Analysis of Suspended Sediment Data from Upper Lee River, Nelson

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Executive Summary

Tasman District Council (TDC) has been monitoring water turbidity and suspended sediment concentration at a site draining 65 km^2 of the native-forested Upper Lee River catchment in the Richmond Range, Nelson, since April 2008. The main objectives of this monitoring are to assess water clarity and potential sedimentation rates in a proposed reservoir. This report analyses the data collected and determines the annual average sediment load expected at the monitoring site.

The analysis approach included calibrating the turbidity record to a record of cross-section mean suspended sediment concentration using sediment samples collected with an auto-sampler and with a depth-integrating sampler. A good relationship was found between event sediment yield and event peak discharge, and this was used to estimate the average suspended sediment yield over the 2.2 year duration of flow record (April 2007 – August 2009). The sediment yield over this period was approximately 2900 t/y (45 t/km^2/y). By comparison with the longer flow record from the adjacent Wairoa catchment, this figure is considered to be representative of the average sediment yield over the past two decades. The Upper Lee sediment yield per unit catchment area is 3-7.5 times less than that from the adjacent Wairoa and Pelorus catchments.

1. Introduction

The Lee River drains the northwest-facing slopes of the Richmond Range, south of Nelson City (Figure 1). The catchment is steep. The upper part lies within the DOC Estate and is native forest. The lower part is exotic forest. A water storage dam is proposed for the upper catchment.

Figure 1: **The Lee River catchment in southeast Nelson. Red circle locates the sediment monitoring site on Upper Lee River. Blue and green circles show past sediment monitoring sites on Wairoa and Pelorus Rivers, respectively.**

Since April 2008, Tasman District Council (TDC) has been monitoring water turbidity and suspended sediment at a site on the Upper Lee River at the approximate location of the proposed dam (Figure 1). The main objectives of this monitoring are to assess water clarity and potential sedimentation rates in the proposed reservoir.

This report responds to a brief from TDC to analyse these data and determine the annual average sediment load expected at the monitoring site. The investigation has been funded by an Envirolink Small Grant (Grant Number 758-TSDC55).

2. Data

Data collected at the monitoring site (site number 57536, catchment area 65 km^2) includes stage and water discharge, turbidity, auto-sampled total suspended solids (TSS) concentration, and manually gauged cross-section mean suspended sediment concentration.

Stage is measured with a 0-5m pressure transducer and recorded via an Aquitel telemetry interface. The stage-discharge rating is considered to be good (Tom Kennedy, TDC, 1 September 2009, pers. comm.). Inspection of flow gauging and rating data confirmed this: a stable rating has been maintained since December 2006, and the highest gauged flow (168 m^3/s) is sufficiently close to the highest flow on record (235 m^3/s) that extrapolation over the intervening flow range can be made with some confidence. The automated stage record began on 20 April 2007, and for this study flow data have been analysed up to 17 August 2009. There are no gaps in the stage record for this period.

Turbidity is monitored at 15 minute intervals with a Greenspan SDI-12 turbidity probe. The probe is exposed to the air at low flows, so data from low flow periods is coded with a “-1” value. The turbidity data commenced on 15 April 2008 and (for this study) extended to 27 July 2009.

During periods of high flow (greater than 20 m^3/s), discrete water samples were collected using a Manning auto-sampler. The samples were scheduled on a flow-weighted basis (i.e., more samples as the flow increased). The samples were analysed for TSS by the Cawthron Institute. Ad hoc turbidity measurements were also made of the auto-samples in the Cawthron laboratory. This was done to check for drift in the field sensor.

Multi-vertical, depth-integrated samples were collected during many of the high flow events in order to measure the cross-section average discharge-weighted suspended sediment concentration (SSC). This used a D-49 sediment bomb from the bridge located approximately 500 m upstream from the recorder site. Four to five verticals were sampled across the river at various times on the rising and falling stages of runoff events. Each group of 4-5 samples took about 5-10 minutes to collect so their weighted mean represents the concentration for the average flow during the sampling interval.

3. Analysis methods

3.1. Analysis approach

The analysis involved four tasks:

- Checking and adjusting the field turbidity record
- Deriving calibration relationships between turbidity and auto-sampled SSC, auto-sampled and cross-section average SSC, and auto-sampled SSC and water discharge
- Calculating and checking event sediment yields
- Deriving a relationship between event sediment yield and event peak discharge
- Calculating the average annual sediment yield for the period of flow record.

3.2. Checking and adjusting field turbidity data

Turbidity sensors sometimes drift (due to instrument ageing) and often the lens fouls with algal growth or a combination of organic material and sediment (grime). The former tends to occur slowly with time, while the latter tends to occur over a few weeks, particularly in the warmer summer months. Often, a flood or fresh will wash the lens clean again.

Sensor drift was checked for by comparing the field and laboratory turbidity data. The regression relation on Figure 2a, $F = 0.394\ L + 10.3$ (where F is field turbidity and L is lab turbidity) shows that the lab turbidity was roughly 2.5 times the field turbidity. Such a difference is not unusual – it occurs because the two instruments measure different things and, besides, the field sensor may not have been calibrated against Formazin as robustly as the lab sensor should have been. Drift was checked by normalising the field turbidity to the lab equivalent L_f (where $L_f = (F – 10.3)/0.394$) and then looking for a time-trend in the ratio of L_f and L. As shown in Figure 2b, while varying, no significant time trend was apparent in this ratio. Thus I conclude no significant drift occurred in the field sensor.

Fouling was checked by inspecting the record and looking for relatively sudden ramps in the ‘baseflow’ turbidity. Where this was detected, the raw turbidity record was ramp-adjusted so that the baseflow turbidity remained approximately constant over the record period. The main adjustment (up to 9 NTU) was required from late August through to late November (Figure 3). The adjusted turbidity record was subsequently used for the rest of the analysis.

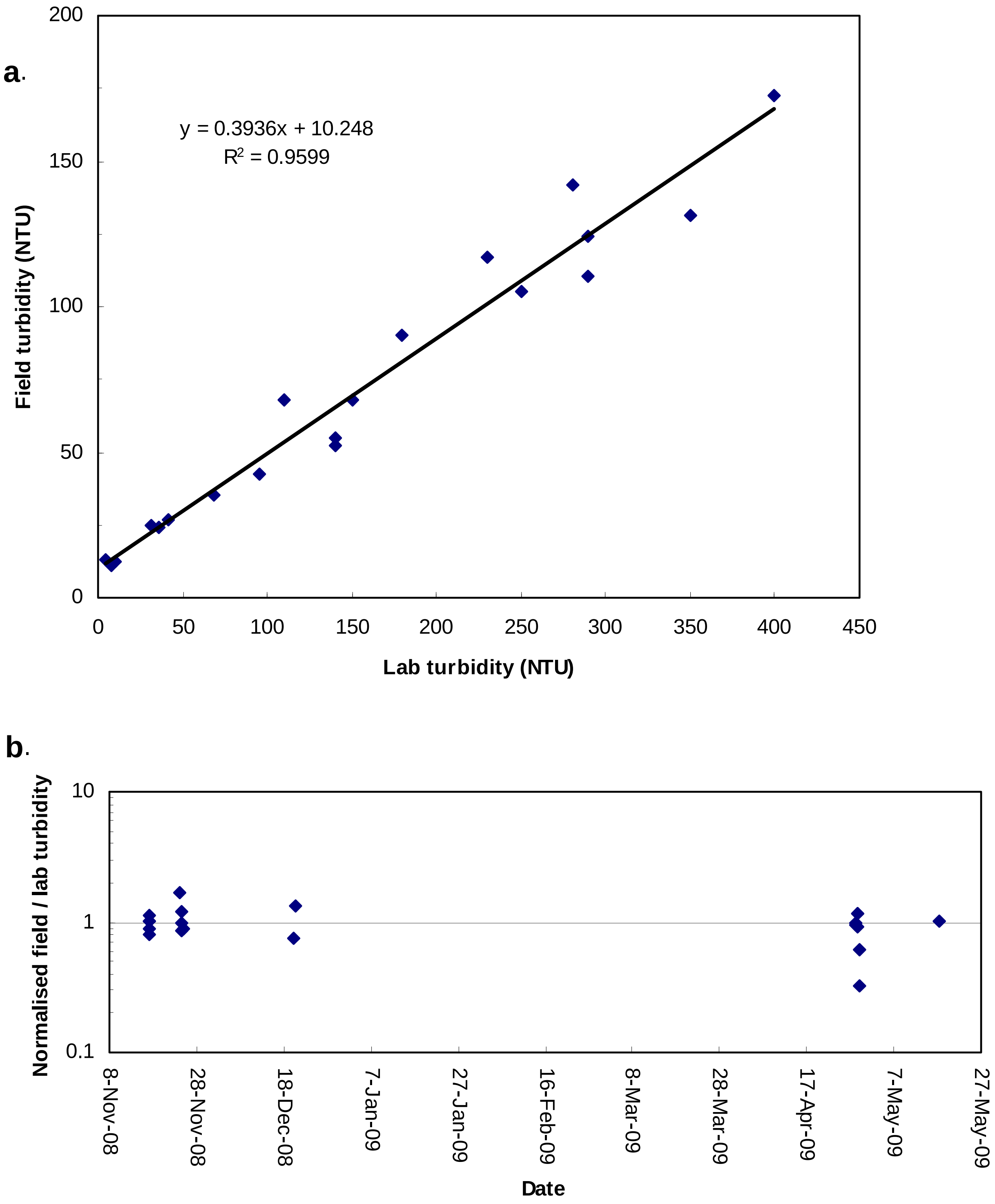

Figure 2: **a. Relationship between field and laboratory turbidity sensor values. b. Variation with time in the ratio normalised field turbidity / laboratory turbidity.**

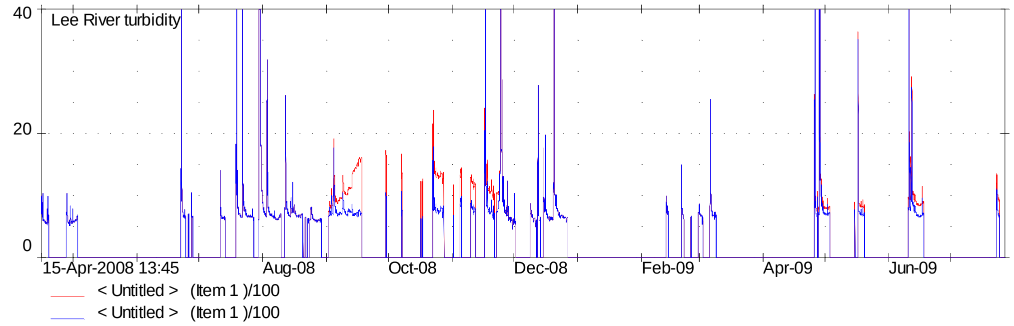

Figure 3: **Raw (red) and adjusted (blue) turbidity record. Raw and adjusted records coincide where only a blue line appears. Vertical scale truncated at 40 NTU to highlight NTU at base flow. Turbidity falls below zero whenever sensor is not immersed in water. Note ramping in raw record due to fouling from late August.**

3.3. Calibration relationships

The relationships between (adjusted) turbidity and auto-sampled SSC and between auto-sampled and cross-section average SSC were linear and so these were determined using linear regression. Time trends in the relationship were checked by plotting the ratio of observed/predicted SSC against sampling time. No significant time trends were found.

The relationship between instantaneous SSC and water discharge was based on a dataset pooled from the auto-sampled data (corrected to cross-section average values) and the manual, depth-integrated samples. This relationship appeared non-linear and showed wide data scatter, thus it was quantified using LOWESS (Locally Weighted Scatterplot Smoothing, Cleveland 1979). The data were first transformed to log values, and the LOWESS curve was fitted using a stiffness factor of 0.33 (i.e., the curve was fitted to a moving window containing one third of the data). The LOWESS curve was corrected for log bias using the method of Duan (1983) using the same stiffness factor (i.e., the correction factor varied across the discharge range according to the scatter in the data). Again, this relationship was assessed for a time trend by comparing observed/predicted SSC with time. No significant trend was observed although the relationship varied within events (as discussed in Section 4.3).

3.4. Event sediment yields

Event sediment yields were calculated by first converting the adjusted turbidity record to cross-section average discharge-weighted SSC using the turbidity vs. auto-sampled and auto-sampled vs. cross-section average SSC relations. This was then integrated with the flow record. Event start and end times were determined as the onset and end of quickflow, which were found using the method of Hewlett and Hibbert (1967). An appropriate quickflow separation slope (0.20 ml/s^2/km^2) was found by inspection of the flow record.

Where permitted by the coverage of auto-samples through individual events, the turbidity-based event yield was checked against the yield integrated directly from the auto-sampled data. This was possible for three events.

The results (Table 1) were used to develop a relationship between event sediment yield and event peak water discharge. While non-linear, this relationship showed a simple power law and uniform variance in residuals, so it was suitable for fitting using linear regression of the log-transformed data. The resultant curve was corrected for log bias as above. Events with quickflows less than 1 mm carried less than 1% of the total load and were discarded from the curve-fitting.

3.5. Average annual sediment yield

Average annual suspended sediment yield was calculated for the 1.28 year period of turbidity record by (i) direct integration using the calibrated turbidity record, (ii) using the event yield vs. peak flow rating, and (iii) using the instantaneous discharge vs. SSC rating. The first is most accurate and enables a check on the accuracy of the rating-based approaches. The yield over the longer, 2.33 year period of flow record was determined using the two rating-based approaches.

4. Results

4.1. Turbidity vs. SSC relationship

The turbidity vs. auto-sampled SSC relationship is shown in Figure 4. The relationship is linear overall but shows variation between events. For example, SSC values were higher for a given turbidity for the 17 November 2008 event, while the 20 December 2008 event showed a broad hysteresis loop. Most likely, this variability relates to changes in the size grading of the sampled suspended load within and between events, with the 17 November 2008 event indicating a coarser load on average. There appears to be no consistent pattern from one event to the next, thus the regression relation from the overall dataset was used to calibrate the turbidity record to SSC.

The regression relation for the overall dataset is:

$$C_a = 3.81\ T - 22.0 \qquad (1)$$

Where C_a is auto-sampled SSC (mg/l) and T is the adjusted field turbidity (NTU). R^2 is 0.92 for this relation, the standard error of the estimate is 45 mg/l, and the standard factorial error is 1.42.

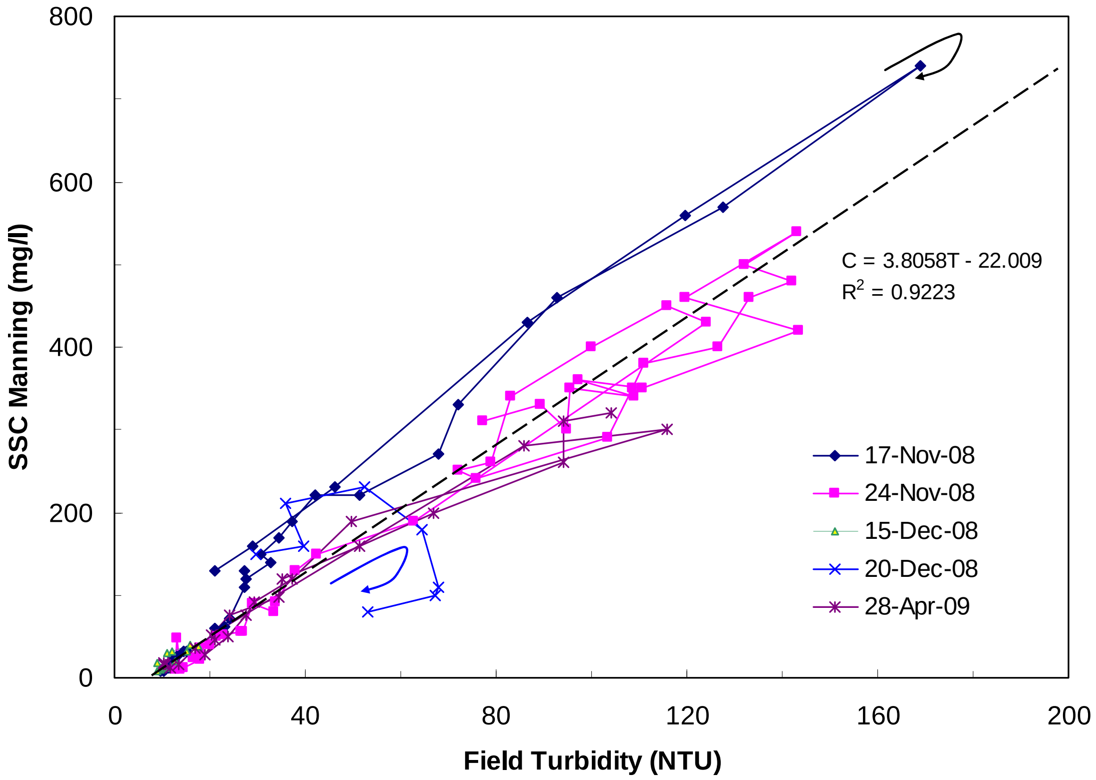

Figure 4: **Relationship between SSC sampled by manning auto-sampler and (adjusted) field turbidity. Points coloured differently for separate events. Arrows show direction of increasing time through events.**

4.2. Auto-sampled vs. gauged SSC relationship

The relationship between auto-sampled SSC (C_a) and gauged cross-section average SSC (C_g) is shown in Figure 5. The regression fit is:

$$C_g = 0.779\ C_a \qquad (2)$$

R^2 for this relation is 0.98, the standard error of the estimate is 16 mg/l, and the standard factorial error is 1.149. There was no significant relationship between the ratio C_g/C_a and C_a ($R^2 = 0.0096$) or water discharge ($R^2 = 0.028$). In the author's experience, it is less common for the gauged cross-section average SSC to be less than the auto-sampled SSC but there is nothing untoward about this result – it simply indicates that the SSC was higher at the sampler intake point than the spatial average SSC.

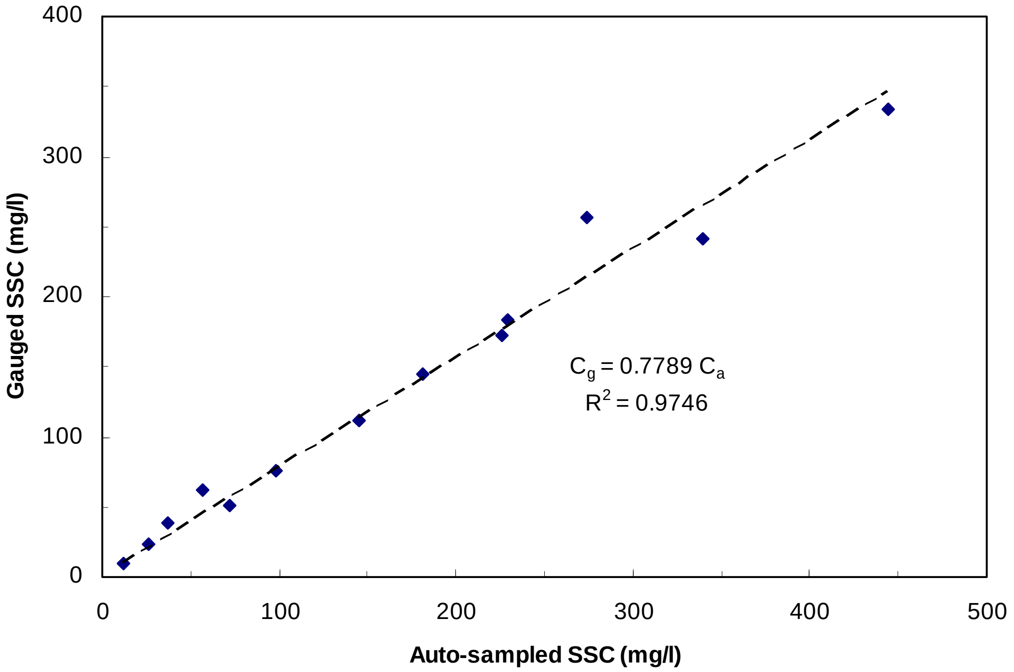

Figure 5: **Relationship between auto-sampled and gauged cross-section average SSC.**

4.3. SSC vs. water discharge relationship

The relationship between instantaneous water discharge and sampled SSC is shown in Figure 6. This shows substantial variability between events, and within events there appears to be no consistent hysteresis pattern. For example, the 20 December 2008 and 28 April 2009 events show clockwise hysteresis (indicating higher concentrations during rising stages), but the 17 November 2008 event showed anti-clockwise hysteresis and the 28 November 2008 event showed a complex pattern. This variability likely reflects varying sediment sources over time.

Because of this variability, LOWESS was used to fit a rating relation to these data. This is shown in Figure 7. The pink line shows the log-bias corrected LOWESS fit. This was approximated by the following step function (green line on Figure 7):

$$\begin{aligned}
&\text{For } Q < 42.7,\ C = 0.0319Q^{1.89}\\
&\text{For } 42.7 < Q < 62.1,\ C = 0.037Q^{1.85}\\
&\text{For } 61 < Q < 83,\ C = 0.000617Q^{2.85}\\
&\text{For } 83 < Q < 161,\ C = 10.2Q^{0.65}\\
&\text{For } Q > 161,\ C = 1.091Q^{1.088} \qquad (3)
\end{aligned}$$

where C is cross-section average SSC (mg/l) and Q is water discharge (m^3/s). The overall standard factorial error for this relation is 1.63. $R^2 = 0.97$.

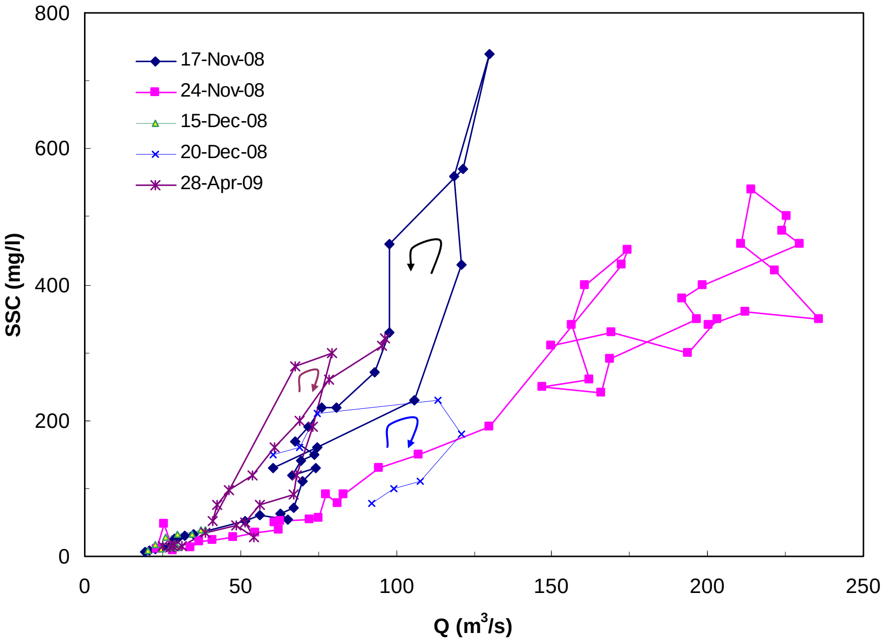

Figure 6: **Relationship between instantaneous water discharge and sampled SSC. Points coloured differently for separate events. Arrows show direction of increasing time through events.**

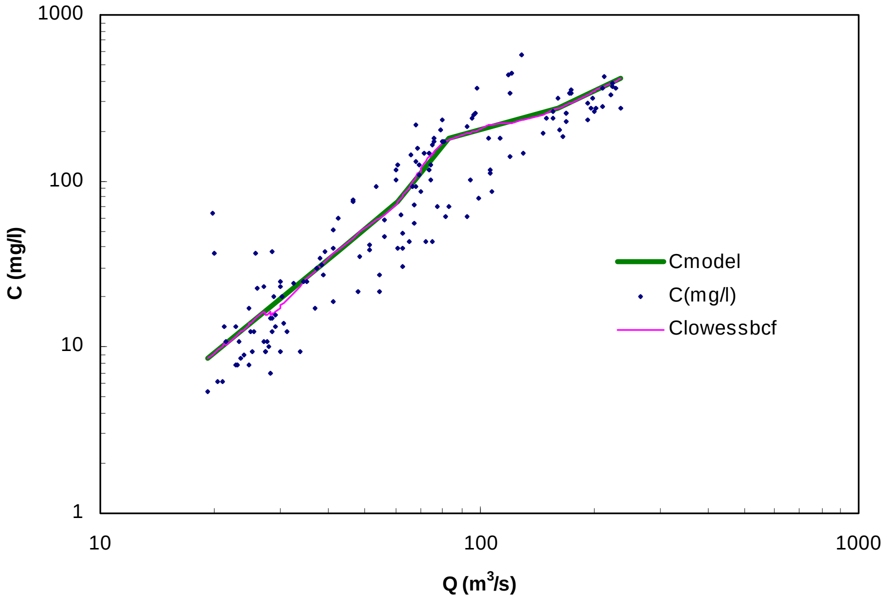

Figure 7: **Relation between instantaneous SSC and water discharge. The auto-sampled SSC values have been adjusted to cross-section average values suing equation (2). The pink line shows the log-bias-corrected LOWESS line; the green line shows the step-function model.**

4.4. Event sediment yields

The event sediment yield results, obtained by direct integration of the flow and calibrated turbidity records, are listed in Table 1. Checks were possible by directly integrating the sediment yield from the auto-sampler SSC data (corrected to cross-section mean values) for several events, as in Table 2. The results for individual events agree to within ~ 30%. The differences will relate to both the turbidity calibration and to the sparser auto-sampled record (which required linear interpolation between samples). Most importantly, the yields totalled over the three events by the two approaches differed by less than 3%.

The best event sediment yield response relationship was found to be with event peak discharge (Figure 8). The power-law regression relation (fitted to events with peak flows above 9 m^3/s because these carried 99.9% of the total sediment yield) is:

$$SSY = 0.020\, Q_p^{\,2.10} \qquad (4)$$

where SSY is event sediment yield (t), Q_p is event peak discharge (m^3/s), and the coefficient 0.020 incorporates a log-bias correction factor of 1.063 applied to the raw regression coefficient of 0.01886. $R^2 = 0.96$, and the standard factorial error is 1.42.

Table 1 shows also that the time-averaged SSC tends to be lower on event recessions, particularly for larger events.

4.5. Sediment yield over monitoring period

The sediment yield over the 1.28 year turbidity monitoring period was calculated in three ways: by integration of the calibrated turbidity record (Direct method), by application of equation (3) to the flow record (Sediment Rating method), and by application of equation (4) to the flow record (Event Yield Rating method). The Direct method is the most accurate and serves as a baseline for assessing the accuracy of the other two methods when they are applied to the full period of flow record. For the turbidity record period, the Event Yield Rating estimate agrees with the Direct estimate to within 2% (Table 3). The Sediment Rating method agrees to within 14%. Thus I regard the Event Yield rating based estimate over the full flow record (2908 t/y) as the best estimate of the annual average suspended sediment yield from the Upper Lee catchment. This equates to a specific sediment yield of 44.7 $t/km^2/y$.

Table 1: **Event sediment yields and other hydrological characteristics.**

Date start	Time start	End date	End time	Peak flow (m^3/s)	Quickflow runoff (mm)	Total runoff (mm)	Event sediment yield (t)	% on rising stage	SSC max (mg/l)	Average SSC on rising stage (mg/l)	Average SSC on falling stage (mg/l)	Event duration (hrs)	Time to flow peak (hrs)	Time to SSC peak (hrs)
20080427	102100	20080409	090900	15.9	9	14	3.47	31	14	2	2	47	16	16
20080622	82100	20080624	161500	24.3	20	26	21.23	59	116	22	5	56	13	10
20080711	45100	20080713	103900	19.0	13	19	9.46	9	24	3	4	54	6	5
20080719	42100	20080722	030300	45.5	31	42	49.78	30	107	20	7	71	7	7
20080722	55100	20080724	163300	31.4	23	41	35.35	37	183	42	7	59	6	5
20080729	233300	20080802	132700	79.8	73	92	423.48	32	199	37	30	86	17	17
20080802	182100	20080804	194500	70.2	33	52	84.79	32	77	18	12	50	11	11
20080811	192100	20080815	222700	56.0	44	70	67.63	36	60	17	7	99	12	11
20080823	235100	20080826	115700	14.2	12	27	4.96	26	7	2	2	60	19	19
20080901	215100	20080906	201500	49.0	67	102	65.82	48	35	6	7	118	70	70
20080908	125100	20080912	051500	34.5	37	71	30.45	31	14	7	5	88	18	17
20080929	150300	20080930	141500	9.9	3	5	2.40	6	14	1	7	23	5	9
20081007	63300	20081008	013300	4.0	1	3	0.52	9	14	1	3	19	6	7
20081022	120300	20081025	224500	24.7	21	37	21.52	27	35	8	6	83	16	15
20081104	173300	20081105	195100	7.4	3	6	2.55	9	12	2	8	26	6	25
20081110	22100	20081111	180300	14.0	9	15	6.74	28	10	5	6	40	9	11
20081116	232100	20081119	143300	128.1	49	60	318.69	37	455	51	16	63	6	6

Date start	Time start	End date	End time	Peak flow (m^3/s)	Quickflow runoff (mm)	Total runoff (mm)	Event sediment yield (t)	% on rising stage	SSC max (mg/l)	Average SSC on rising stage (mg/l)	Average SSC on falling stage (mg/l)	Event duration (hrs)	Time to flow peak (hrs)	Time to SSC peak (hrs)
20081123	132100	20081127	060300	235.7	144	172	1717.87	67	397	68	29	89	30	29
20081208	152100	20081210	220900	14.2	11	19	4.75	39	9	3	2	55	19	14
20081212	175100	20081213	123300	5.1	1	4	2.01	70	64	23	3	19	4	2
20081215	43900	20081218	070300	38.5	39	56	35.28	23	35	8	6	75	13	14
20081220	40300	20081223	051500	129.7	67	89	888.95	20	1942	55	45	73	10	11
20090212	210900	20090214	080300	11.3	6	9	3.54	31	12	4	5	35	10	9
20090220	40900	20090221	212100	22.5	9	13	7.88	24	27	5	5	41	7	7
20090228	85100	20090302	101500	14.1	12	18	5.52	49	9	4	4	50	21	22
20090306	22100	20090308	075100	35.5	24	32	38.51	57	58	16	7	54	12	7
20090425	232100	20090427	193900	41.9	20	23	35.95	25	403	19	10	44	5	14
20090428	3900	20090501	050900	143.1	91	108	714.45	35	439	81	29	77	8	14
20090515	73300	20090516	022100	5.5	1	3	0.46	19	6	1	2	19	5	11
20090517	30300	20090519	065100	37.9	12	19	19.73	12	83	10	8	52	4	5
20090610	45100	20090615	115700	65.2	103	130	161.33	65	153	15	7	127	52	20
20090723	75100	20090725	020900	12.5	9	12	4.90	29	16	5	4	42	8	5
						Total	**4789.95**							

Table 2: **Comparison of event sediment yields derived from turbidity and auto-sample records.**

Event	Yield from turbidity record (t)	Yield from auto-sampler record (t)
16 Nov 2008	304	399
23 Nov 2008 (rising stage only)	1126	1069
15 December 2008	21.6	16.9

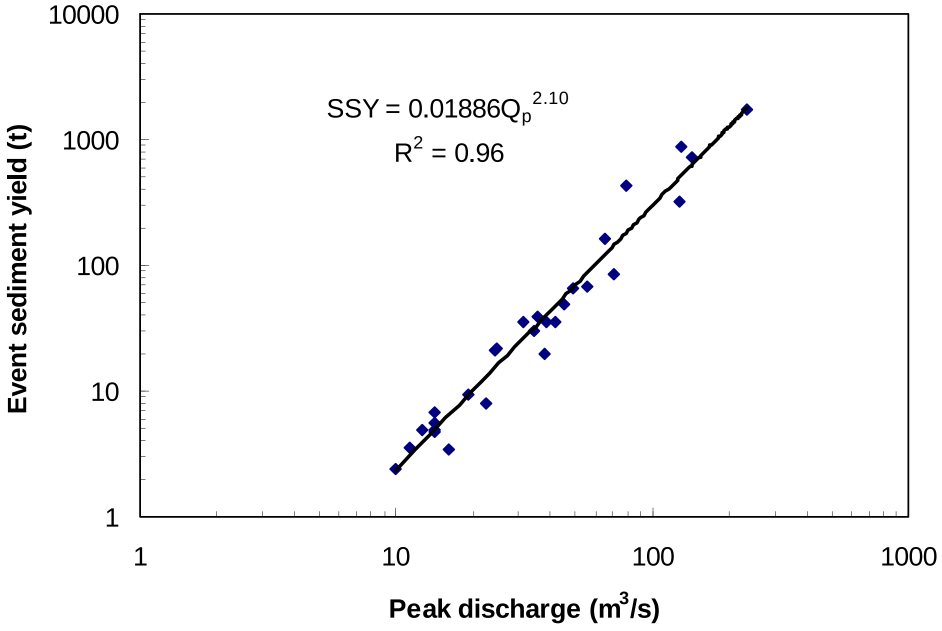

Figure 8: **Relationship between event sediment yield and event peak discharge.**

Table 3: **Sediment yields for periods of turbidity record (15 April 2008 – 27 July 2009: 1.28 years) and flow record (20 April 2007 – 17 August 2009: 2.32 years) obtained by Direct, Sediment Rating, and Event Yield Rating methods.**

Period	Direct method (t/y)	Sediment Rating method (t/y)	Event Yield Rating method (t/y)
15 April 2008 – 27 July 2009	3742	3243	3682
20 April 2007 – 17 August 2009	-	2274	2908

5. Discussion

5.1. Comparison with neighbouring catchments

It is well known that sediment yields can vary by over a factor of ten from year to year due to rainfall and runoff variability, thus the 2.32 years of record does not, on its own, provide a robust indication of the long-term average sediment yield (for example, this period may have been relatively benign in terms of floods). To evaluate this issue, the Lee River data were compared with SSC and flow data from two sites in adjacent catchments: Wairoa at Irvines and Pelorus at Bryants (Figure 1). Both of these have sediment rating data from gaugings done up to the mid 1990s, and they have flow records extending back to 1992 (Wairoa) and 1977 (Pelorus). I have previously calculated specific suspended sediment yields for the Wairoa and Pelorus River sites as 136 and 336 t/km^2/y, respectively. These are 3 and 7.5 times the estimate for the Lee (45 t/km^2/y).

Figure 9 compares the sediment rating data for the Lee, Wairoa, and Pelorus sites. The discharge has been normalised by dividing by the mean discharge (2.96, 15.56, and 19.91 m^3/s for Lee, Wairoa, and Pelorus, respectively). The Lee River clearly has lower sediment concentrations at a given normalised discharge, and the separations of the three datasets are in line with the factors of difference in yield given above.

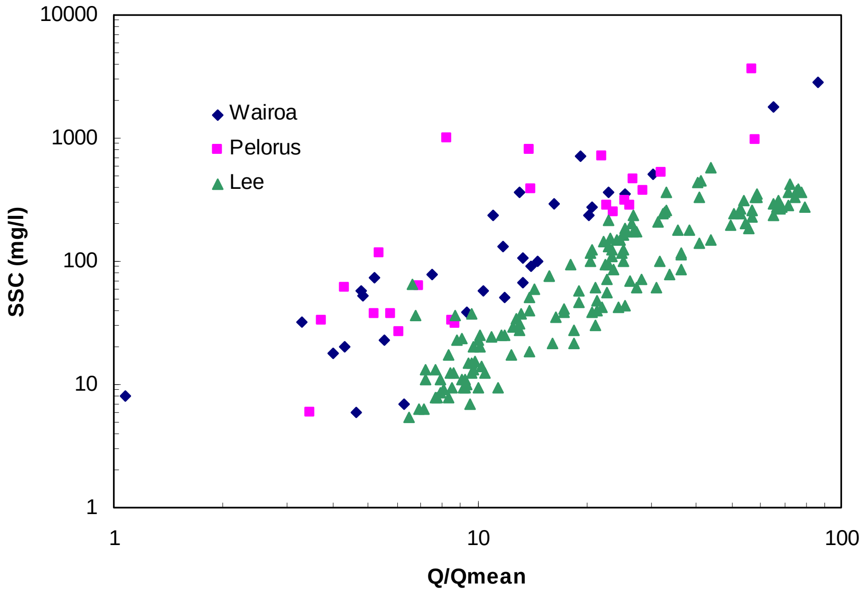

Figure 9: **Sediment rating data for the Upper Lee River, Wairoa at Irvines, and Pelorus at Bryants. Discharge has been normalised by dividing by the mean discharge.**

A sediment rating curve was fitted to the Waiora data and was used with the Wairoa flow record to estimate sediment yields averaged (i) over the full period of flow record available (31 March 1992 – 30 June 2009) and (ii) for the shorter period that overlaps with the Lee River record (20 April 2007 – 30 June 2009). This gave a specific sediment yield of 138.5 t/km^2/yr averaged over the full 17.2 years of record and 134.5 t/km^2/yr for the 2.2 year overlap period. The close agreement suggests that the period of monitoring at the Lee has been representative of the past two decades. Indeed, this is also indicated by inspection of the Wairoa at Irvines flow record (Figure 10).

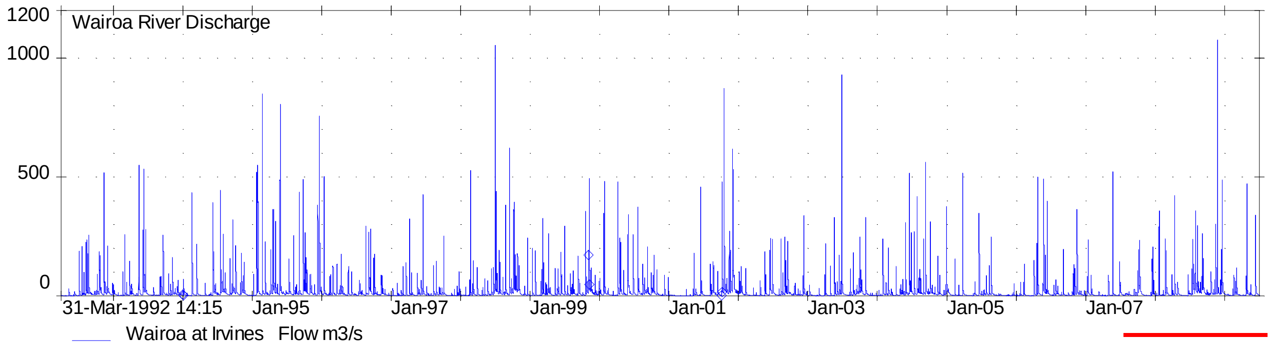

Figure 10: Flow record for Wairoa at Irvines since 1992. Red bar shows period of flow record at Upper Lee River site.

I conclude that the Upper Lee River's suspended sediment yield derived for this study (~ 2900 t/y or ~ 45 t/km^2/y) should be reasonably representative of the long-term average yield.

The most likely reason that the Upper Lee's sediment yield is lower than that of its neighbouring catchments is its cover in pristine native forest. The yields from the Wairoa and Pelorus will have been affected by landuse including exotic forestry operations.

6. Conclusions

The suspended sediment yield of the Upper Lee River catchment over the period April 2007 – August 2009 is approximately 2900 t/yr (45 t/km^2/y). This figure is considered to be representative of the average sediment yield over the past two decades.

7. Acknowledgements

It has been a pleasure to work with such a good set of data as was provided by TDC. The study was funded by an Envirolink Small Grant (Grant Number 758-TSDC55).

8. References

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