2.27 to 17.21 for NTU. If the NTU sensor was tested by the manufacturer using Formazin or similar solution rather than water samples with particles of variable size/levels of mobility, air bubbles, colour due to tannins, etcetera, this may explain the difference.

Are there any recommendations for storage or measurement of future samples?

It appears that storage temperature and length of storage can affect water quality parameters of NTU, EC, pH but not in any predictable way. It also appears that measuring turbidity with the DRT–15CE is problematic and that repeatability under the conditions of the Forestry Tasmania laboratory is less than the advertised 1% of reading. Storage should be kept to a minimum and, in order to be consistent with other laboratories, be kept to less than two days, with samples stored in the coolroom.