NIWA
Taihoro Nukurangi

Annual and event suspended sediment loads for the Aparima River (2015-2019)

Prepared for DairyNZ

June 2020

Prepared by:
Andrew Hughes
Manawa Huirama

For any information regarding this report please contact:

Andrew Hughes
Land-Water Scientist
Catchment Processes
+64-7-856 1794
andrew.hughes@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 11115
Hamilton 3251

Phone +64 7 856 7026

NIWA CLIENT REPORT No: 2020177HN
Report date: June 2020
NIWA Project: DNZ20203

Quality Assurance Statement		
[signature]	Reviewed by:	Neale Hudson
[signature]	Formatting checked by:	Alison Bartley
[signature]	Approved for release by:	Scott Larned

Contents

Executive summary **5**

1 Introduction **7**

2 Study site **9**

3 Methods **11**

3.1 Environment Southland data 11

3.2 Estimating suspended sediment loads 11

4 Results and discussion **13**

4.1 Turbidity and suspended sediment data 13

4.2 Annual suspended sediment loads 15

4.3 Specific suspended sediment yields 17

4.4 Monthly and event suspended sediment loads 18

4.5 Event sediment dynamics 22

5 Summary and conclusions **24**

6 Acknowledgements **25**

7 References **26**

Appendix A Flow and estimated suspended sediment concentration annual time series data 29

Appendix B Monthly suspended sediment load and runoff data **31**

Appendix C Event peak discharge and suspended sediment load data **32**

Tables

Table 4-1: Summary statistics of the two methods of two measures of suspended particulate material (TSS and SSC) 13

Table 4-2: Suspended sediment loads for the Aparima at Thornbury site (2015-2019). 16

Table 4-3: Specific sediment yields for the Aparima River catchment(2015-2019). 17

Table B-1: Monthly suspended sediment load and flow data for 2015-2019 (excluding 2017). 31

Table C-1: Event peak discharge and event suspended sediment load data for all events with a peak discharge >100 m^3/sec for 2015, 2016, 2018 and 2019. 32

Figures

Figure 2-1:	**Aparima River location and elevation map.**	10
Figure 4-1:	Field turbidity vs SSC and field turbidity vs TSS for the Aparima at Thornbury site (2015-2019).	13
Figure 4-2:	Field turbidity vs laboratory turbidity measurements from the Aparima at Thornbury site (2015-2019).	14
Figure 4-3:	Flow vs SSC for the Aparima at Thornbury site (2015-2019).	15
Figure 4-4:	Suspended sediment loads for the Aparima at Thornbury site (2015-2019).	16
Figure 4-5:	Specific suspended sediment yield of the main South Island rivers.	18
Figure 4-6:	Monthly suspended sediment loads for the Aparima River (2015-19, excluding 2017).	19
Figure 4-7:	Mean monthly rainfall at three rainfall stations within the Aparima River catchment.	19
Figure 4-8:	Total monthly flow for the Aparima River (2015-19, excluding 2017).	20
Figure 4-9:	Event discharge vs event SSL load relationship for all events with a peak greater than 100 m^3/sec for the Aparima River (2015-19, excluding 2017).	21
Figure 4-10:	The relationship flow and SSC for a selection of events from 2018.	23
Figure A-1:	Flow and estimated suspended sediment concentration data recorded at the Aparima River at Thornbury site (2015).	29
Figure A-2:	Flow and estimated suspended sediment concentration data recorded at the Aparima River at Thornbury site (2016).	29
Figure A-3:	Flow and estimated suspended sediment concentration data recorded at the Aparima River at Thornbury site (2018).	30
Figure A-4:	Flow and estimated suspended sediment concentration data recorded at the Aparima River at Thornbury site (2019).	30

Executive summary

The Jacobs River Estuary (JRE) is a large Southland estuary where large areas of poor ecological health have been identified. There is concern that sediment and nutrients derived from the agriculture-based contributing catchments are the primary driver of this estuarine degradation. As the largest inflow to the JRE, the Aparima River is potentially the major source of catchment-derived sediment and nutrients.

DairyNZ want to better understand the contaminant pressures on the ecosystem health of the JRE, in particular the potential for adverse impacts from large, episodic sediment deposition events. To this end, DairyNZ commissioned NIWA to use flow, suspended sediment data and continuous turbidity data collected by Environment Southland (ES) within the Aparima River catchment to:

- Calculate catchment annual sediment loads/yields
- Calculate event loads and determine whether there is a time of year when events transport a disproportionately high sediment load. The rationale for this is that the reduction in groundcover and soil damage caused by winter forage crop grazing has been identified as a potential significant source of catchment sediment. If land used for winter forage crops is a disproportionately significant source of sediment then the continuous turbidity record may indicate periods of increased sediment flux during the period when forage crops are grazed by cattle.

We determined annual suspended sediment loads (SSLs) using two rating curve approaches (flow vs suspended sediment concentration (SSC) and turbidity vs SSC). The turbidity vs SSC rating curve results are favoured because the relationship between SSC and turbidity is more precise than the relationship between flow and SSC. The mean annual SSL for the turbidity-SSC method was 34.6 kt/y (2015-2019, excluding 2017). The mean annual SSL for the flow-SSC method was 42.4 kt/y (2015-2019). The SSLs estimated by the two methods are similar, although the less precise flow-SSC rating curve method resulted in consistently higher loads. The mean annual SSL calculated here compare well to previously modelled mean annual SSLs. Regardless of which estimation method is used, the estimated mean annual SSL of the Aparima River is low compared to other large New Zealand catchments.

Annual SSLs give us an indication of the sediment mass delivered to the JRE; however, they are not very informative for determining the relative important of the catchment as a source of sediment. The specific sediment yield (SSY; SSL divided by catchment area) is more informative about the extent of erosion in catchment. The mean SSY for the turbidity-SSC method was 28.7 t/km^2/y (2015-2019, excluding 2017). The mean SSY for the flow-SSC method was 35.1 t/km^2/y (2015-2019). The SSYs calculated here are very low by New Zealand standards.

Suspended sediment loads were determined for events in the years 2015, 2016, 2018 and 2019 when peak event flows were greater than 100 m^3/sec. Analysis of these data indicates that flow events that occur during winter (the time when winter forage crops are grazed) do not deliver disproportionately more sediment than events that occur throughout the rest of year. Although this observation appears inconsistent with the findings of previous small-scale studies that demonstrated elevated sediment loads from grazed winter forage crop land, several reasons help explain the findings:

i. The relatively small proportion of the catchment (5%) in winter forage crops is probably an important explanatory factor. The increased yield of sediment from forage crops (if

any), is indistinguishable from the larger sediment load derived from the rest of the catchment (the other 95% of land area).

ii. The deposition and storage (temporary or permanent) of eroded sediment within hillslopes, floodplains or within the river channel is also a feasible explanation. This is partly validated by the behaviour of SSC vs flow during discrete events.

Analysis of the SSC-flow relationship can provide information on the spatial distribution of major sediment sources within catchments. The SSC-flow relationships for events from the Aparima River show that all events exhibit a clock-wise hysteresis loop. This is interpreted to mean that the main source of sediment are near or within the river channel (e.g., bank erosion). The persistence of clock-wise hysteresis throughout the year also suggests that there is no switching of sources during the winter forage crop grazing period.

The SSY of the Aparima River is low by New Zealand standards and there is no evidence within the data presented here of a marked increased flux of suspended sediment during the winter forage crop grazing period. However, this does not mean that winter forage crop grazing does not generate more sediment than grazed pasture. The detection of the input of small areas of locally high suspended sediment at the catchment-scale is difficult. Winter forage crop grazing significantly reduces groundcover and damages soil structure during a time of the year when soils are saturated. It is likely that winter forage crops that are adjacent to stream channels, have convergent flow pathways and/or are situated on steeper terrain will be locally important areas of elevated sediment delivery. Improved land management practices will help reduce sediment loss and delivery to the river system. Further field-based studies are required to identify these areas and measure the actual delivery of sediment from them.

1 Introduction

Many of the estuaries within the Southland Region have been identified as having poor ecological health (e.g. Townsend and Lohrer 2015; Robertson, B.M., Stevens et al. 2017; Zeldis, Measures et al. 2019). Eutrophication, through the increased delivery of catchment-derived nutrients (mainly nitrogen and phosphorus), and the deposition of fine sediment are identified as being the principal causes of their poor condition (Robertson, B.M., Stevens et al. 2017). There is some evidence that the eutrophic zones in these estuaries have been expanding over the last 15-20 years (Robertson, B.M., Stevens et al. 2017). This worsening condition has been attributed to the expansion and intensification of agricultural land uses in the contributing catchments.

The Jacobs River Estuary (JRE) is one of the large Southland estuaries that has been identified as having large areas of poor ecological health. Ongoing monitoring is showing that its ecological health continues to degrade (e.g. Robertson, B. and Stevens 2013; Robertson, B.M., Stevens et al. 2017; Stevens 2018). The main riverine inputs into the JRE are the Aparima and Pourakino rivers. The catchment of the Aparima River, at 1320 km^2, is over five times larger than the catchment of the Pourakino River (247 km^2). Land cover in the Aparima catchment is predominantly high producing grassland, while land cover in the Pourakino catchment is predominantly native forest. It is therefore highly likely that the Aparima River is the single largest contributor of sediment and nutrients to the JRE. This is supported by CLUES modelling that predicts that the Aparima River accounts for 85% of the suspended sediment load (SSL) entering the JRE (Stevens 2018).

Dairy farming is an important land use within the Aparima River catchment. Because dairy farming generally takes place on low elevation, low gradient land, the suspended sediment yields from dairy-dominated catchments tend to be low (McDowell, R.W. and Wilcock 2008). However, there is concern that winter forage crops (on both dairy and dry-stock farms) may be a major source of catchment sediment (and nutrients). The use of winter forage crops as a supplementary feed supply is common in Southland due to limited pasture growth over the winter months (McDowell, R. W. 2006). Common winter crops in Southland include brassica, such as kale, swedes, and turnips. During the winter months, animals are placed in paddocks where forage crops have been grown (which usually results in almost complete removal of the groundcover). Cattle treading on bare ground during a time when the soil is likely to be saturated often results in extensive soil damage (McDowell, R. W. 2006). A number of small-scale New Zealand studies have demonstrated that grazed winter forage crop land produces significantly more sediment and nutrients than grazed pasture land (e.g. McDowell, R. W., Drewry et al. 2003; McDowell, R. W. 2006; Monaghan, Wilcock et al. 2007).

To date, most research related to the JRE has focussed on the estuarine ecological health with little work being carried out on quantifying the inputs of sediment and nutrients from the contributing catchments. Estimates of total nitrogen, total phosphorus, and suspended sediment loads delivered from the catchments are available from CLUES modelling. However, there is a need to validate these load estimates using field measurements (Robertson et al. 2017).

DairyNZ want to better understand the contaminant pressures on the ecosystem health of the JRE, in particular the potential for adverse impacts from large, episodic sediment deposition events. To this end, DairyNZ commissioned NIWA to use suspended sediment data and continuous turbidity data collected by Environment Southland (ES) within the Aparima River catchment to:

- Calculate catchment annual sediment loads and yields

- Calculate event loads and determine whether there is a time of year when events transport a disproportionately high sediment load.
  - The rationale for this is that the reduction in groundcover and soil damage caused by winter forage crop grazing has been identified as a potential significant source of catchment sediment. If land used for winter forage crops is a disproportionately significant source of sediment then the continuous turbidity record may indicate periods of increased sediment flux during the period when forage crops are grazed by cattle
  - For the purpose of this study, winter is considered to cover the period June, July and August annually.

We summarise the results of these assessments in the report, which has been structured as follows:

- Section 2 describes key features of the Aparima River catchment relevant to this work.
- Section 3 describes the methods used.
- The results of the assessment are reported and discussed in Section 4, and
- We summarise our findings in Section 5.

2 Study site

The Aparima River catchment, at 1320 km^2 in area, is the fourth largest catchment in Southland. The headwaters of the river are within the Takitimu mountains and the river flows south for over 100 km before entering the Jacob's River Estuary, which then enters the Foveaux Strait, at Riverton. Although the headwaters of the Aparima River are steep and rise to over 1600 m in elevation, much of the catchment is relatively flat and low lying (Figure 2-1).

The Land Cover Database Base 4 (LCDB4) indicates the catchment is dominated by pasture-based land uses, with high producing exotic grassland making up around 58% of the catchment. Indigenous forest (11%) and exotic plantations (10%) are the next two largest land uses by extent. The forested areas tend to be in the steeper, higher elevations areas on the margins of the catchment.

Data supplied by Environment Southland (ES) indicate that during 2017, approximately 7000 ha were planted in winter forage crops, comprising around 5% of the total catchment area. However, winter forage crops in Southland are not necessarily planted in the same paddocks every year, therefore the actual location of cropping and total area in forage crops is likely to vary from year to year.

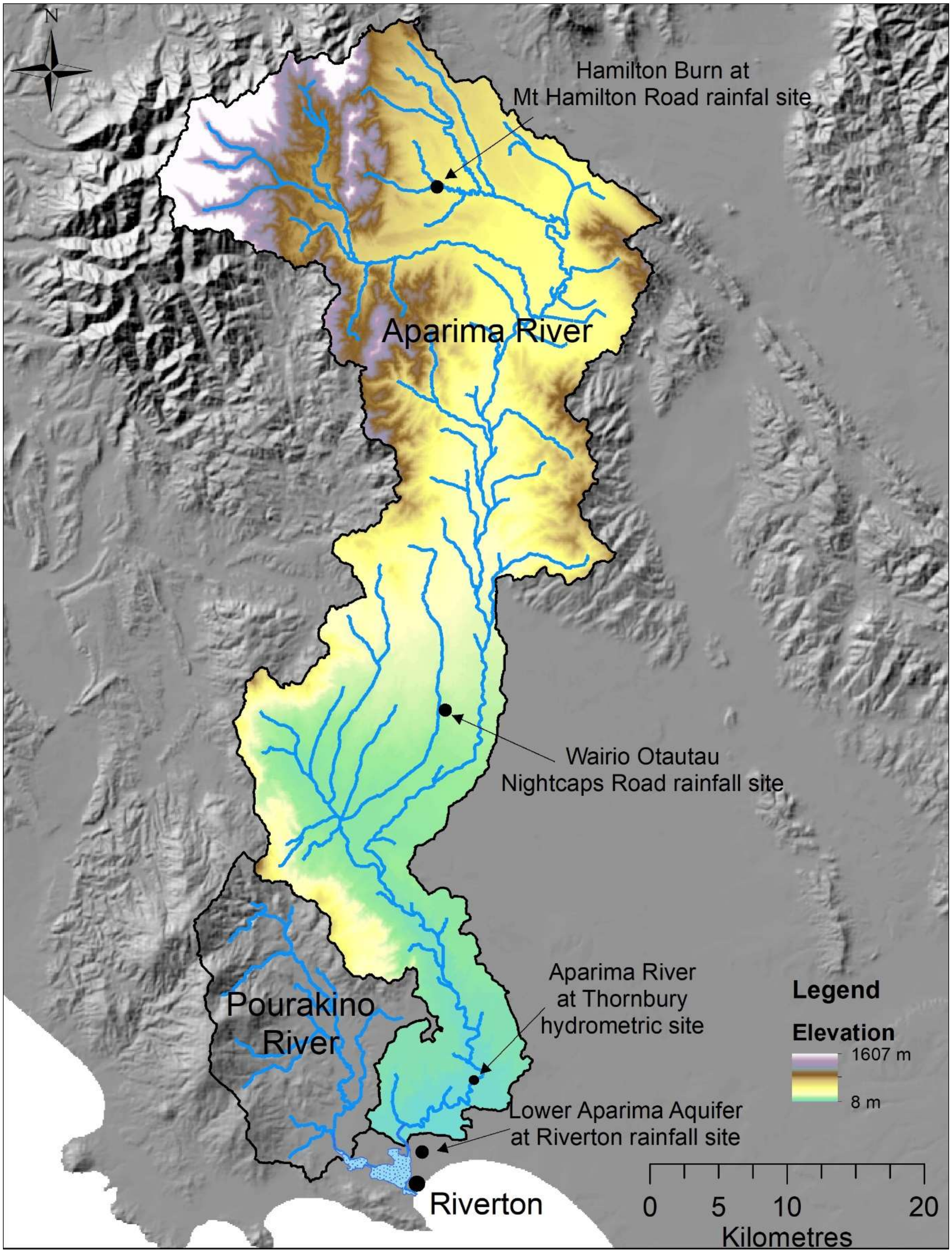

Figure 2-1: Aparima River location and elevation map. Discharge is measured continuously at Aparima at Thornbury hydrometric site, where water quality samples are collected.

3 Methods

3.1 Environment Southland data

ES operates seven hydrometric stations with the Aparima River catchment. The Aparima River at Thornbury site is the most-downstream site on the River and captures 1208 km^2 of the 1320 km^2 catchment. Since 2015 ES has carried out comprehensive event-based suspended sediment monitoring at the Aparima at Thornbury site (Figure 2-1). This monitoring includes the collection of storm event suspended sediment samples by automatic water samplers and the recording of continuous nephelometric turbidity data by an in-situ turbidimeter. The event sediment samples are supplemented by monthly suspended sediment samples (generally taken under low flow conditions) carried out as part of Environment Southland's State of the Environment (SoE) water quality monitoring programme.

Environment Southland have operated a WTW Visoturb turbidimeter (0 – 4000 FNU range) at the Aparima River at Thornbury site since 2013. As is typical of long-term continuous turbidity datasets, the raw turbidity data provided to NIWA contained periods of missing or noisy data and periods when the sensor output had drifted (possibly due to fouling of the sensor face). After reviewing the turbidity dataset from 2013 to 2019 it was concluded that it was only possible to determine sediment loads from the continuous turbidity record for 2015, 2016, 2018 and 2019.

All water samples were analysed by Hills Laboratories for laboratory turbidity (on a Hach 2100N turbidimeter), total suspended solids (TSS), and suspended sediment concentration (SSC). Although some samples were analysed for both TSS and SSC, most samples were analysed for only one or the other. The Hill Laboratories detection limits for turbidity and SSC were 0.05 NTU, and 10 mg/L, respectively. The detection limit of the TSS method varied between 1 and 4 mg/l, dependent on available sample volume.

There is a subtle, but important, difference in the laboratory analysis methods of the two measures of suspended particulate material (SPM), TSS and SSC. The differences and pro and cons of each were described in detail by Gray, Glysson et al. (2000). In brief, while both methods use the same analysis technique (i.e., filtering, drying at ~104°C and weighing all matter in a known volume of water sample), the TSS method involves sub-sampling from the original sample while the SSC method uses the entire sample. Because sub-sampling of the water sample in the TSS method (i.e., pouring a sub-sample from a shaken bottle) is difficult to do representatively with respect to rapidly-settling sand, the TSS method tends to underestimate the concentration of SPM. Hence the SSC method is the preferred technique for quantifying SPM in traditional sediment load studies.

3.2 Estimating suspended sediment loads

Several methods are available for estimating the SSLs of rivers and these are reviewed by (Degens and Donohue 2002). One of the most commonly used approaches (when there are sufficient data) is the rating curve approach. The rating curve method is based on extrapolating suspended sediment concentration measurements over the entire period of interest by developing a relationship between SSC and stream discharge (at the time of sampling) (Letcher, Jakeman et al. 1999). This relationship is then applied to the entire discharge record. Rating curves describe the average relation between discharge and SSC for a specific location (Asselman, N.E.M. 2000). The relationship between suspended sediment concentration and discharge is typically log-log in nature, i.e., the relationship between the log of the contaminant concentration and the log of discharge is linear. Therefore the most commonly used rating curve is a power function:

$$C = aQ^b$$

Where C is the suspended sediment concentration (usually in mg/L), Q is the discharge (usually in m^3/sec), a and b are regression coefficients. Suspended sediment fluxes were determined by multiplying each interpolated SSC data point by the corresponding discharge data point and assuming these values were representative of the entire period (i.e., 10 minutes) between each measurement. Annual SSLs were simply determined by summing each 10 minute flux for a calendar year.

A commonly used (e.g. Rasmussen, Gray et al. 2009; Hughes, Quinn et al. 2012) variation to the rating curve approach is the use of nephelometric turbidity instead of stream discharge to determine SSC. Sediment loads determined from continuous turbidity records are usually more accurate than those determined from continuous stream discharge (Rasmussen, Gray et al. 2009). This is primarily because turbidity is an excellent surrogate for suspended sediment concentration (Davies-Colley and Smith 2001), while stream flow predicts SSC less reliably. This is because there is often a hysteresis in the relationship between flow and SSC in rivers. That is, sediment concentrations at the same discharge on the rising and falling limbs of the hydrograph of many rivers can differ considerably. This hysteresis effect means that linear regression fits determined from flow and SSC can exhibit considerable scatter.

In this report we have determined annual SSLs using both rating curve approaches. As the turbidity-based rating curve approach has been shown by Rasmussen, Gray et al. (2009) to produce more accurate results, we consider this to be the primary load estimation method. The flow-based rating curve approach has been applied to provide an estimate of the annual load for 2017 (the year of missing/poor quality turbidity data). Determining loads for all the years between 2015 and 2019 and comparing with the turbidity-SSC estimates also provides some indication of how reliable the flow-based rating curve load estimate is for 2017.

Because the regression relationships between field turbidity and SSC and flow and SSC were curvilinear; the relationships were linearised by log transforming the data. Retransformation bias and data non-normality can complicate regression models used to estimate concentrations (Helsel and Hirsch 1992). Therefore the non-parametric smearing estimate of Duan (1983) was used to correct for retransformation bias of the log-transformed data.

When determining SSLs from samples collected from a single river location it is advisable to relate the point SSC at the sampling location (i.e., the autosampler intake) to the discharge-weighted cross-section mean SSC. This is usually done by carrying out a full suspended sediment gauging using depth-integrating samplers at multiple verticals while also taking samples at the same time from point sampling location. The resulting relationship will indicate how well mixed the suspended sediment is across the entire cross-section of the river. A relationship equalling unity indicates perfect mixing of the suspended sediment across the river. If the relationship does not equal unity, it can be used to adjust the suspended sediment concentrations collected at the point sampling location. In the case of the Aparima River at Thornbury site, no sediment gauging data are available, therefore we have to assume perfect mixing of the suspended sediment across the river.

4 Results and discussion

4.1 Turbidity and suspended sediment data

Figure 4-1 illustrates the relationship between field turbidity and the two measures of suspended sediment (SSC and TSS) and Table 4-1 includes the summary statistics of the TSS and SSC datasets. Interestingly, the slope of the regression fits between the two sets of data are very similar. A t-test performed to test the equality of the slopes of the two regression fits (alpha = 0.05) indicated that the slopes are statistically indistinguishable. Although the R^2 and standard errors of the turbidity-TSS relationship are superior to the turbidity-SSC relationship, the SSC dataset sampled higher turbidity and SSC values (SSC = 449.8 FNU; TSS = 213.5 FNU). The highest field turbidity value recorded over the 2015-2019 period was 453 FNU. Therefore, by using the turbidity-SCC regression fit there would be basically no extrapolation of the relationship outside of the range of measured values (at least for the most important higher turbidity values/suspended sediment concentrations).

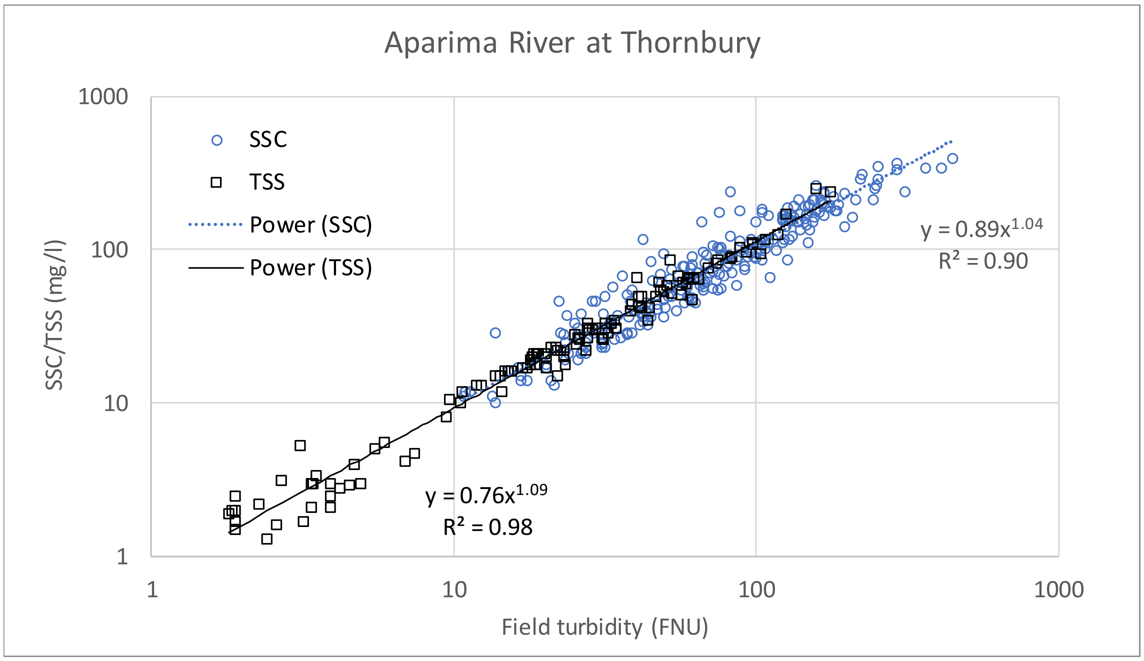

Figure 4-1: Field turbidity vs SSC and field turbidity vs TSS for the Aparima at Thornbury site (2015-2019).

Table 4-1: Summary statistics of the two methods of two measures of suspended particulate material (TSS and SSC)

Analysis method	N	Field turbidity-SSC/TSS Regression slope	R^2	Minimum turbidity (FNU)	Maximum turbidity (FNU)	Minimum conc.(mg/L)	Maximum conc.(mg/L)
TSS	120	1.0861	0.98	1.8	213.5	1.3	250
SSC	252	1.0422	0.90	10.0	449.8	10	390

Figure 4-2 illustrates the relationship between the laboratory turbidity values measured on samples and the field turbidity measurement at the time of sample collection. Despite calibration to formazin standards, differences in instrument design and light sources (e.g., visible vs near-infrared radiation) lead to turbidity values measured by the laboratory turbidimeter (Hach 2100N) on water samples being numerically different from those from the field turbidity sensor (WTW Visoturb). Regardless of this, the relationship between the two turbidity measurements is very good. The sound relationship between the two measures of turbidity provide confidence that the turbidity sensors operated correctly, and no detectable sensor drift occurred.

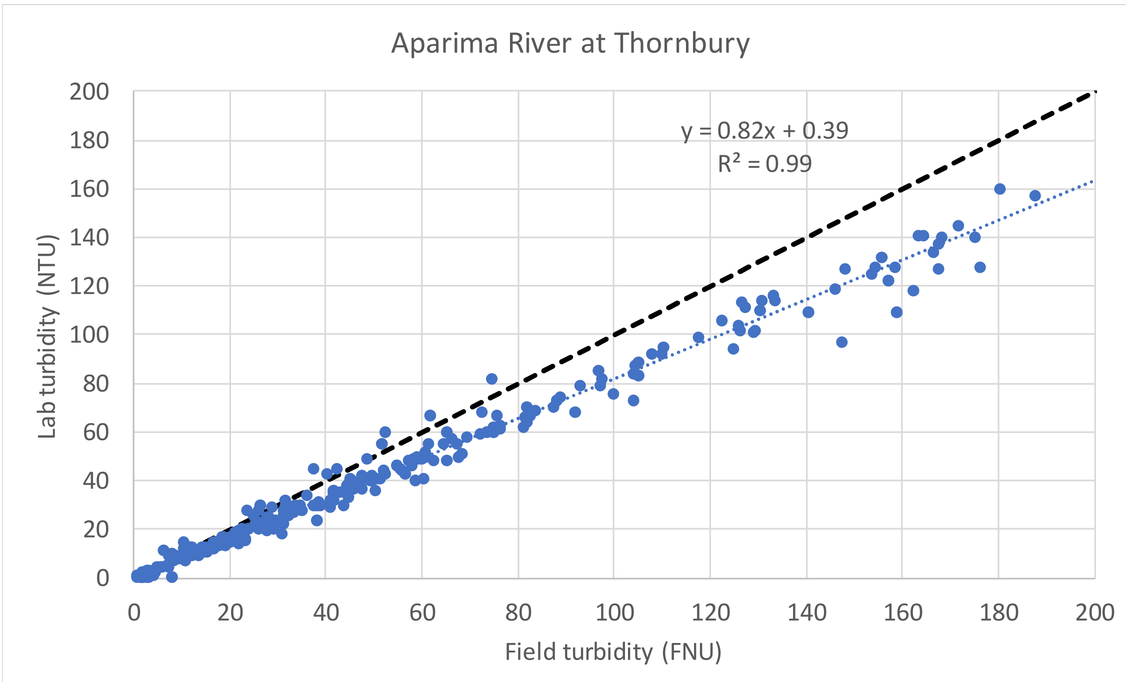

Figure 4-2: Field turbidity vs laboratory turbidity measurements from the Aparima at Thornbury site (2015-2019). The dashed line is the 1:1 line.

Figure 4-3 illustrates the relationship between flow and SSC at the Aparima at Thornbury. In comparison to the turbidity-SSC relationship (Figure 4-1) there is considerable scatter in the flow-SSC relationship. Indeed, the modest R^2 of 0.57 indicates that the flow is a much less precise predictor of suspended sediment concentration than turbidity (compare data in Table 4-1).

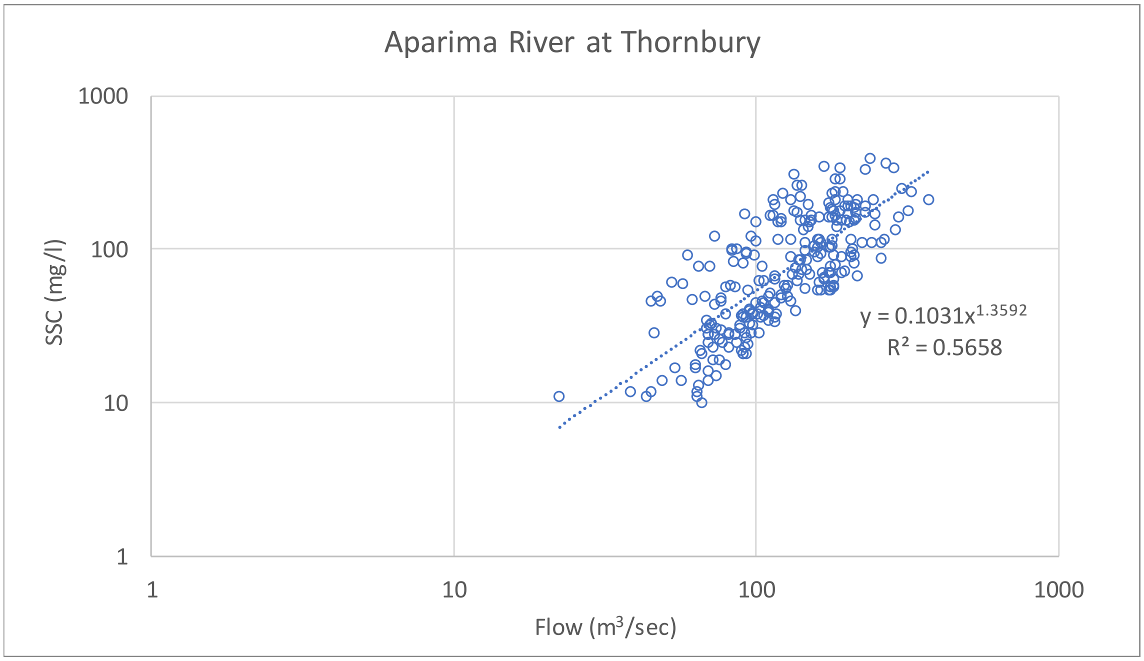

Figure 4-3: Flow vs SSC for the Aparima at Thornbury site (2015-2019).

4.2 Annual suspended sediment loads

Figure 4-4 illustrates the suspended sediment loads (SSLs) estimated using the flow-SSC and turbidity-SSC rating curve approaches for the Aparima River between 2015 and 2019. The SSLs range between 26.2 and 42.5 kt/y for the turbidity-SSC rating curve method and between 14.5 and 76.9 kt/y for the flow-SSC rating curve method (Table 4-2). The mean annual SSL for the turbidity-SSC method was 34.6 kt/y (2015-2019, excluding 2017). The mean annual SSL for the flow-SSC method was 42.4 kt/y (2015-2019). The SSLs determined by the two methods are reasonably similar, although the less precise flow-SSC rating curve method resulted in consistently higher loads.

Because of the potential for multiple potential sources of data bias and imprecision, determining accurate estimates of catchment SSLs is difficult (Littlewoood 1992). However, the mean annual SSLs calculated here for the Aparima compare well to SSLs estimated by national-scale models. Stevens (2018) stated that the CLUES (Version 10.5, LCDB4 in default mode in October 2018) predicted a mean annual SSL of 49.6 kt. Hicks, M., Semadeni-Davies et al. (2019) used an empirical raster GIS-based model to predict river sediment loads at the national scale to predict a mean annual SSL of 60 kt/y for the Aparima River. This model was calibrated from actual measured loads from 273 sites throughout New Zealand. One of the calibration sites was the Aparima River at Thornbury site. Hicks, M., Semadeni-Davies et al. (2019) used SEDRATE toolbox to fit a rating to the available flow and suspended sediment data and calculated an SSL of 52.5 t/y.

Regardless of which measurement method is used, the estimated SSL of the Aparima River is low compared to other large New Zealand catchments. Indeed, the Hicks, M., Semadeni-Davies et al. (2019) model determined that out of the 41 largest South Island rivers, the Aparima River had the fourth lowest SSL (60 kt/y) and delivers only 0.09% of all the sediment delivered to the coast by all South Island Rivers.

Although the SSL of the Aparima River is comparatively small, it still delivers a considerable amount of sediment to a small estuary (JRE area = 729 ha). If we assume 100% of this sediment is deposited evenly over the 729 ha JRE (assuming a sediment bulk density of 2.0 t/m^3), it would result in around 9 mm/y of sediment accumulation. The deposition (and retention) of all the sediment delivered to the JRE is, of course, an unlikely scenario. In fact, available evidence suggests that most of the suspended sediment delivered by the Aparima River bypasses the JRE and is transported straight to the coast (Lohrer, Dudley et al. 2020).

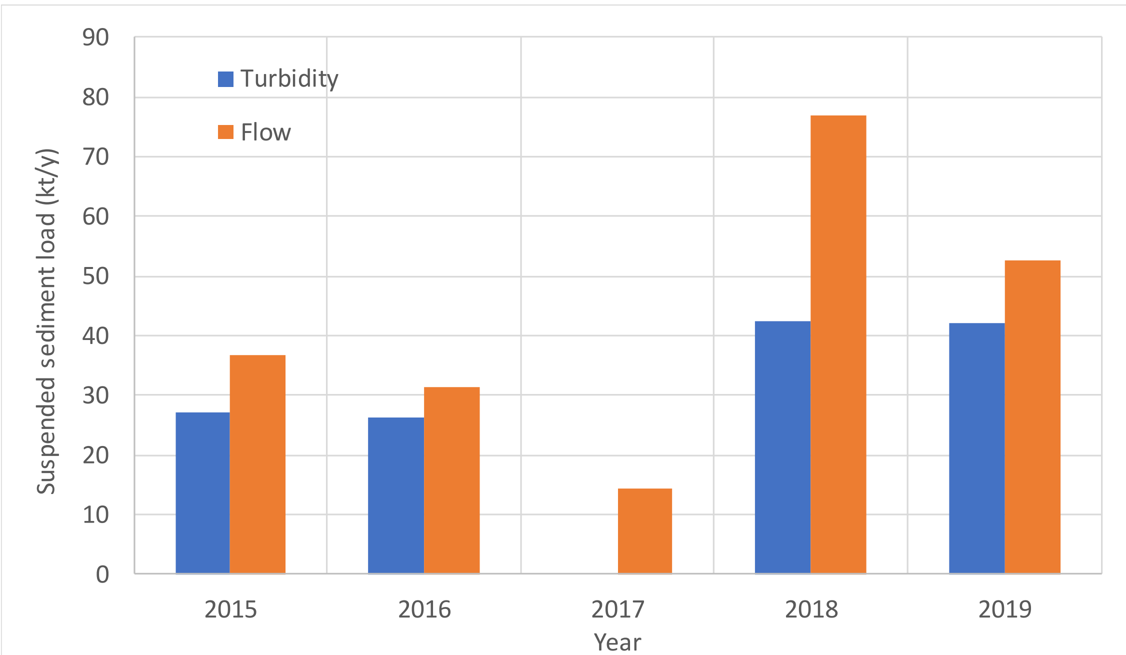

Figure 4-4: Suspended sediment loads for the Aparima at Thornbury site (2015-2019). "Turbidity" loads were determined from the turbidity-SSC rating curve method. "Flow" loads were determined from the flow-SSC rating curve method.

Table 4-2: Suspended sediment loads for the Aparima at Thornbury site (2015-2019).

Year	Suspended sediment load (kt)	
	Turbidity-SSC-derived load	Flow-SSC-derived load
2015	27.6	36.7
2016	26.2	31.5
2017	n/a	14.5
2018	42.5	76.9
2019	42.2	52.5
Mean (2015-2019)	34.6	42.4

4.3 Specific suspended sediment yields

Annual SSLs give us an indication of the mass delivered to the receiving environment (the JRE in this case). Knowledge of the total sediment delivered by the river is useful as it allows estuarine scientists to assess the potential effects of the delivery of large amounts of sediment to the estuary. However, annual SSLs are not very informative for determining the relative importance of the catchment as a source of sediment. Generally, large catchments deliver large amounts of sediment and small catchments deliver small amounts of sediment. A better measure of the relative importance of a catchment as a source of sediment is the sediment yield (SSY; SSL divided by the catchment area). The SSY is much more revealing about the extent of erosion in catchment.

Table 4-3 illustrates the SSYs determined by the two rating curve methods used in this study. The SSYs range between 21.7 and 35.1 t/km^2/y for the turbidity-SSC rating curve method and between 12.0 and 63.6 t/km^2/y for the flow-SSC rating curve method (Table 4-2). The mean SSY for the turbidity-SSC method was 28.7 k/km^2/y (2015-2019, excluding 2017). The mean SSY for the flow-SSC method was 35.1 t/km^2/y (2015-2019).

Table 4-3: Specific sediment yields for the Aparima River catchment(2015-2019).

Year	Specific suspended sediment yield (t/km^2/y)	
	Turbidity-SSC-derived yield	Flow-SSC-derived yield
2015	22.9	30.4
2016	21.7	26.0
2017	n/a	12.0
2018	35.1	63.6
2019	35.0	43.5
Mean (2015-2019)	28.7	35.1

As with the SSLs, the annual SSYs calculated in this study are similar to SSYs determined using other methods. The SSY determined from the CLUES data presented in Stevens (2018) is 37.6 t/km^2/y, while the SSY determined from Hicks, M., Semadeni-Davies et al. (2019) model is 38.2 t/km^2/y

The SSY calculated here (and those from the other sources) are very low by New Zealand standards. Using a sediment rating approach, Hicks, D.M., Hill et al. (1996) calcuated SSLs and SSYs for 203 New Zealand catchments. They found that the SSYs of New Zealand's main rivers ranged between 20 and 30 000 t/km^2/y. In a more recent study, Hicks, M., Semadeni-Davies et al. (2019) determined that the SSYs of 81 major New Zealand rivers ranged between 10.9 and 23 000 t/km^2/y, with the median SSY being 209 t/km^2/y. The SSY of 38.2 t/km^2/y determined by Hicks, M., Semadeni-Davies et al. (2019) for the Aparima River is the third lowest SSY out of the 41 largest South Island Rivers (Figure 4-5) and ninth lowest out of the 81 largest rivers throughout New Zealand.

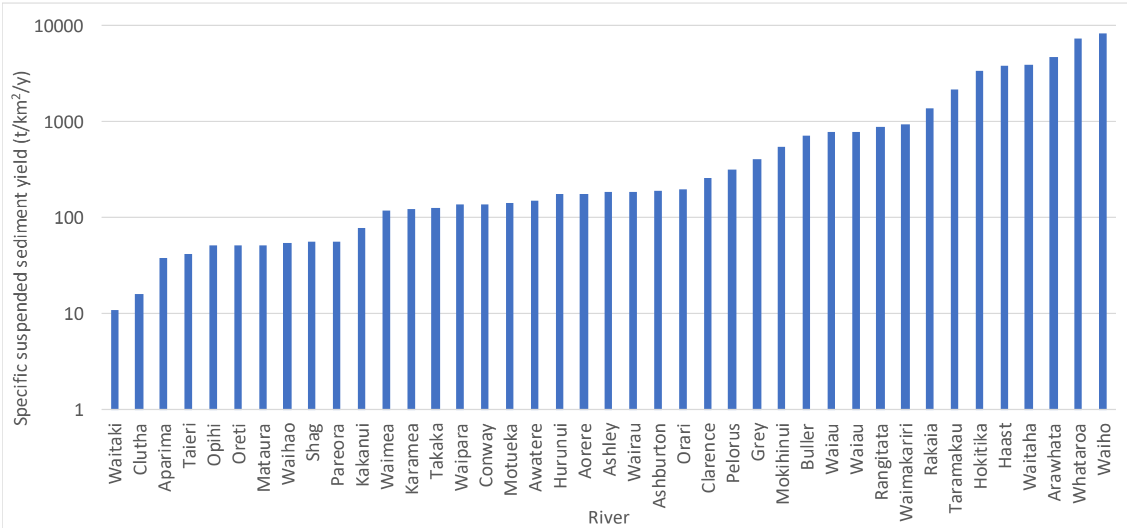

Figure 4-5: Specific suspended sediment yield of the main South Island rivers. Note: a base-10 log scale is used for the y axis. Source: Hicks, et al. (2019).

The low SSY within the Aparima catchment is probably largely a function of the flat terrain that dominates the catchment. Those parts of the catchment that are steep are largely forested or have a cover of native tussock, hence the land is largely protected from excessive erosion.

4.4 Monthly and event suspended sediment loads

Figure 4-6 illustrates SSLs by month for the Aparima River at Thornbury site for 2015-19 (excluding 2017) (see Appendix B for raw data). Rainfall is relatively evenly distributed throughout the year within the Aparima catchment (Figure 4-7). However, because evapotranspiration rates are lower in late Autumn/winter and soils become saturated, more runoff is generated during the period from May through to August (Figure 4-8). Figure 4-6 shows that there is variability in the monthly loads, both within each year and between years. Based on the four years of data, summer/early autumn period (January through to April) produces the smallest proportion of the total load. In contrast, the month of May produces a consistently high monthly SSL. May tends to be a high rainfall month throughout the catchment (Figure 4-7) and this is also reflected in the consistently high total stream flow for May (Figure 4-8). The monthly loads over the winter period (June-August) exhibit variability with years of high monthly SSL largely mirroring the high total flows recorded during those months. Four years of data is a relatively small sample size, therefore continued collection of suspended sediment /turbidity data into the future will allow a better picture of seasonal trends to be determined.

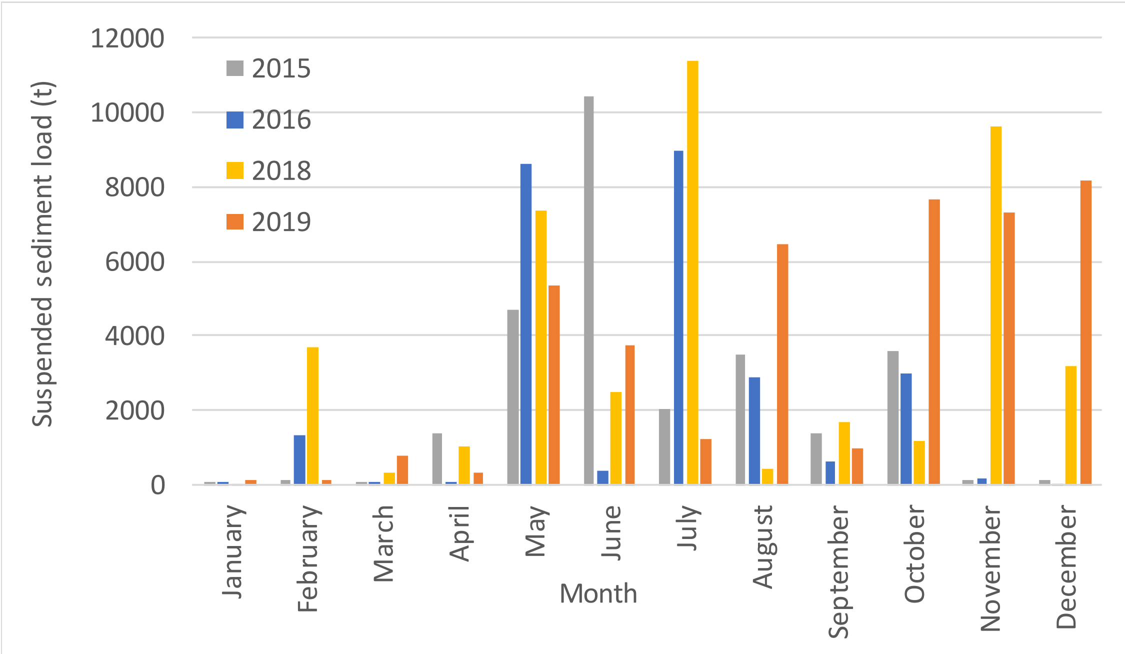

Figure 4-6: Monthly suspended sediment loads for the Aparima River (2015-19, excluding 2017). Monthly loads were estimated using the turbidity-SSC rating curve method.

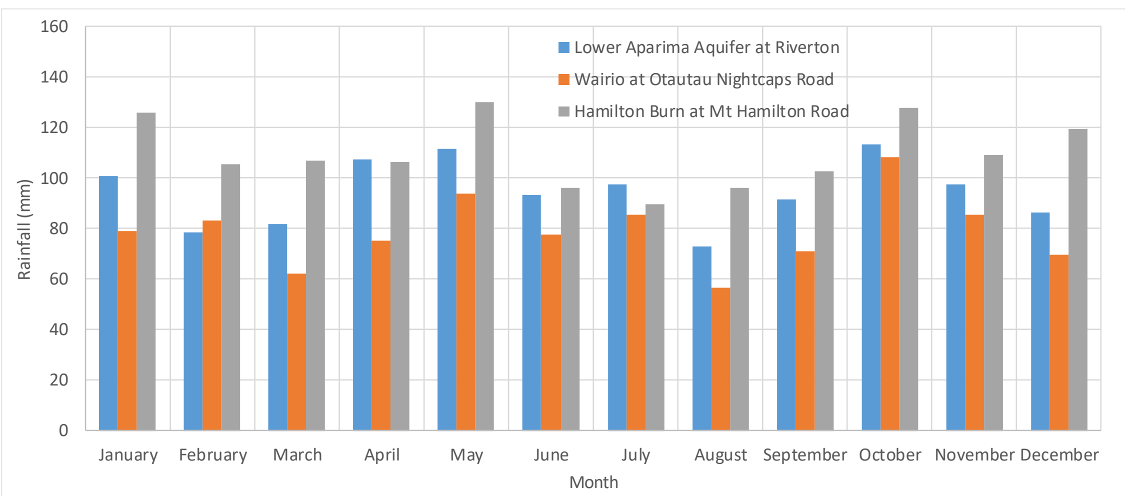

Figure 4-7: Mean monthly rainfall at three rainfall stations within the Aparima River catchment. Figure 2-1 indicates locations of climate stations. Source: Environment Southland.

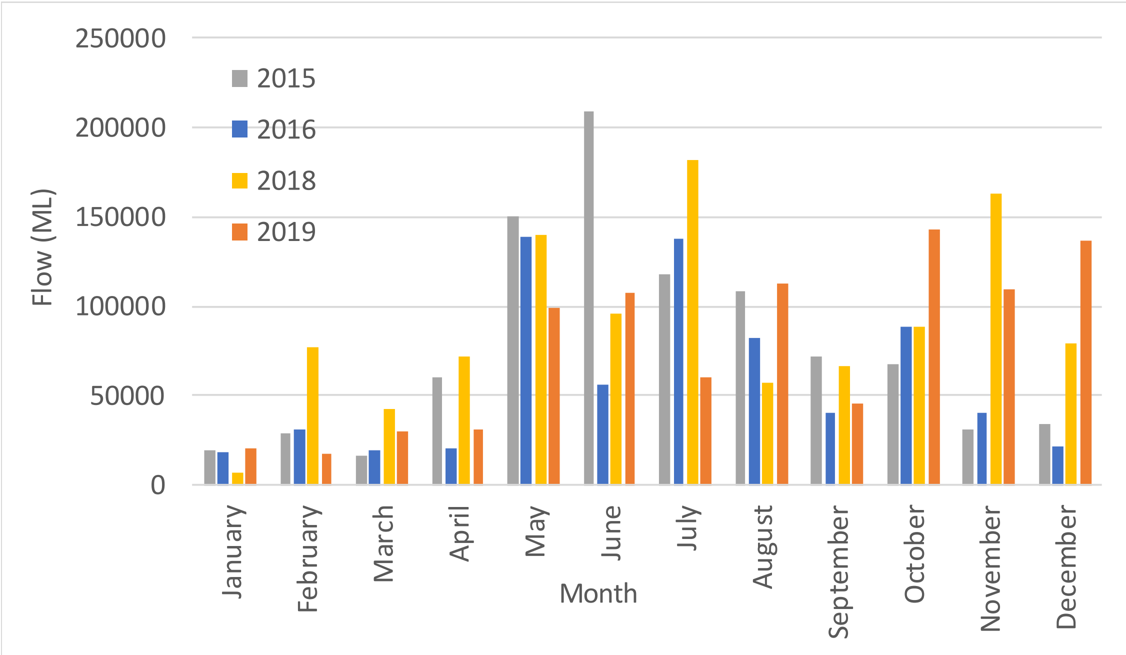

Figure 4-8: Total monthly flow for the Aparima River (2015-19, excluding 2017). Flow is the total flow recorded for each month in Megalitres (ML)

Suspended sediment loads for the events from 2015, 2016, 2018 and 2019 with a peak flow greater than 100 m^3/sec were calculated (Appendix C). Figure 4-9 illustrates the relationship between peak flow and event SSL for these events. This relationship is basically an event-load rating approach and is widely used to predict event SSLs (Hicks, D.M. and Gomez 2002). The Aparima River data in Figure 4-9 were divided into two groupings: i) winter events (i.e., those that occurred between June and August), and ii) all other events (i.e., events that occurred between September and May). Winter forage crop paddocks in Southland are grazed primarily during June and July (McDowell, R. W. 2006). The "winter event" data and the "all other event" data plot within the same space and the linear regression fits are very similar for the two datasets. A t-test performed to test the equality of the slopes of the two regression fits (alpha = 0.05) indicated that the slope are statistically indistinguishable. In other words, the regression slopes for "winter event" data and the "all other event" data are statistically indistinguishable. This means that the flow events that occur during the winter months, when winter forage crops are being grazed (or are recovering from grazing during August), deliver the same amount of suspended sediment to the river system for a given peak discharge as events that occur outside the winter period.

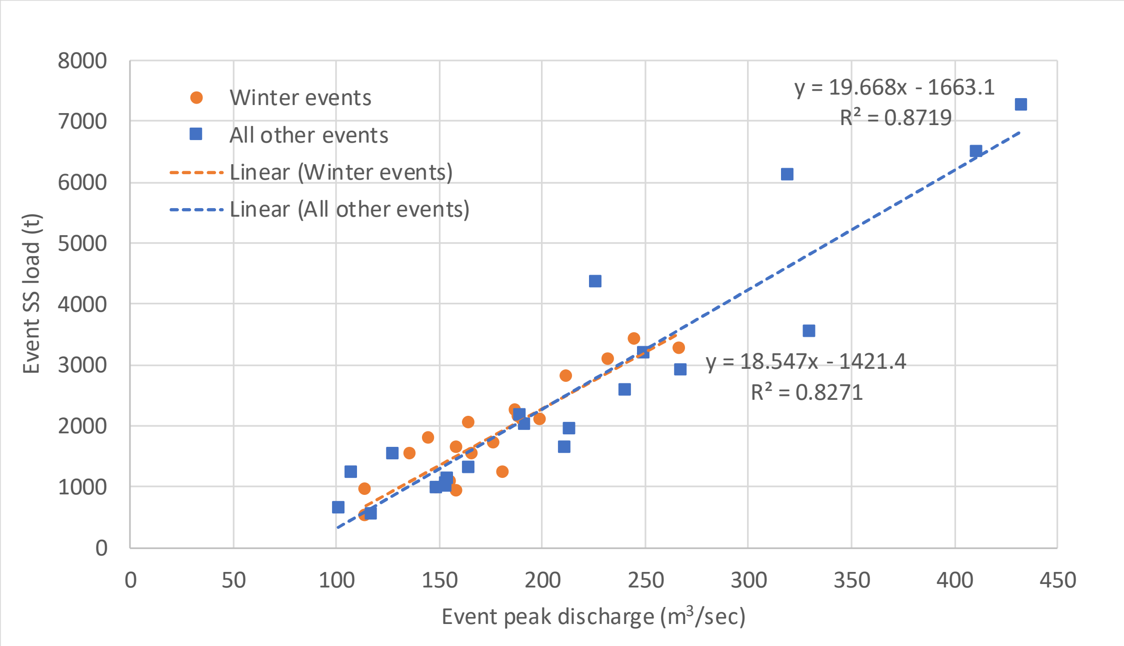

Figure 4-9: Event discharge vs event SSL load relationship for all events with a peak greater than 100 m^3/sec for the Aparima River (2015-19, excluding 2017). Event SSLs were estimated using the turbidity-SSC rating curve method. "Winter events" are those that occurred in June, July and August. "All other events" are those that occurred between September and May.

Several small-scale studies have demonstrated that winter forage cropped areas generate locally elevated levels of suspended sediment (e.g. McDowell, R. W., Drewry et al. 2003; McDowell, R. W. 2006; Monaghan, Wilcock et al. 2007). Therefore, intuitively one would expect an increase in the total amount of suspended sediment transported during time of forage crop grazing. There are a number of likely reasons why an increased flux of sediment has not been detected here. Firstly, the area of livestock damaged winter forage crop land is not extensive enough for the sediment flux to be detected. McDowell, R. W., Drewry et al. (2003) carried out a laboratory-based experiment and demonstrated that the mean suspended sediment concentration delivered from a simulated winter crop cover was five times greater than that from pasture cover (0.076 g/L vs 0.014 g/L). If we extrapolate the factor of five increase in SS concentration to a factor of five increase in SSY across the catchment and assume that winter forage crop land makes up 5% of the Aparima catchment, winter forage crops would still only produce ~20 % of the total sediment generated within the catchment. This scenario (unreasonably) assumes that rainfall would be evenly spread across the catchment during events. Given that winter forage crops only make up 5% of the catchment area, the 20% (of the total catchment load) figure is likely to be an over-estimation. Therefore, the sediment “signal” from winter forage crops may be being swamped by the sediment from all other sources combined.

Another important consideration is the fact that only a very small proportion of the sediment eroded from any one part of the landscape will makes its way to the catchment outlet. This phenomenon has been explained and addressed by previous researchers and has been called “the sediment delivery problem” (e.g. Walling 1983; de Vente, Poesen et al. 2007). In brief, high erosion rates on a hillslope do not always equate with high sediment delivery rates to the river network. Although a hillslope may be undergoing locally high rates of erosion, deposition and storage (temporary or permanent) may occur on the hillslope, particularly when gradients reduce further downslope, at the toe of hillslopes, in swales, on floodplains or within the river channel itself (Walling 1983). The relative effect of this loss is known to increase with increasing catchment area, as large catchments tend to have longer hillslope lengths and more extensive areas of potential sediment storage. Hence, this phenomenon may be playing a role in the relatively large Aparima River catchment.

4.5 Event sediment dynamics

Analysis of the relationship between SSC and flow over the course of a flow event can provide information on the spatial distribution of major sediment sources within catchments (Williams 1989; Lefrançois, Grimaldi et al. 2007). The relationship is, however, complex with many factors (e.g., antecedent moisture conditions, rainfall amount and intensity) potentially affecting the SSC-flow response during a specific event (Asselman, N.E. 1999; Smith and Dragovich 2009).

For the Aparima River at Thornbury site, the SSC-flow relationships over all events with a flow peak greater than 100 m^3/sec were assessed. All of these events exhibited a strong clockwise hysteresis in the SSC-flow relationship (i.e., peak SSC concentration preceded peak flow). Clockwise hysteresis is widely documented and has been attributed to the rapid entrainment of sediment from sources in and near channels (i.e., river bank erosion) (e.g. Williams 1989; Lefrançois, Grimaldi et al. 2007). The peaking of SSC before flow indicates that sediment sources are limited and are exhausted quickly (Seeger, Errea et al. 2004). On the other hand, anti-clockwise hysteresis pattern has been attributed to the delivery of sediment from sources that are distant to the channel network (i.e., hillslopes) (Williams 1989; Brasington and Richards 2000).

A representative selection of these SSC-flow relationships from events from the Aparima River at Thornbury site during 2018 are illustrated in Figure 4-10. Figure 4-10 contains data for two events prior to the winter period (February and May), two events from the winter period (July), and two events after the winter period (November and December). The SSC-flow plots indicate that clockwise hysteresis is persistent throughout the year. One would expect that if winter forage crops became an important source of sediment there would be a change in this relationship. However, the persistence of clockwise hysteresis in the SSC-discharge relationship during flow events in the Aparima River suggest that the primary source of sediment are within or near the river channel.

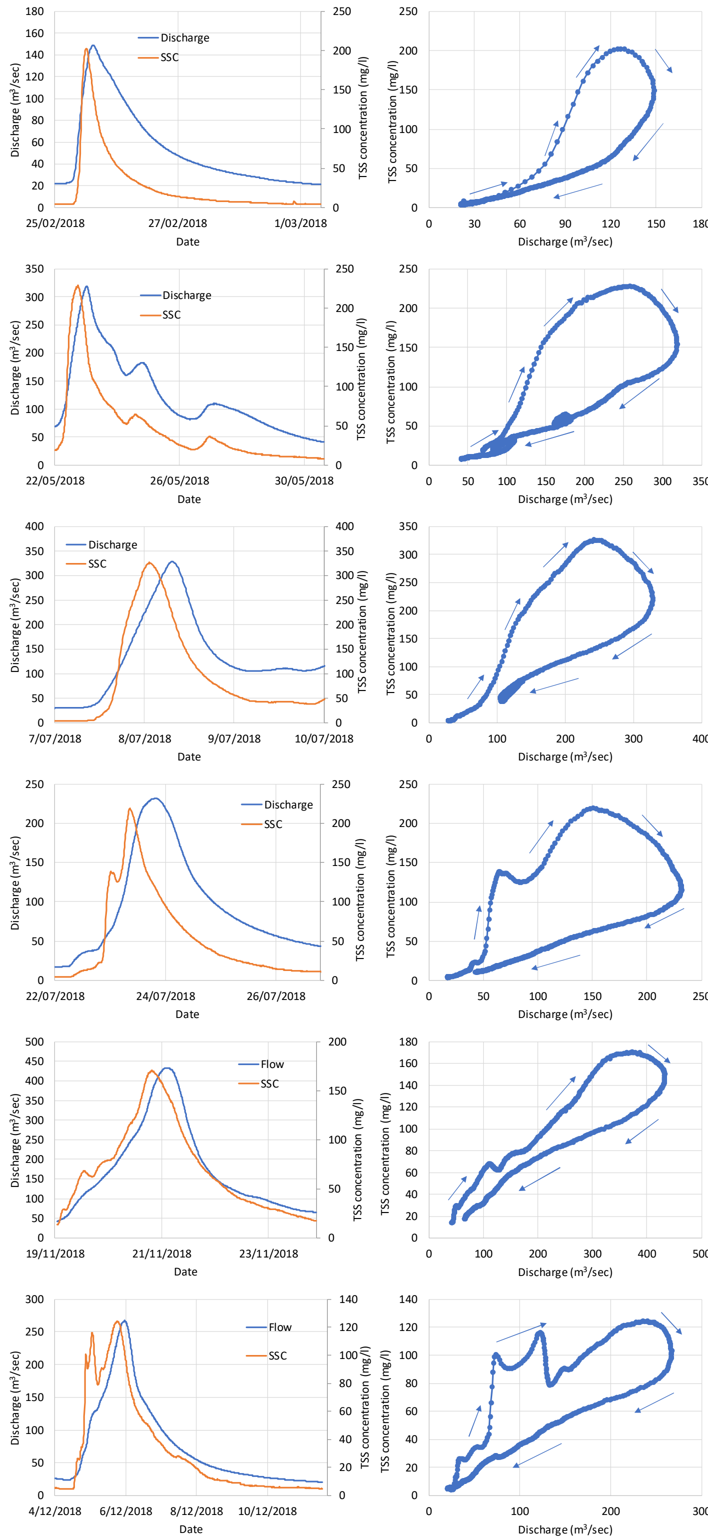

Figure 4-10: The relationship flow and SSC for a selection of events from 2018. The panels on the right indicate the timeseries data for both flow and SSC over 8 events from 2018. The panel on the right indicate the relationship between flow and suspended sediment concentration over each event (arrows indicate the hysteresis direction).

5 Summary and conclusions

Using suspended sediment data and continuous turbidity data collected by Environment Southland, we determined the mean annual SSL of the Aparima River between 2015-19 (excluding 2017) to be 34.6 kt/y. This is similar to loads determined by previous modelling approaches. This is a large amount of sediment and if deposited within the JRE each year, it would likely result in significant adverse environmental effects. However, evidence from other research suggests that much of the sediment delivered by the Aparima River is transported through the estuary and is discharged into the Foveaux Strait (e.g. Lohrer, Dudley et al. 2020).

Because large rivers tend to generate large amounts of sediment annually, the SSL data tell us little about the relative importance of the catchment as a source of sediment. The specific suspended yield is a better measure as it is much more revealing about the extent erosion in a catchment. Specific suspended sediment yields calculated here indicate that the mean annual SSY of the Aparima River between 2015-19 (excluding 2017) was 28.7 t/km^2/y. By New Zealand standards, 28.7 t/km^2/y is a very low SSY. This suggests that there are not serious erosion and sediment delivery issues in the catchment.

Analysis of event SSL data indicates that flow events that occur during winter (the time when winter forage crops are grazed) do not delivery a disproportionately large amount of sediment. This is inconsistent with the findings of previous small-scale studies that demonstrated elevated sediment loads from grazed winter forage crop land. The relatively small proportion of the catchment (5%) in winter forage crops is probably an important explanatory factor. The deposition and storage of eroded sediment within hillslopes, floodplains or within the river channel is also presented as a feasible explanation for the absence of an increased suspended sediment flux at a time when winter forage crop grazing greatly reduces groundcover.

Analysis of the SSC-flow relationships for events from the Aparima River show that all events exhibit a clock-wise hysteresis loop. This is interpreted to mean that the main sources of sediment are near or within the river channel (e.g., bank erosion). The persistence of clock-wise hysteresis throughout the year also suggests that there is no switching of sources during the winter forage crop grazing period.

The SSY of the Aparima River is low by New Zealand standards and there is no evidence within the data presented here of a marked increased flux of suspended sediment during the winter forage crop grazing period. However, this does not mean that winter forage crop grazing does not generate more sediment than grazed pasture. The detection of the input of small areas of locally high suspended sediment at the catchment-scale is difficult. Winter forage crop grazing significantly reduces groundcover and damages soil structure during a time of the year when soils are saturated. It is likely that winter forage crops that are adjacent to stream channels, have convergent flow pathways and/or are situated on steeper terrain will be locally important areas of elevated sediment delivery. Improved land management practices will help reduce sediment loss and delivery to the river system. Further field-based studies are required to identify these areas and measure the actual delivery of sediment from them.

6 Acknowledgements

Thanks to Roger Hodson and Aaron Taylor of Environment Southland for the providing flow, suspended sediment, turbidity and rainfall data used in this report. Thanks to Justin Kitto of DairyNZ for providing information on the extent of winter forage crops in the Aparima River catchment.

7 References

Asselman, N.E. (1999) Suspended sediment dynamics in a large drainage basin: the River Rhine. *Hydrological Processes*, 13: 1437-1450.

Asselman, N.E.M. (2000) Fitting and interpretation of sediment rating curves. *Journal of Hydrology*, 234: 228-248.

Brasington, J., Richards, K. (2000) Turbidity and suspended sediment dynamics in small catchments in the Nepal Middle Hills. *Hydrological Processes*, 14(14): 2559-2574. 10.1002/1099-1085(20001015)14:14<2559::aid-hyp114>3.0.co;2-e

Davies-Colley, R.J., Smith, D.G. (2001) Turbidity, suspended sediment, and water clarity: a review. *Journal of the American Water Resources Association*, 37(5): 1085-1101.

de Vente, J., Poesen, J., Arabkhdri, M., Verstraeten, G. (2007) The sediment delivery problem revisited. *Progress in Physical Geography*, 31(2): 155-178.

Degens, B.P., Donohue, R.D. (2002) Sampling mass loads in rivers - A review of approaches for identifying, evaluating and minimising estimation errors, Report No. WRT 25: 43.

Duan, N. (1983) Smearing estimate: a nonparametric retransformation method. *Journal of the American Statistical Association*, 78: 605-610.

Gray, J.R., Glysson, D.G., Turcois, L.M., Schwarz, G.E. (2000) Comparability of suspended-sediment concentration and total suspended solids data: 14.

Helsel, D.R., Hirsch, R.M. (1992) *Statistical Methods in Water Resources*. Elsevier Science Publishers B.V., Amsterdam.

Hicks, D.M., Gomez, B. (2002) Sediment Transport. In: H. Piegay & G.M. Kondolf (Eds). *Tools in Fluvial Geomorphology*. John Wiley and Sons Ltd, Chichester, England: 425-461.

Hicks, D.M., Hill, J., Shankar, U. (1996) Variation of suspended sediment yields around New Zealand: the relative importance of rainfall and geology. In: D.E. Walling & B.W. Webb (Eds). *Erosion and Sediment Yield: Global and Regional Perspectives*. IAHS, Exeter: 149-156.

Hicks, M., Semadeni-Davies, A., Haddadchi, A., Shankar, U., Plew, D. (2019) Updated sediment load estimator for New Zealand, NIWA Client Report No: 2018341CH: 190.

Hughes, A.O., Quinn, J.M., McKergow, L.A. (2012) Land use influences on suspended sediment yields and event sediment dynamics within two headwater catchments, Waikato, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 46(3): 315-333.

Lefrançois, J., Grimaldi, C., Gascuel-Odoux, C., Gilliet, N. (2007) Suspended sediment and discharge relationships to identify bank degradation as a main sediment source on small agricultural catchments. *Hydrological Processes*, 21(21): 2923-2933.

Letcher, R.A., Jakeman, A.J., Merritt, W.S., McKee, L.J., Eyre, B.D., Baginska, B. (1999) Review of Techniques to Estimate Catchment Exports: 110.

Littlewoood, I.G. (1992) Estimating contaminant loads in rivers: a review, IH Report No. 117.

Lohrer, D., Dudley, B., Swales, A., Hughes, A., Barr, N., Bulmer, R., Hicks, M., Plew, D., Zeldis, J. (2020) Findings from an interdisciplinary workshop on Jacobs River Estuary, NIWA Client Report No: 2020148HN: 31.

McDowell, R.W. (2006) Phosphorus and sediment loss in a catchment with winter forage grazing of cropland by dairy cattle. *Journal of Environmental Quality*, 35(2): 575-583. 10.2134/jeq2005.0364

McDowell, R.W., Drewry, J.J., Paton, R.J., Carey, P.L., Monaghan, R.M., Condron, L.M. (2003) Influence of soil treading on sediment and phosphorus losses in overland flow. *Soil Research*, 41(5): 949-961. https://doi.org/10.1071/SR02118

McDowell, R.W., Wilcock, R.J. (2008) Water quality and the effects of different pastoral animals. *New Zealand Veterinary Journal*: 289-296.

Monaghan, R.M., Wilcock, R.J., Smith, L.C., Tikkisetty, B., Thorrold, B.S., Costall, D. (2007) Linkages between land management activities and water quality in an intensively farmed catchment in southern New Zealand. *Agriculture, Ecosystems & Environment*, 118: 211-222.

Rasmussen, P.P., Gray, J.R., Glysson, G.D., Ziegler, A.C. (2009) Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data. *U.S. Geological Survey Techniques and Methods book 3*: 53.

Robertson, B., Stevens, L. (2013) Jacobs River Estuary - Fine Scale Monitoring of Highly Eutrophic Arms 2012/13, Report prepared by Wriggle Coastal Management for Environment Southland: 29.

Robertson, B.M., Stevens, L.M., Ward, N., Robertson, B.P. (2017) Condition of Southland's Shallow, Intertidal Dominated Estuaries in Relation to Eutrophication and Sedimentation: Output 1: Data Analysis and Technical Assessment - Habitat Mapping, Vulnerability Assessment and Monitoring Recommendations Related to Issues of Eutrophication and Sedimentation. , Report prepared by Wriggle Coastal Management for Environment Southland: 172.

Seeger, M., Errea, M.P., BeguerIa, S., Arnáez, J., MartI, C., GarcIa-Ruiz, J.M. (2004) Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish pyrenees. *Journal of Hydrology*, 288(3-4): 299-311. 10.1016/j.jhydrol.2003.10.012

Smith, H.G., Dragovich, D. (2009) Interpreting sediment delivery processes using suspended sediment-discharge hysteresis patterns from nested upland catchments, south-eastern Australia. *Hydrological Processes*, 23: 2415-2426.

Stevens, L.M. (2018) Jacobs River Estuary: Broad Scale Habitat Mapping 2018. , Report prepared by Wriggle Coastal Management for Environment Southland: 53.

Townsend, M., Lohrer, D. (2015) A review of the ecological health and water quality in four Southland estuaries, NIWA Client Report HAM2015-054: 52.

Walling, D.E. (1983) The sediment delivery problem. *Journal of Hydrology*, 65: 209-237.

Williams, G.P. (1989) Sediment concentration versus water discharge during single hydrological events in rivers. *Journal of Hydrology*, 111: 89-106.

Zeldis, J., Measures, J., Stevens, L., Matheson, F., Dudley, B. (2019) Remediation Options for Southland Estuaries, NIWA Client Report 2019344CH: 73.

Appendix A Flow and estimated suspended sediment concentration annual time series data

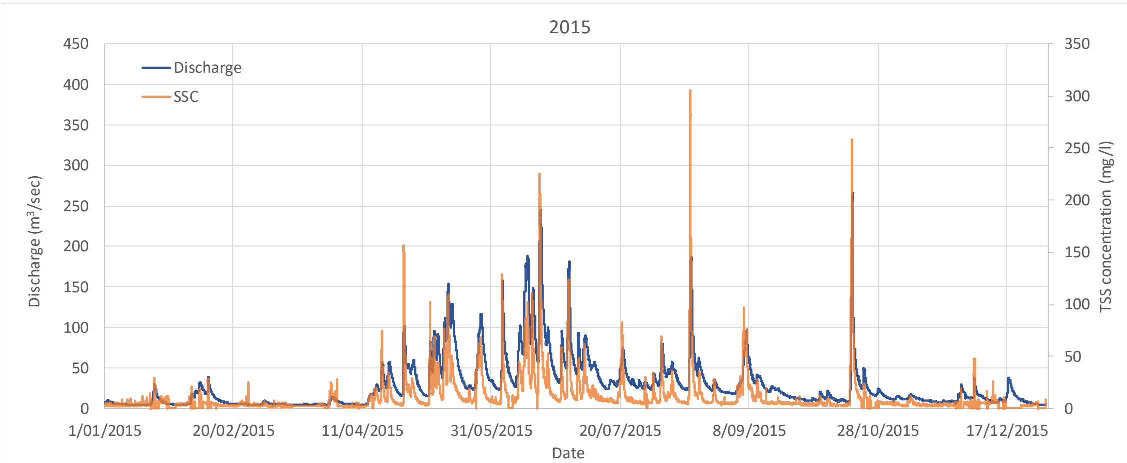

Figure A-1: Flow and estimated suspended sediment concentration data recorded at the Aparima River at Thornbury site (2015).

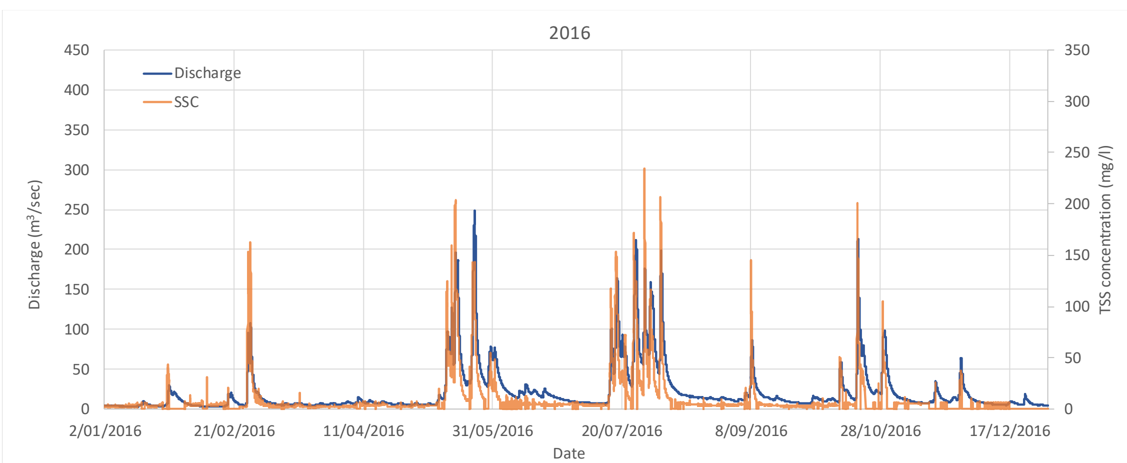

Figure A-2: Flow and estimated suspended sediment concentration data recorded at the Aparima River at Thornbury site (2016).

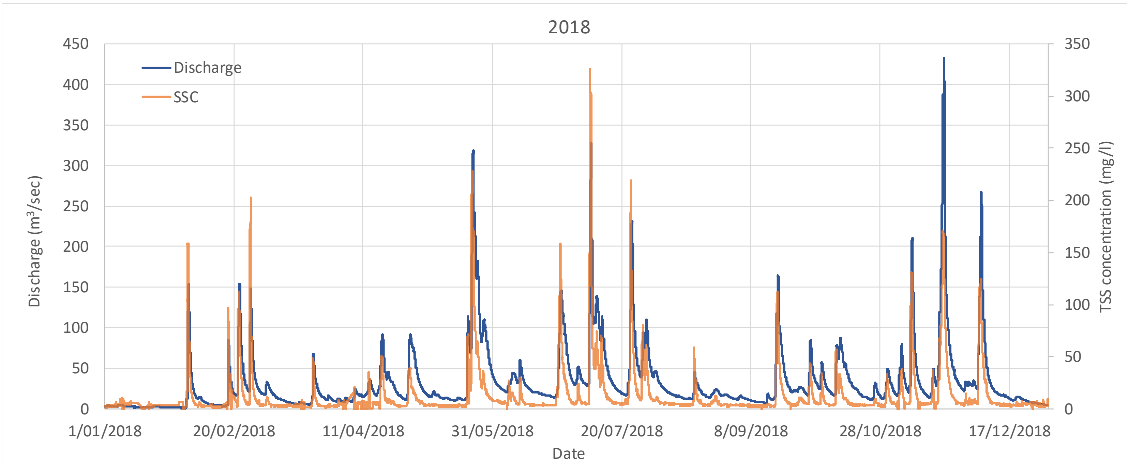

Figure A-3: Flow and estimated suspended sediment concentration data recorded at the Aparima River at Thornbury site (2018).

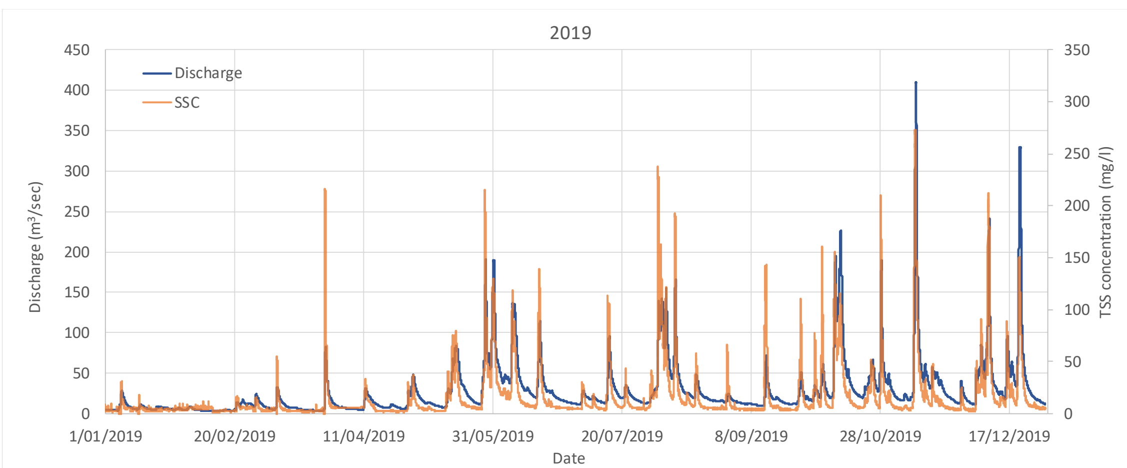

Figure A-4: Flow and estimated suspended sediment concentration data recorded at the Aparima River at Thornbury site (2019).

Appendix B Monthly suspended sediment load and runoff data

Table B-1: Monthly suspended sediment load and flow data for 2015-2019 (excluding 2017).

Month	2015		2016		2018		2019	
	SSL (t)	Flow (ML)	SSL (t)	Flow (ML)	SSL (t)	Flow (ML)	SSL (t)	Flow (ML)
January	78.4	18940	53.7	18889	26.4	6925	112.1	20353
February	150.2	28835	1324.5	31466	3688.8	76931	106.7	17078
March	73.3	16293	67.7	19458	324.8	42057	761.2	30195
April	1387.4	60430	65.0	20175	1019.4	71767	351.0	31243
May	4700.3	150311	8627.9	138676	7355.4	140095	5365.9	99306
June	10451.6	209252	356.1	55632	2488.7	95904	3741.6	107473
July	2018.8	117436	8985.4	138190	11392.1	182041	1233.3	59894
August	3499.2	108964	2892.9	82330	447.1	57245	6446.4	112791
September	1409.2	71456	630.1	40356	1670.1	66810	991.5	45919
October	3589.5	67223	2989.3	88664	1204.0	88464	7694.1	142862
November	124.8	30593	179.4	40268	9646.2	162828	7293.4	109818
December	135.0	33851	10.4	21195	3191.5	79356	8158.4	136753
Total	27617.8	18940	26182.3	18889	42454.5	6925	42255.7	20353

Appendix C Event peak discharge and suspended sediment load data

Table C-1: Event peak discharge and event suspended sediment load data for all events with a peak discharge >100 m^3/sec for 2015, 2016, 2018 and 2019.

Event date	Event peak discharge (m^3/sec)	Event load (t)
27/04/2015	101	658
14/05/2015	153	1051
27/05/2015	117	555
4/06/2015	158	940
14/06/2015	189	2157
15/06/2015	149	987
19/06/2015	245	3414
30/06/2015	181	1245
16/08/2015	187	2258
18/08/2015	266	3259
26/02/2016	107	1227
13/05/2016	128	1549
24/05/2016	249	3184
18/07/2016	165	2040
25/07/2016	212	2803
28/07/2016	177	1723
31/07/2016	159	1650
4/08/2016	199	2105
19/10/2016	214	1939
2/02/2018	154	1002
22/02/2018	154	1126
26/02/2018	149	978
23/05/2018	319	6109
26/06/2018	145	1784
8/07/2018	114	531
23/07/2018	232	3099
18/09/2018	165	1302
9/11/2018	211	1654

Event date	Event peak discharge (m^3/sec)	Event load (t)
21/11/2018	433	7253
6/12/2018	267	2910
28/05/2019	191	2037
31/05/2019	189	2180
8/06/2019	136	1532
18/06/2019	114	950
4/08/2019	156	1089
9/08/2019	166	1545
10/10/2019	226	4375
11/11/2019	411	6508
9/12/2019	240	2574
21/12/2019	330	3557