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REGIONAL COUNCIL
Te Pane Matua Taiao

Te Awarua-o-Porirua Harbour catchment turbidity monitoring

Results of continuous turbidity monitoring 2014/15

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Contents

1. Introduction

Between August 2012 and June 2013 Greater Wellington Regional Council (GWRC) installed continuous turbidity monitoring stations in the lower reaches of the three main tributaries of Te Awarua-o-Porirua Harbour (Porirua Harbour). This followed initial catchment sediment modelling using CLUES (Catchment Landuse for Environmental Sustainability) that identified the Horokiri, Pauatahanui and Porirua Stream subcatchments as delivering the most sediment to the harbour (Green et al. 2014). The turbidity monitoring will be used to quantify actual sediment inputs from these subcatchments.

1.1 Monitoring objectives

The objectives of GWRC's Porirua Harbour catchment turbidity monitoring programme are to:

1. Collect continuous turbidity data from the three subcatchments identified as having the highest sediment yields;

2. Collect stream water samples across a range of turbidity measurements for the purposes of converting the continuous turbidity record into a suspended sediment concentration record; and

3. Use the suspended sediment concentration record to derive annual sediment yields for each of the three subcatchments being monitored.

1.2 Report purpose

This report outlines the monitoring site set-up, methods of data processing and analysis, and summarises the monitoring results obtained between July 2014 and 30 June 2015. Sediment loads and yields are also presented for the full monitoring period (2013–2015).

2. Monitoring sites and methods

The physical locations of each of the three sites chosen for continuous turbidity monitoring were selected because they were already well established hydrological monitoring sites equipped with power and flow gauges (Figure 2.1). Stream flow has been monitored since September 1965 at the Porirua Stream site, since February 2002 at the Horokiri Stream site, and since May 1975 at the Pauatahanui Stream site.[1] Table 2.1 broadly summarises the land use types in the monitored catchments.

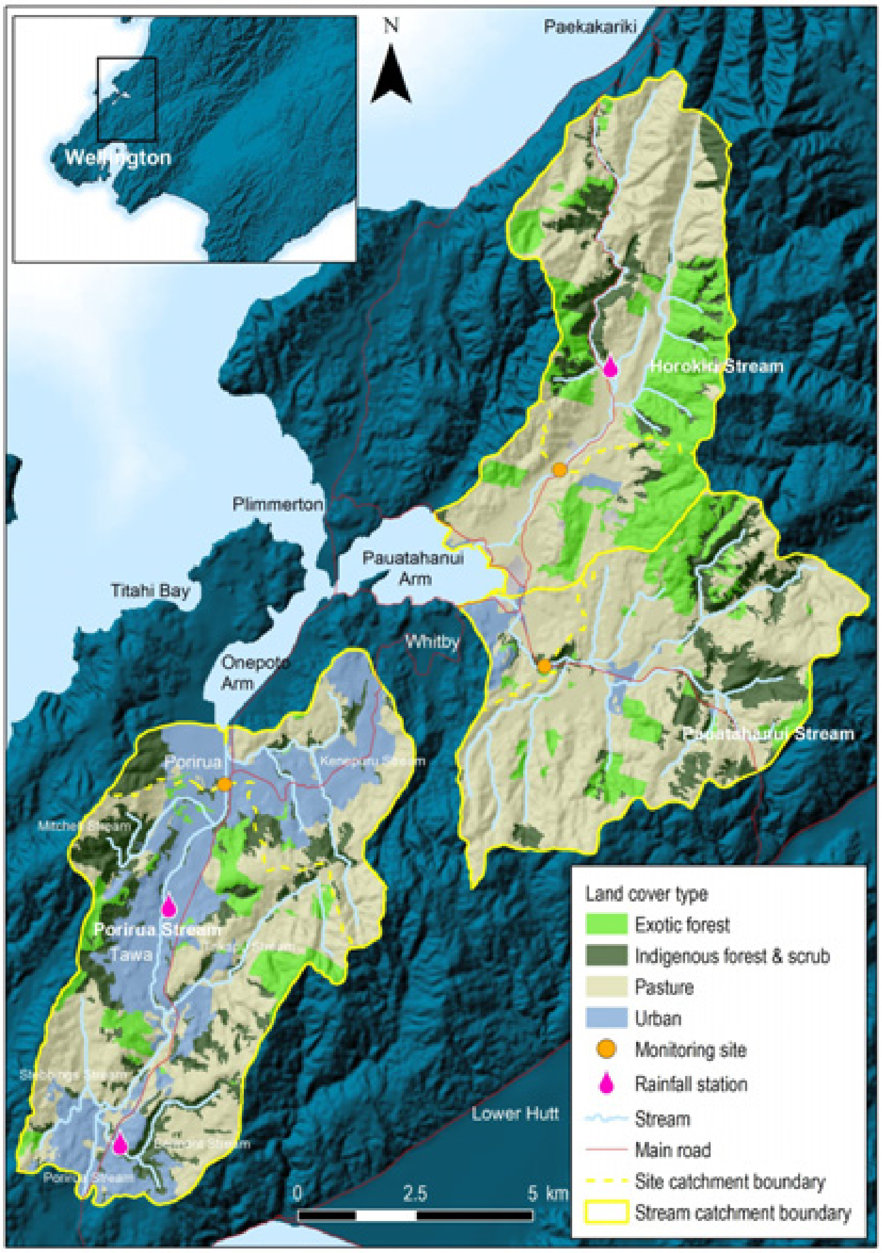


Figure 2.1: Location of the three continuous turbidity monitoring sites in the Porirua Harbour catchment and the major land cover types within each catchment. Areas downstream of the dashed site catchment line are not captured by the monitoring site

[1] The Pauatahanui Stream flow recording equipment is maintained by NIWA as part of their national freshwater monitoring network.

Table 2.1: Percentage of main land cover types in the catchment upstream of each turbidity monitoring site (Source: LUCAS – MfE 2010)

Land cover type (%)	Porirua Stream	Horokiri Stream	Pauatahanui Stream
Indigenous forest	17.3	15.2	17.1
Exotic forest	11.0	26.2	12.9
Pasture	41.2	58.7	68.7
Urban	30.5	–	1.3
Total	*100.0*	*100.0*	*100.0*
Total area of upstream catchment (Ha)	3,937	2,873	3,763

2.1 Site set up and maintenance

The three monitoring sites were established with guidance from environmental monitoring staff at Auckland Council, Horizons Regional Council and Dr Andrew Hughes at NIWA. This predates the release of the National Environmental Monitoring Standards (NEMS) for Turbidity Recording (NEMS 2013). Table 2.2 lists the specific equipment deployed at each monitoring site and Figures 2.2 to 2.4 illustrate the site set up.

Table 2.2: Turbidity-related monitoring equipment at each of the three sites

Equipment		Porirua Stream		Horokiri Stream		Pauatahanui Stream	
		Easting	Northing	Easting	Northing	Easting	Northing
		1754669	5443961	1761804	5450652	1761480	5446486
Data logger	Model	iQuest DS4483		Campbell 850 logger		Campbell 850 logger	
Turbidity sensor	Model	Hach Solitax T-line sensor with SC 200 module					
	Data collection start date	29/08/2012		14/11/2012		12/06/2013	
	Log interval	5 minutes					
	Range	0.001–4,000 FNU					
	Wipe interval	30 minutes					
Back-up Turbidity sensor (Horokiri Stream site only)	Model	-		Campbell Scientific OBS-3 sensor		-	
	Data collection start date	-		28/10/2014		-	
	Log interval	-		Median value taken over 5 minutes		-	
	Range	-		0.001–4,000 FNU		-	
	Wipe interval	-		No wiper		-	
Automatic sampler	Model	ISCO 6712		ISCO 6712		ISCO 6700	
	Installation date	27/03/2013		29/04/2013		12/06/2013	
	No. of bottles	24					
	Sampler trigger type	Stage		Turbidity		Turbidity	
	Sampling interval	5–15 minutes[1]					
	Bottle size	1,000 mL					
Camera	Model	Jablocom EYE-20		-		-	
	Log interval	5 minutes		-		-	

[1] Sampling interval varied according to event size and data requirements

Turbidity monitoring commenced in the lower Porirua Stream at the end of August 2012. Broadly, the setup is a Hach Solitax T-line in-stream turbidity sensor housed in piping connected to an SC-200 control unit (Figure 2.2). This unit then outputs the turbidity data to a logger and the data are telemetered back to the GWRC office. An ISCO automatic water sampler was also installed at the site to collect samples for suspended sediment analysis with which to convert the turbidity sensor data into suspended sediment concentration (SSC) data.

Figure 2.2: Porirua Stream at Town Centre site. Top left inset: Turbidity sensor in the stream with lens and wiper showing. Bottom right inset: SC-200 control unit (top right) and logger (top left) setup

Similar monitoring set ups were established at existing hydrological monitoring sites in the lower reaches of Horokiri Stream (Figure 2.3) in November 2012 and Pauatahanui Stream (Figure 2.4) in June 2013. In October 2014, a back-up turbidity sensor (Campbell Scientific OBS-3) was installed at the Horokiri Stream site due to ongoing issues with the site's primary sensor during high flow events and also to assess whether the weir at the site may be adversely affecting the primary sensor turbidity readings. This followed the recommendations of the previous turbidity monitoring report (Morar et al. 2015).

Routine site maintenance is carried out every five weeks; four-weekly routine visits were trialled following recommendations of Morar et al. (2015) but were found to be unnecessary. During these visits, the turbidity sensor lens and housing are cleaned. Every three months the sensor is calibrated using a two point calibration with distilled water and Stablcal® (a Formazin 800 FNU) standard. In addition to this, each sensor is sent away for servicing and re-calibration annually.

During early summer, algal growth on the sensor lens and housing is a persistent problem and site visits every three to five days are necessary.

Figure 2.3: Horokiri Stream at Snodgrass site with insets of the SC-200 control unit and logger setup (top left), and primary in-stream turbidity sensor (bottom left inset and pipe near weir). The back-up turbidity sensor can be seen (approximately 3 m) downstream of weir

Figure 2.4: Pauatahanui Stream at Gorge site with insets of the SC-200 control unit and logger setup (top right) and in-stream turbidity sensor with auto-sampler intake hose attached to sensor housing (bottom left)

2.2 Data collection

Turbidity, stage and flow time-series data have been collected continuously since site installation was completed. Data are telemetered via HydroTel and checked daily for faults, equipment malfunctions and wet weather events. Data are also collected from the SC-200 logger memory during routine site visits every five weeks.

The ISCO autosamplers can take up to 24 discrete water samples (Figure 2.5.). Sampling is triggered by stage at the Porirua site and by turbidity at the

Horokiri and Pauatahanui sites, with the samplers programmed to collect samples at set intervals (eg, 5-15 minutes) (Table 2.2). Sampling ceases when the stage or turbidity has dropped below a set trigger. All samples taken by the automatic samplers are dispatched to Hill Laboratories, typically within 48 hours, for determination of turbidity and suspended sediment concentration (SSC) (see Appendix 1 for a summary of laboratory methods). The lab turbidity data are used to validate whether the field sensor is operating correctly.

For the 2014/15 monitoring period, only a selection of autosamples were sent to the laboratory for SSC and turbidity analysis, based on gaps in the existing turbidity record where there were few or no SSC results.

Figure 2.5: Autosampler bottle carriage with 24 samples collected on 14 May 2015 at the Horokiri Stream monitoring site. This flood was a 10-year return period event for the Horokiri catchment

2.3 Data processing

Turbidity data can be very 'noisy' and often need editing to remove erroneous values (Figure 2.6). Spiking occurs in the data when debris floats past the turbidity sensor face or fouling of the sensor lens has occurred.

Data are manually edited where possible or removed from the record and a data gap created as per the procedures outlined in NEMS (2013). During the reporting period, the cause of spiking at the three monitoring sites was typically debris (rubbish, leaves, branches, etc.) snagged around or passing by the sensor housing, algal growth on and around the sensor face/housing and loitering fish.

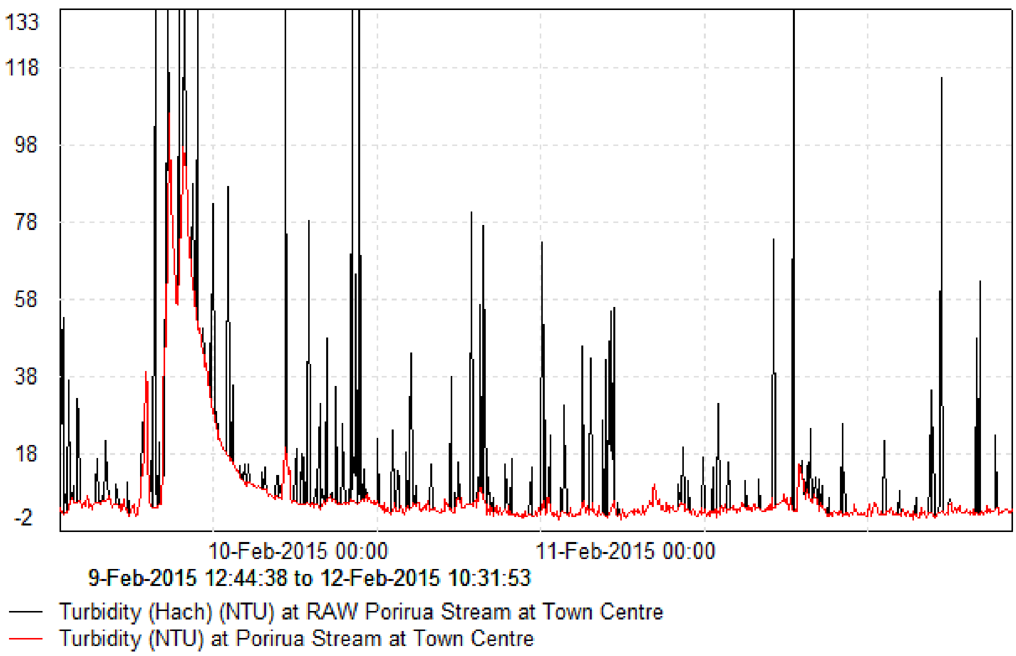


Figure 2.6: Continuous turbidity record illustrating the raw (black) versus edited (red) turbidity data. The original raw turbidity trace shows the amount of noise that needs to be removed

Less than three days (~0.8%) of data were lost at both the Porirua and Pauatahanui Stream sites and two days (~0.55%) of data were lost at the Horokiri Stream site. This was a significant improvement on the previous monitoring period where approximately 17%, 11% and 19% of the data were lost at the Porirua, Horokiri and Pauatahanui sites, respectively.

The NEMS for Turbidity Recording (2013) recommends that derived data be generated to patch large periods of data lost due to sensor malfunction or discarded as a result of the editing process. During the flood event on 14 and 15 May 2015 the SC-200 unit at the Horokiri Stream site malfunctioned which resulted in approximately 28 hours of lost data. The OBS-3 back-up sensor however, remained fully functional throughout this period. This back-up record was used to create a derived record for the primary sensor as per the procedures outlined by NEMS (2013). To do this overlapping periods of edited data from both sensors were used to build a relationship between the two sensors (Figure 2.7) and the resulting function applied to the back-up sensors record during this 28-hour gap. This was also done for several other gaps in the primary sensor's record during periods of algal fouling in March and April 2014. Any derived data was quality coded QC300 to specifications outlined in (NEMS 2013).

Gaps in the turbidity records of both the Porirua and Pauatahanui sites (and the Horokiri site before the OBS-3 sensor was installed) were left in the record. With no back-up sensor, derived data to patch these gaps has to be created from a rating relationship between turbidity and stream discharge. This is still a 'work in progress'. The NEMS (2013) also recommends assigning quality codes to archived turbidity data. With the exception of the derived data generated for the Horokiri site, this practice is still to be implemented.

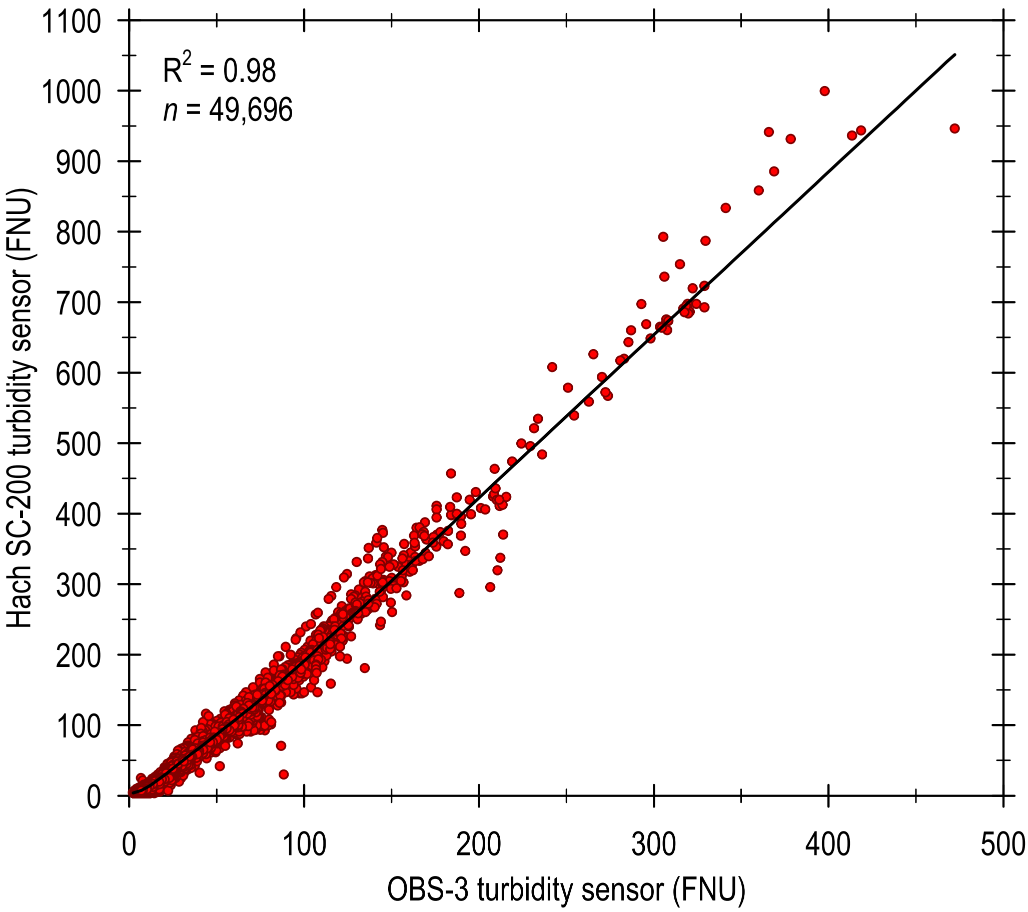


Figure 2.7: Relationship between the primary turbidity sensor (Hach SC-200 unit) and the back-up turbidity sensor (OBS-3) at the Horokiri Stream site

2.3.1 Turbidity and SSC

In Section 3 linear regression is used to examine the field and laboratory turbidity data. While a strong linear relationship may exist between the two data sets, it is not unusual for there to be differences between field and laboratory turbidity data. This is because the instruments do not measure nephelometric turbidity in the same way (mainly due to differences in optical design), sensors sometimes drift and the field sensor calibration may not be as robust as the laboratory sensor calibration (Davies-Colley & Smith 2001; Hicks 2009).

The underlying relationship between SSC and flow is typically represented by a power-law model, therefore, the untransformed SSC and flow data are displayed with the corresponding power-law functions.

Site-specific regression relationships between log-transformed field turbidity data and SSC were used to convert the turbidity time series into a record of SSC.[2] The resulting equations were then used to calculate annual and event-specific suspended sediment loads and yields for each stream catchment. These relationships are constantly being refined as more SSC samples are collected and thus sediment loads and yields in this report will vary from those reported in Morar et al. (2015) and in future reports.

[2] Retransformation bias was corrected for using the smearing estimate of Duan (1983).

2.3.2 Sediment loads and yields

The field data are used to calculate both annual and event-specific sediment loads and yields. However, the calculated loads and yields are strictly provisional for the following reasons:

- As outlined above, there are many gaps in the continuous turbidity data which are yet to be ‘patched’. Some of these gaps coincide with storm or flood events (when the majority of sediment is transported) which means the sediment loads/yields presented in this report may be underestimates.

- It is necessary to collect many years of data before we can fully characterise the annual and event-based sediment yields for each catchment.

- Sediment gaugings and particle grain size analyses still need to be carried out at each site to determine whether the turbidity sensor’s data are representative of suspended sediment concentrations over the entire stream width and what influence sediment grain size has on suspended sediment concentrations.

For completeness of analysis, event-specific sediment yields were calculated for events with a ≥ 1-year return period[3] going back to the installation of each turbidity sensor in 2012/13. The start of each event was defined as the point when flow began to rise, while the end of was determined manually by visually delineating when flows and turbidity had dropped to a stable level (turbidity <10 FNU). Whilst it was essential to determine the start point, the point at which an event is defined to have ended is unlikely to influence the sediment load significantly (Andrew Hughes, pers. comm.). Sometimes events were combined when several peaks occurred (due to ongoing rainfall) before flows returned to a stable level (ie, some events are of longer duration than others).

[3] Deriving return period flood flows using an annual maximum series assumes that exactly one flood occurs per year. The analysis associated with the annual maximum series is commonly used for deriving low-frequency high magnitude floods, but does not adequately represent low magnitude floods – which may occur several times a year. A peaks over threshold (POT) flood analysis explicitly considers multiple flood events per year and was used here for estimating return periods of common events such as a 6-month return period (Maidment 1992).

3. Results

This section presents a summary of the field turbidity and SSC data collected at each of the three monitoring sites between 1 July 2014 and 30 June 2015. In addition, provisional event-based sediment loads and annual sediment yields are presented for all three stream catchments for the full monitoring period, 2013–2015. These loads are converted from turbidity data with several data gaps. Some of these have occurred during major flood events. Therefore the sediment loads presented here may underestimate the annual yields.

3.1 Porirua Stream

3.1.1 Continuous record

The edited turbidity and flow records at the Porirua Stream monitoring site for the 2014/15 monitoring period are shown in Figure 3.1. This figure also presents daily rainfall totals recorded at the Seton Nossitor Park rainfall station. Fouling of the sensor resulted in one major gap in the turbidity record at the beginning of October which lasted more than two days. Two other minor gaps (<5 hours each) in February were also the result of sensor fouling. These gaps coincided with small flood events of less than 0.25-year return period event.

A turbidity reading of 3,167 FNU was recorded at the site during a 20-year return period event (66 m^3/s) on 14 May 2015 (Figure 3.1). This was the biggest event at this site since the turbidity sensor was installed in August 2012. The Seton Nossitor Park rainfall gauge recorded 37 mm of rainfall in the 24 hours preceding the event and then ongoing rainfall during the event (daily total of 76 mm). A turbidity reading of 1,314 FNU was also recorded on 7 March 2015 following 17.4 mm of rainfall as recorded at the Tawa Pool rainfall gauge.

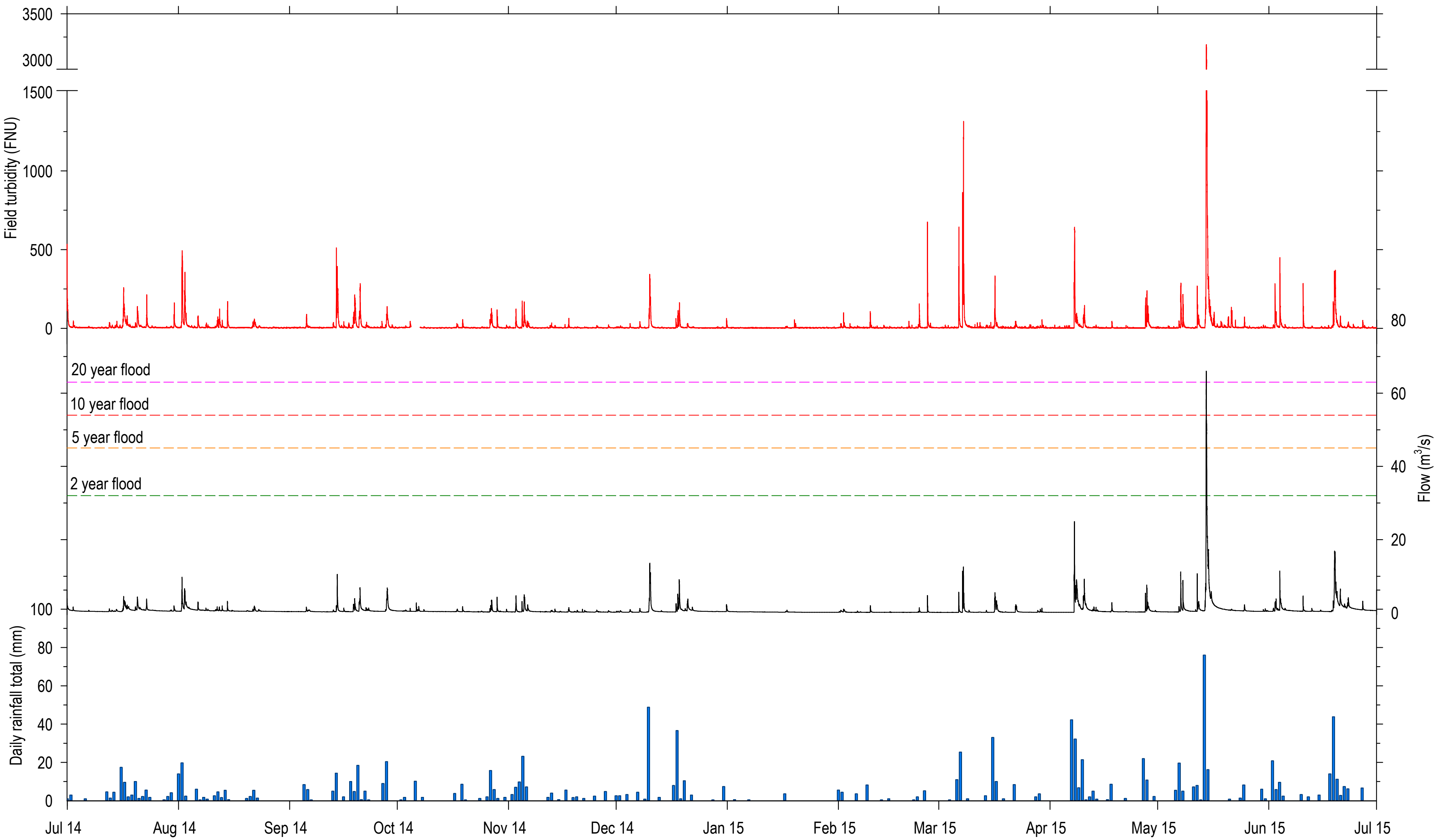


Figure 3.1: Plots of (continuous) turbidity and flow at the Porirua Stream monitoring site and total daily rainfall at Seton Nossitor Park (or Tawa Pool where data missing) between 1 July 2014 and 30 June 2015

3.1.2 Autosampler results

In 2014/15, 78 stream samples were sent for laboratory analysis across six different events. As mentioned in Section 2.2, these samples were selected based on gaps in the SSC/turbidity relationship. A summary of the sample results is given in Table 3.1. No sample below a turbidity of 189 FNU was sent for analysis with 68 (87 %) of samples being ≥ 500 FNU. This was done to provide more confidence at the higher end of the SSC/turbidity relationship, where fewer samples had been collected to date.

Table 3.1: Range (minimum and maximum) of turbidity and suspended sediment concentrations (SSC) in water samples taken by the autosampler at Porirua Stream, along with total rainfall recorded at Seton Nossiter Park prior to sample collection. Each date is a separate 'event' (ie, samples collected in sequence)

Date	Total rainfall (mm) prior to first sample		*n*	Lab turbidity (NTU)	Field turbidity (FNU)	SSC (g/m³)
	0–6hr	6–24hr				
14/09/2014	12.4	4.0	1	280	344	730
07/03/2015	17.4*	0*	20	187 – 910	381 – 1,233	500 – 1,700
07/04/2015	27.8	0	24	113 – 260	189 – 423	290 – 730
14/05/2015	28.8	7.8	21	191 – 4,300	570 – 3,118	570 – 5,800
04/06/2015	4.0	12.4	3	290 – 330	375 – 447	780 – 1,200
19/06/2015	26.4	17.2	8	220 – 260	271 – 364	470 – 980

*Rainfall data from Seton Nossitor Park not available so rainfall data from Tawa Pool used.

The results of all samples collected at the site are also presented in Figure 3.2, with the 2014/15 results highlighted in blue to distinguish them from the 2012–2014 results.

(a) Field turbidity versus lab turbidity

The 2014/15 lab turbidity and field turbidity data show a strong relationship (R^2=0.95). This indicates that the field sensor performed well during the reporting period.

(b) SSC, field turbidity and flow

With the addition of the 2014/15 data, the relationship between SSC and field turbidity continues to improve and indicates a good relationship between the two variables (R^2=0.95) (Figure 3.2). On 14 May 2015, a SSC of 5,800 g/m^3 was recorded following 29 mm of rainfall in the preceding six hours. This is the highest SSC recorded at this site.

The fitted power law relationship between SSC and flow is shown in Figure 3.2 (R^2=0.78). For the 2014/15 period, no stream samples below a flow of 7 m^3/s were analysed for SSC. The 20-year return period event on 14 May 2015 (66 m^3/s) was the biggest recorded at the site since the turbidity sensor was installed in 2012. Twenty one SSC samples were collected over a three hour and 20 minute period between a flow range of 14 and 66 m^3/s during this event with SSC results between 570–5,800 g/m^3. The largest event prior to this for which SSC results were collected, was 25 m^3/s (1.5-year return period event) on 16 April 2014.

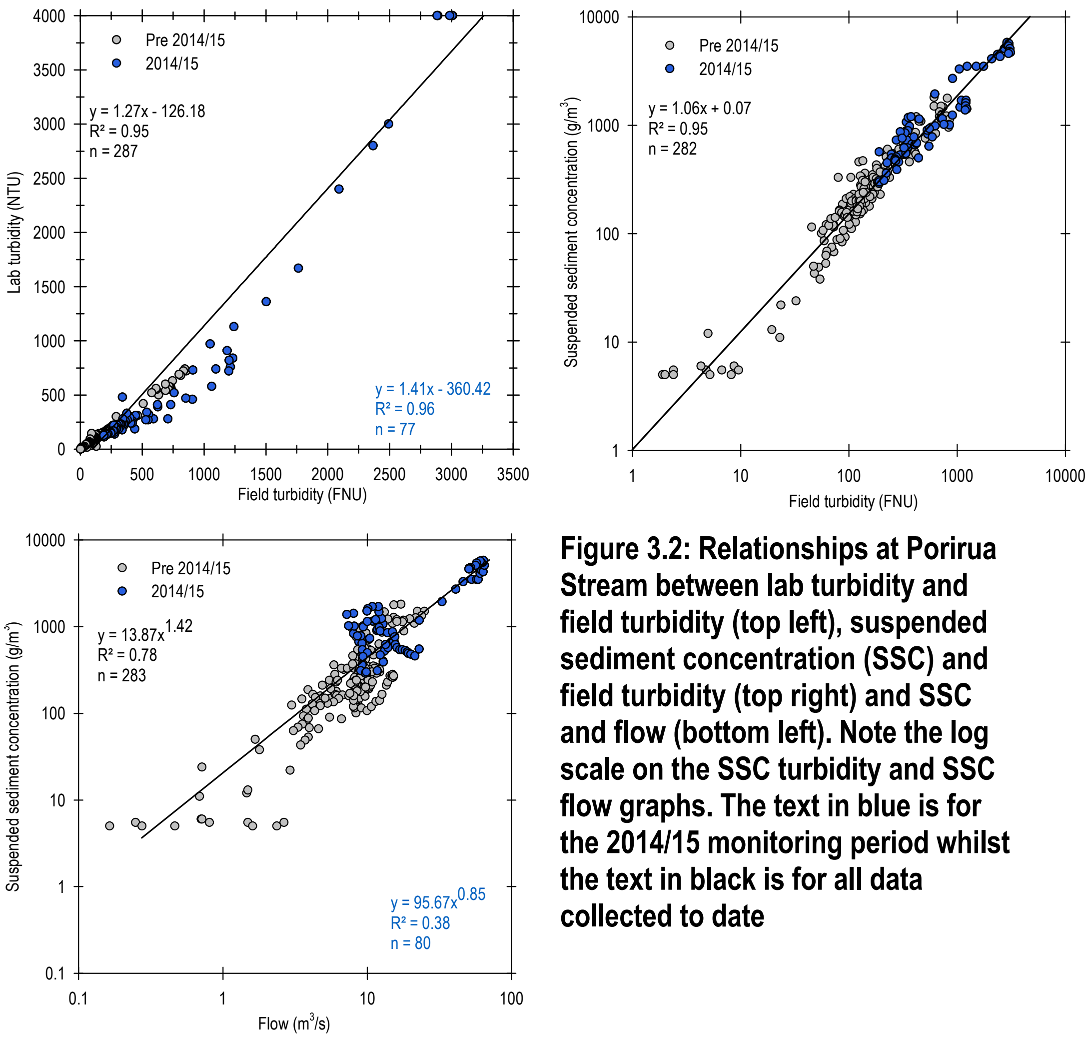


Figure 3.2: Relationships at Porirua Stream between lab turbidity and field turbidity (top left), suspended sediment concentration (SSC) and field turbidity (top right) and SSC and flow (bottom left). Note the log scale on the SSC turbidity and SSC flow graphs. The text in blue is for the 2014/15 monitoring period whilst the text in black is for all data collected to date

The relationship between flow and sampled SSC for five flood events in 2014/15 is shown in Figure 3.3. Whilst the events on 7 March, 14 May and 4 June 2015 show anti-clockwise hysteresis, the event on 19 June 2015 has a clockwise pattern. This variability between events is consistent with hysteresis patterns of the 15 flood events sampled for SSC prior to the 2014/15 monitoring period (not shown) and suggests different sediment sources prevail within and between events. For example, clockwise hysteresis suggests riparian sources that exhaust (flush-out) early during events, while anti-clockwise loops may indicate distant (ie, headwater) sources, delayed turbid runoff (eg, spill from retention ponds), or erosion mechanisms more prominent during recessions (eg, bank erosion driven by pore-water pressure associated with rapid stage fall).

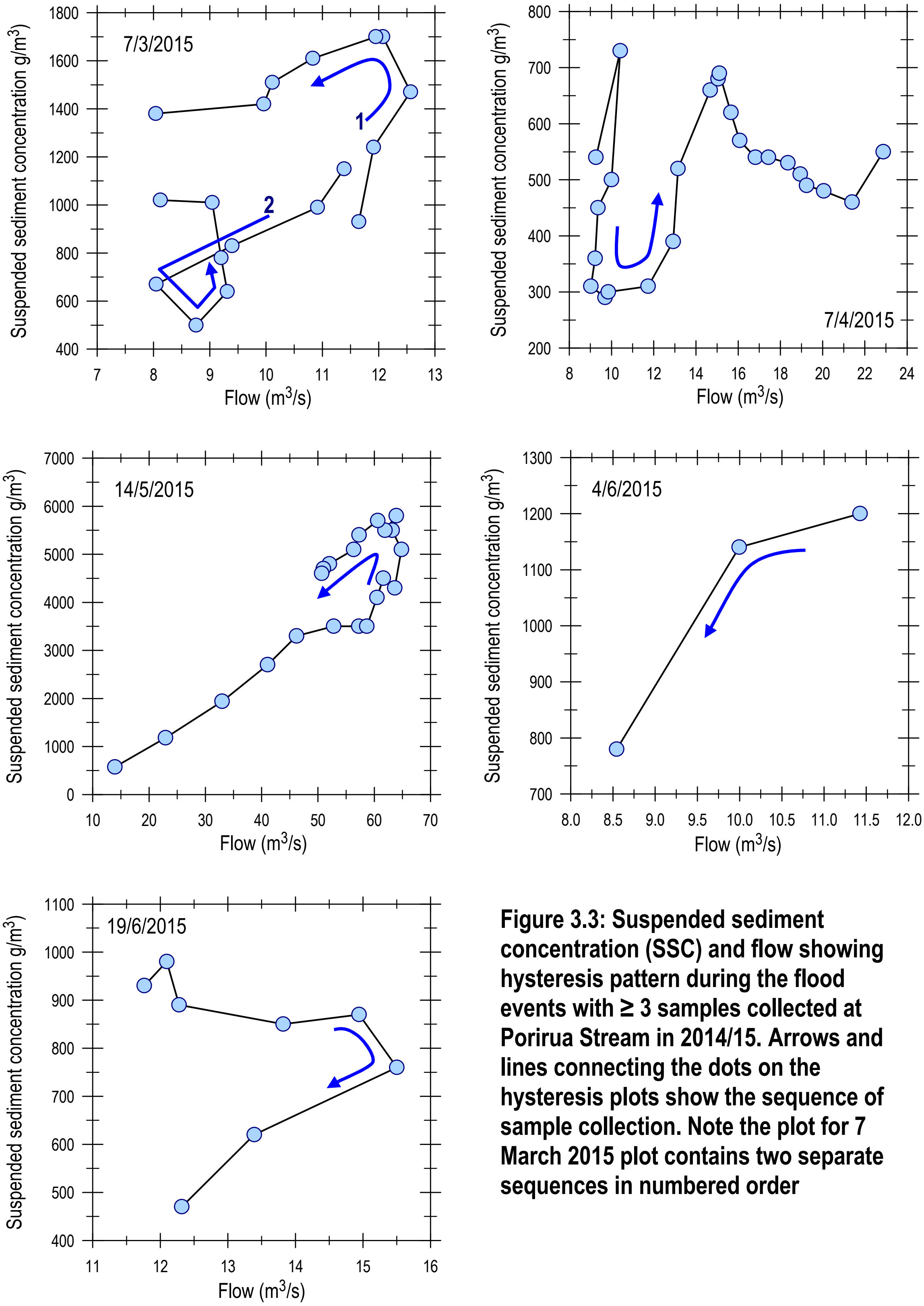


Figure 3.3: Suspended sediment concentration (SSC) and flow showing hysteresis pattern during the flood events with ≥ 3 samples collected at Porirua Stream in 2014/15. Arrows and lines connecting the dots on the hysteresis plots show the sequence of sample collection. Note the plot for 7 March 2015 plot contains two separate sequences in numbered order

3.1.3 Sediment yield calculations

(a) Annual specific suspended sediment yield

The annual specific yield estimates for the Porirua Stream catchment since monitoring began are summarised in Table 3.2. The annual yields for 2013, 2014 and the first six months of 2015 thus far were 0.25, 0.13 and 0.51 t/ha/yr, respectively. For comparison, the estimate of average annual sediment yield generated by the CLUES (Catchment Land Use for Environmental Sustainability) model for the Porirua Stream catchment was approximately 2 t/ha/yr (Green et al. 2014), assuming the worst-case scenario with no mitigation for sediment runoff. With sediment runoff mitigation, best management practices and refined land use yields that more accurately represent the Porirua Harbour catchment, the CLUES-based sediment yield estimate is 0.6 t/ha/yr (Green et al. 2014).

Annual specific sediment yields presented in Morar et al. (2015) for the Porirua Stream catchment differ from those reported here. As mentioned earlier the relationship between turbidity and SSC is continually changing as new data are collected. Prior to 2014/15, the highest turbidity ever registered at this site was 1,172 FNU; most of the SSC samples collected during the floods of 7 March 2015 and 14 May 2015 had a turbidity of >1,200 FNU, where there was a large gap in the SSC/turbidity relationship. Therefore, the annual sediment yield of 0.67 t/ha/yr calculated for 2013 presented in Morar et al. (2015) has now been recalculated as 0.25 t/ha/yr (Table 3.2).

Table 3.2: Estimated annual specific sediment loads and yields for the Porirua Stream catchment from 29 August 2012 to 30 June 2015. Note these calculations do not account for missing data or the contribution from the Kenepuru Stream subcatchment

Year	Total time monitored	Period of data lost (%)	Total sediment load (kt)	t/ha/yr
2012	124 days 10 hrs 5 mins	23 days 0 hrs 45 mins (19%)	0.08	0.021
2013	365 days	38 days 3 hrs 35 mins (10%)	0.99	0.252
2014	365 days	56 days 21 hrs 55 mins (16%)	0.51	0.130
2015	181 days	7 hrs 30 mins (0.2%)	2.00	0.508
Total	*1035 days 10 hrs 5 mins*	*118 days 9 hours 15 mins (11%)*	*3.59*	*0.911*

(b) Event suspended sediment yield

Table 3.3 summarises the sediment yields of 10 events from the 29 August 2012 to the 30 June 2015 and Figure 3.4 illustrates the contribution of each event to the total sediment load. There were 19 events with a ≥ 1-year return period during this time but some of these were combined into single events because the flood prior to this hadn't ended before another one began. These multi-peaked events demonstrate the flashy nature of the Porirua Stream and hence the short duration of floods compared to the Horokiri and Pauatahanui streams (Table 3.3).

The 14 May flood (Figure 3.5) produced more sediment (1.62 kt) in two days of elevated flow than was produced in the 854 days from 29 August 2012 to the 31 December 2014 (1.59 kt). This 20-year return period event was the biggest since a 50-year return period event on 20 June 1980. One other notable flood on 4 February 2013 produced 0.2 kt; this is likely to be a slight underestimate of the total sediment load for this event because eight hours' of data were lost when the sensor dislodged from its housing towards the end of the event.

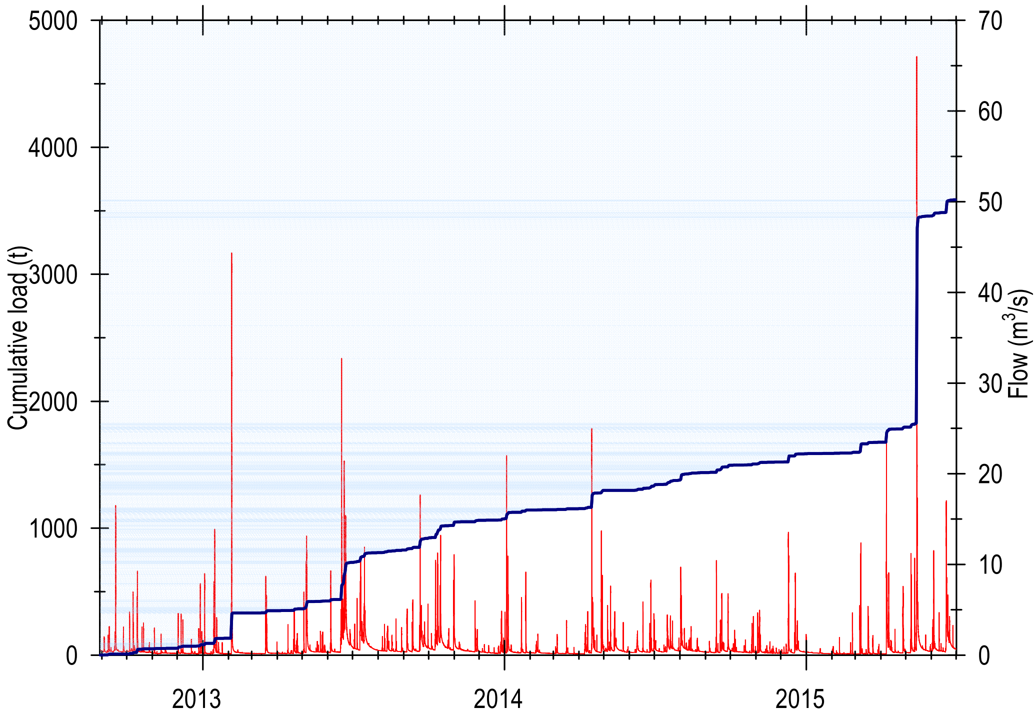


Figure 3.4: Cumulative sediment load (blue line) versus stream flow (red line) in the Porirua Stream at Town Centre from 29 August 2012 to 30 June 2015

Table 3.3: Estimated sediment yields for Porirua Stream at Town Centre during events with ≥ 1-year return period from 29 August 2012 to 30 June 2015

Year	Events (≥ 1 year return period)	Duration (time)	Lost data (time)	Maximum turbidity (FNU)	Total sediment load (t)	t/ha	Maximum flow (m^3/s)	Flood return period
2012	17/09/2012	19 hrs 15 mins	19 hrs 15 mins	-	-	-	16.49	1 year
2013	04 – 05/02/2013	1 day 15 hrs 5 mins	8 hrs 5 mins	1,131	198.7	0.051	44.34	2 years
	16 – 18/06/2013	2 days 15 hrs 25 mins	-	870	120.2	0.031	32.72	2 years
	19 – 23/06/2013	4 days 17 hrs 55 mins	-	384	165.5	0.042	21.40	1 year
	20 – 22/09/2013	2 days 0 hrs 30 mins	-	820	62.1	0.016	17.67	1 year
2014	03 – 04/01/2014	15 hrs 55 mins	-	474	33.4	0.009	21.99	1 year
	16 – 18/04/2014	2 days 2 hrs 20 mins	-	857	108.7	0.028	25.00	1 year
2015	07 – 09/04/2015	2 days 1 hr 35 mins	-	642	91.4	0.023	24.70	1 year
	14 – 17/05/2015	2 days 18 hrs 45 mins	-	3,167	1,623	0.412	66.00	20 years
	18 – 20/06/2015	1 day 16 hrs 55 mins	-	370	89.5	0.023	17.00	1 year

Figure 3.5: Porirua Stream during the 14 May 2015 flood event (top – photo courtesy of Keith Calder, Porirua City Council) and at low flow (bottom). Photos taken approximately 200 m downstream of GWRC's turbidity sensor site

3.2 Horokiri Stream

3.2.1 Continuous turbidity

Figure 3.6 displays the continuous turbidity, stream flow and total daily rainfall at the Horokiri Stream monitoring site from 1 July 2014 until 30 June 2015.

The amount of data lost due to the primary sensor fouling or malfunctioning was less in 2014/15 than previous years. The installation of the back-up sensor also allowed the missing data to be patched with the derived record generated from the relationship between the primary and back-up sensors. However, simultaneous fouling of both sensors during periods of low flow in January 2015 resulted in nearly two days of lost data. During the 14 May 2015 flood almost 28 hours of the primary sensor's data were missing after the sensor malfunctioned; the back-up sensor remained fully functional during this period and was subsequently used to generate derived data.

A turbidity reading of 1,002 FNU was recorded at the site during a 10-year return period event (60 m^3/s) on 14 May 2015 (Figure 3.6). This followed 50 mm of rainfall in the upper Horokiri Stream catchment (Battle Hill Park rain gauge) in the preceding 10 hours plus ongoing rainfall during the event (daily total of 141 mm). Whilst this was the biggest flood event at this site since the turbidity sensor was installed in November 2012, a higher turbidity reading of >4,000 FNU was recorded during a 2-year return period event on 4 February 2013. A turbidity reading of 1,398 FNU on 19 September 2014 was the second highest measurement recorded during the 2014/15 year and followed 52.5 mm of rainfall.

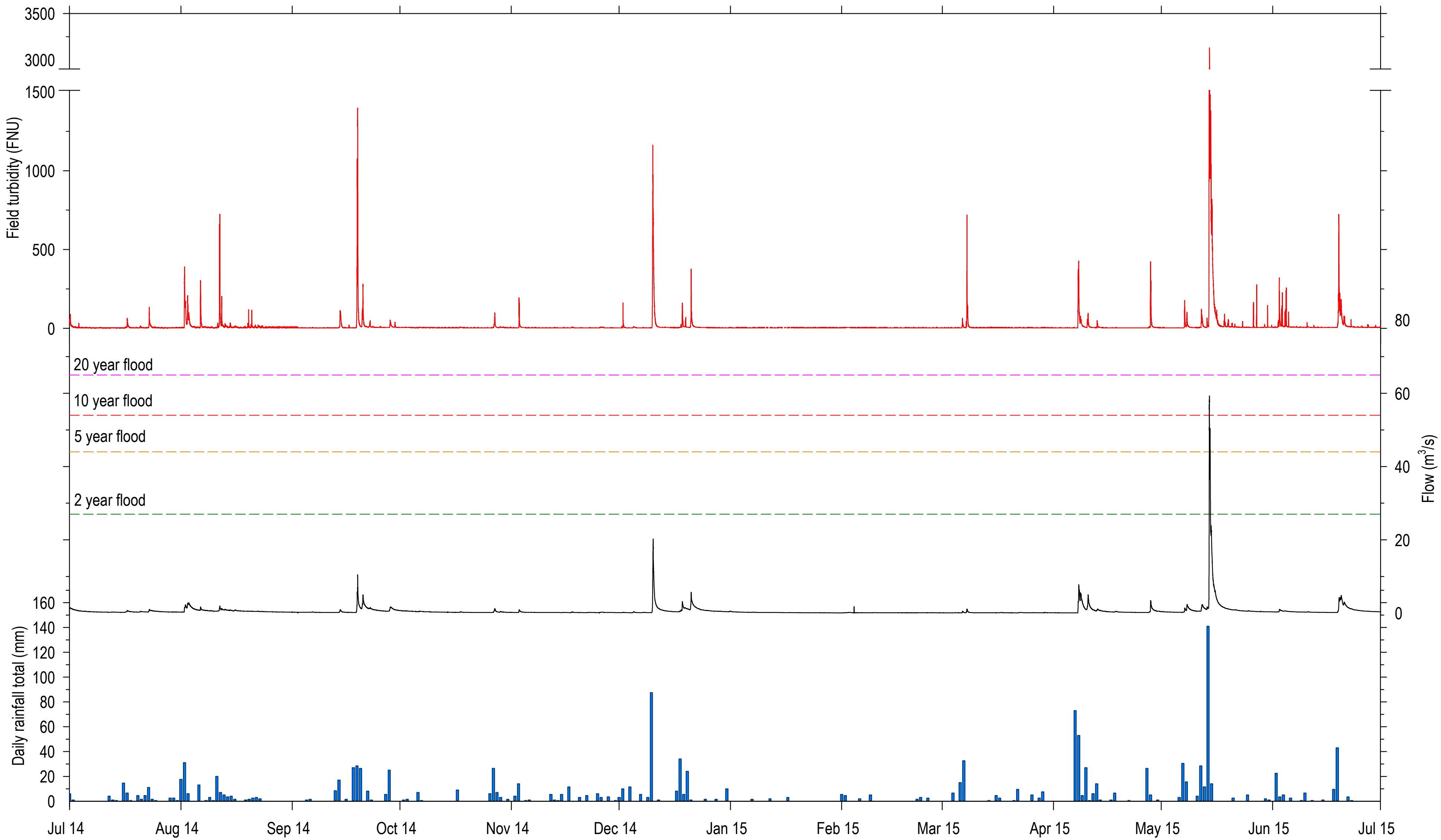


Figure 3.6: Plots of (continuous) turbidity and flow at the Horokiri Stream monitoring site and total daily rainfall at Battle Hill Park between 1 July 2014 and 30 June 2015 (note the turbidity record for May 2015 includes some derived data)

3.2.2 Autosampler results

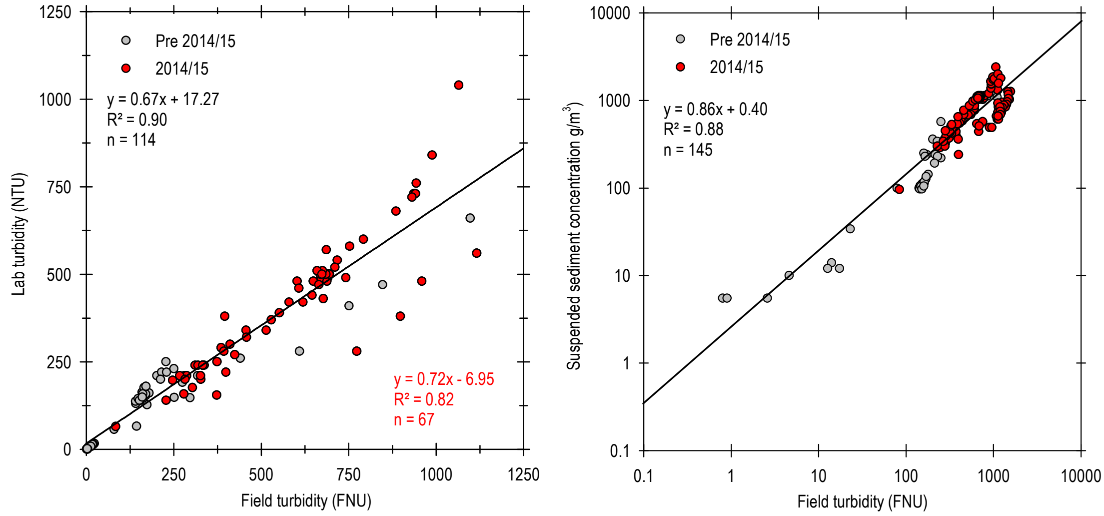
In 2014/15, 103 stream samples were sent for laboratory analysis across eight different events. Samples sent for laboratory analysis were selected to fill gaps in the SSC/turbidity relationship. A summary of the sample results is provided in Table 3.4. Of the 103 stream samples, 28 (25%) recorded turbidity values were <500 FNU.

Table 3.4: Range (minimum and maximum) of turbidity and suspended sediment concentrations (SSC) in water samples taken by the autosampler at Horokiri Stream, along with total rainfall recorded at Battle Hill prior to sample collection. Each date is a separate 'event' (ie, samples collected in sequence)

Date	Total rainfall (mm) prior to first sample		*n*	Lab turbidity (NTU)	Field turbidity (FNU)	SSC (g/m^3)
	0–6hr	6–24hr				
19/09/2014	2	53	1	65	83.7	96
20/09/2014	18.5	8	2	197 – 210	247 – 281	290 – 320
10/12/2014	58.5	10.5	11	280 – 580	514 – 1,116	440 – 1,310
21/12/2014	24.5	0	2	155 – 158	279 – 373	300 – 400
07/03/2015	31	0	5	140 – 570	228 – 686	240 – 510
07/04/2015	47.5	0	11	200 – 300	267 – 424	340 – 590
14/05/2015	55.5	13	47	210 – 2,700	327 – 1,568	510 – 2,400
19/06/2015	36	16.5	24	200 – 540	282 – 718	450 – 1,130

(a) Field vs lab turbidity

Figure 3.7 shows the relationship between lab turbidity and field turbidity at the Horokiri Stream monitoring site (R^2=0.82) and indicates that the field sensor has performed reasonably well during this period.



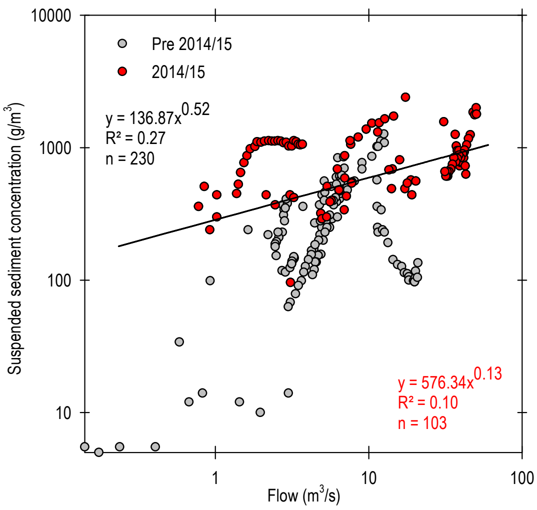


Figure 3.7: Relationships at Horokiri Stream between lab turbidity and field turbidity (top left), suspended sediment concentration (SSC) and field turbidity (top right), and SSC and flow (bottom left). Note the log scale on the SSC turbidity and SSC flow graphs. The text in red is for the 2014/15 monitoring period whilst the text in black is for all data collected to date

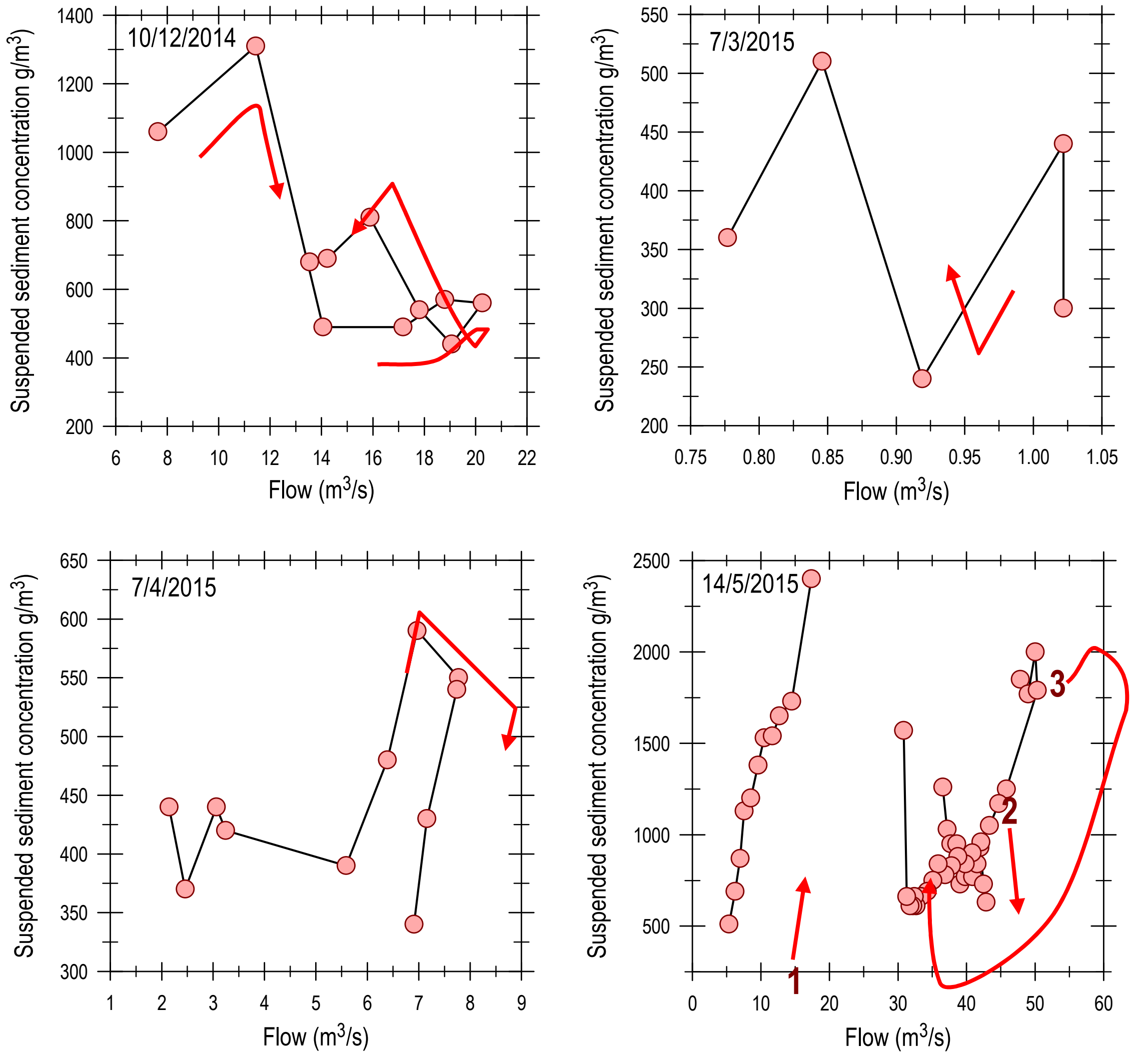
(b) SSC, field turbidity and flow

The linear relationship between field turbidity and SSC is shown in Figure 3.7 (R^2=0.88). The storm event on 14 May 2015 generated the highest suspended sediment concentration (2,400 g/m^3) recorded at this site since monitoring began; this is unlikely to be the highest sediment concentration, however, as the turbidity sensor and by association the autosampler, malfunctioned after this sample was taken. This sample was taken following 55 mm of rainfall in the upper catchment (Battle Hill Park) in the preceding six hours. During the reporting period, a further 36 SSC results were >1,000 g/m^3. Prior to 2014/15, the highest SSC result was 1,270 g/m^3 during an event on 3 May 2013.

The fitted power law relationship between SSC and flow is shown in Figure 3.7 (R^2=0.27). For the 2014/15 period, no samples below a stream flow of 7 m^3/s were analysed for SSC.

The relationship between flow and sampled SSC for five flood events in 2014/15 is shown in Figure 3.8. The events on 10 December 2014, 7 April, 14 May and 19 June 2015 all display clockwise hysteresis with SSC higher on the rising limb compared to the same flow on the falling limb. Five of the six previous events back in 2013 (3 May, 20 June and 11, 15 and 31 October – not shown) also show similar hysteresis with SSC often a magnitude or two higher on the rising limb compared to the falling limb and usually decreasing before flow has peaked. This hysteresis pattern is a characteristic of sediment exhaustion.

3.2.3 Sediment yield calculations



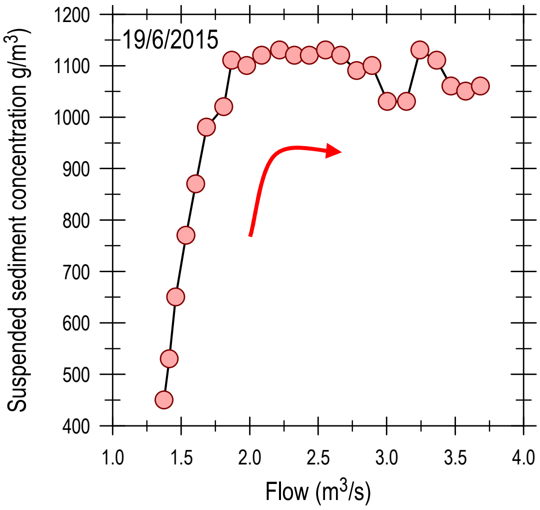


Figure 3.8: Suspended sediment concentration (SSC) and flow showing the hysteresis pattern during the flood events with ≥ 3 samples collected from Horokiri Stream in 2014/15. Arrows and lines connecting dots on the hysteresis plots show the sequence of sample collection. Note the plot for 14 May 2015 contains three separate sequences numbered in order

(a) Annual specific suspended sediment yield

The annual suspended sediment yields for the Horokiri Stream catchment are summarised in Table 3.5. The annual yields for 2013, 2014 and the first 181 days of 2015 were 0.49, 0.23 and 1.16 t/ha/yr, respectively. The annual average estimates of catchment sediment yield predicted using the CLUES model for the same catchment were 2.5 t/ha/yr without sediment mitigation, and 1.01 t/ha/yr with mitigation and implementation of best management practices (Green et al. 2014).

Table 3.5: Estimated annual specific sediment yields for the Horokiri Stream catchment from 14 November 2012 to 30 June 2015. Note these calculations do not account for missing data

Year	Total time monitored	Period data lost (%)	Total sediment load (kt)	t/ha/yr
2012	47 days 12 hrs 55 mins	14 days 9 hrs (30%)	0.03	0.010
2013	365 days	48 days 11 hrs 50 mins (13%)	1.40	0.486
2014	365 days	1 day 1 hr 15 mins (0.3%)	0.65	0.225
2015	181 days	1 day 23 hrs 35 mins (1%)	3.33	1.157
Total	*958 days 12 hrs 55 mins*	*65 days 21 hrs 40 mins (7%)*	*5.40*	*1.878*

(b) Event suspended sediment yield

Unfortunately, there were data gaps for five of the seven flood events with ≥1-year return period (Table 3.6). These gaps were related to sensor malfunctions during the rising stages of each flood. Therefore, the sediment loads calculated for the first four events listed in Table 3.6 are likely to underestimate actual sediment loads given the sensor stopped working before maximum sediment concentrations were reached. A secondary sensor subsequently installed at this site was used to generate derived data for the fifth event during which the primary sensor malfunctioned.

Figure 3.9 shows the contribution of each event to the sediment load. The 2-year return period event on 4 February 2013 was the second biggest flood since the site's establishment, producing 940 t of sediment. The largest flood event recorded at this site to date in May 2015 (Figure 3.10), however, contributed more than 3,000 t of sediment; the greatest load of any event across all three monitored sites.

Table 3.6: Event sediment yields for Horokiri Stream floods with ≥ 1 year return period from 14 November 2012 to 30 June 2015

Year	Events (≥ 1 year return period)	Duration (time)	Lost data (time)	Maximum turbidity (FNU)	Total sediment load (t)	t/ha	Maximum flow (m³/s)	Flood return period
2013	04–07/02/2013	2 days 15 hrs 5 mins	8 hrs 45 mins	4,377	934.0	0.325	39.24	2 years
	18–20/03/2013	2 days 2 hrs	22 hrs 2 mins	2,348	145.5	0.051	16.63	1 year
	03–05/05/2013	2 days 13 hrs 50 mins	10 hrs 35 mins	1,799	46.7	0.016	12.80	1 year
	16–25/06/2013	9 days 9 hrs 20 mins	5 days 4 hrs 40 mins	814	160.4	0.056	22.09	1 year
2014	18–22/09/2014	3 days 7 hrs 25 mins	-	1,398	154.5	0.054	10.43	1 year
	10–12/12/2014	2 days 1 hr 45 mins	-	1,162	314.2	0.109	20.26	1 year
2015	13–19/05/2015	6 days 21 hrs 20 mins	0*	3,131	3,142	1.094	59.25	10 years

*Derived data generated using back-up sensor.

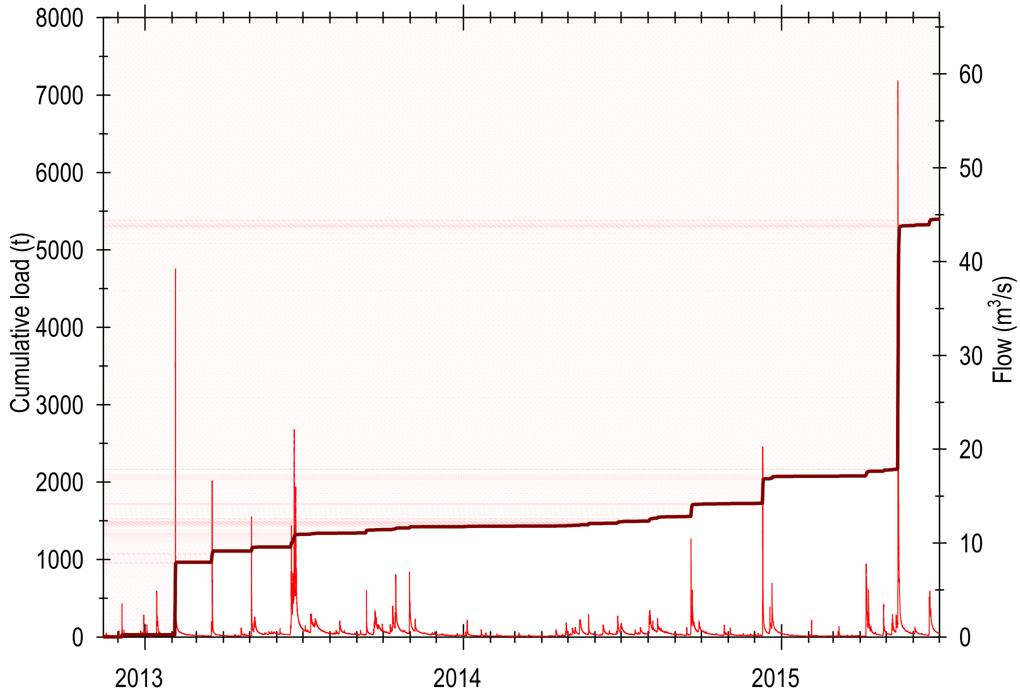


Figure 3.9: Cumulative sediment load (maroon line) versus stream flow (red line) in the Horokiri Stream from 14 November 2012 to 30 June 2015

Figure 3.10: Horokiri Stream monitoring site during the 14 May 2015 flood event (top) and at low flow (bottom)

3.3 Pauatahanui Stream

3.3.1 Continuous turbidity

Figure 3.11 displays the continuous turbidity, stream flow and total daily rainfall at the Pauatahanui Stream monitoring site from 1 July 2014 until 30 June 2015. Less than three days of data were lost from the record in 2014/15 (none of which occurred during elevated flows). Most of the data loss occurred during a period of sensor malfunction at the beginning of May 2015. This was a significant improvement on the previous 13 months when communication issues between the sensor and logger, fouling of the lens and sensor repairs resulted in approximately 54 days of lost data; some of the data loss occurred during moderate flood events.

3.3.2 Autosampler results

Table 3.7 summarises the sample results collected in 2014/15 at the Pauatahanui Stream monitoring site. A total of 82 stream samples were analysed for SSC across seven events during this 12-month period. As for the other sites, samples sent for laboratory analysis in 2014/15 were based on gaps in the SSC/turbidity record.

A turbidity value of 3,553 FNU was the highest recorded at the site during a 4-year return period event (47 m^3/s) on 14 May 2015 (Figure 3.9). This followed nearly 63 mm of rainfall in the upper catchment at the Battle Hill Park rain gauge in the preceding six hours. However, a higher turbidity reading of >4,000 FNU was recorded during a <1-year return period event (9 m^3/s) on 20 September 2013. A turbidity value of 2,543 FNU on 19 September 2014 was the second highest turbidity recorded during the 2014/15 period. This was during a <1-year return period event (14 m^3/s) following 33 mm of rainfall in the preceding six hours.

Table 3.7: Range (minimum and maximum) of turbidity and suspended sediment concentrations (SSC) in water samples taken by the autosampler at Pauatahanui Stream together with total rainfall recorded at Battle Hill prior to sample collection. Each date is a separate 'event' (ie, samples collected in sequence)

Date	Total rainfall (mm) prior to first sample		*n*	Lab turbidity (NTU)	Field turbidity (FNU)	SSC (g/m^3)
	0–6hr	6–24hr				
19/09/2014	33	20	10	43 – 2,900	61 – 2,543	53 – 3,400
13/11/2014	0*	6*	13	470 – 1,360	660 – 1,598	710 – 2,000
10/12/2014	60.5	14.5	1	250	671	750
07/04/2015	46.5	0	12	450 – 810	644 – 1,058	510 – 1,470
27/04/2015	17	9.5	12	530 – 2,500	713 – 2,262	760 – 2,600
12/05/2015	10.5	1.5	8	550 – 1,670	709 – 1,808	610 – 1,890
14/05/2015	62.5	14.5	26	580 – 4,200	763 – 3,545	830 – 3,800

*Rainfall highly localised to Pauatahanui Stream catchment

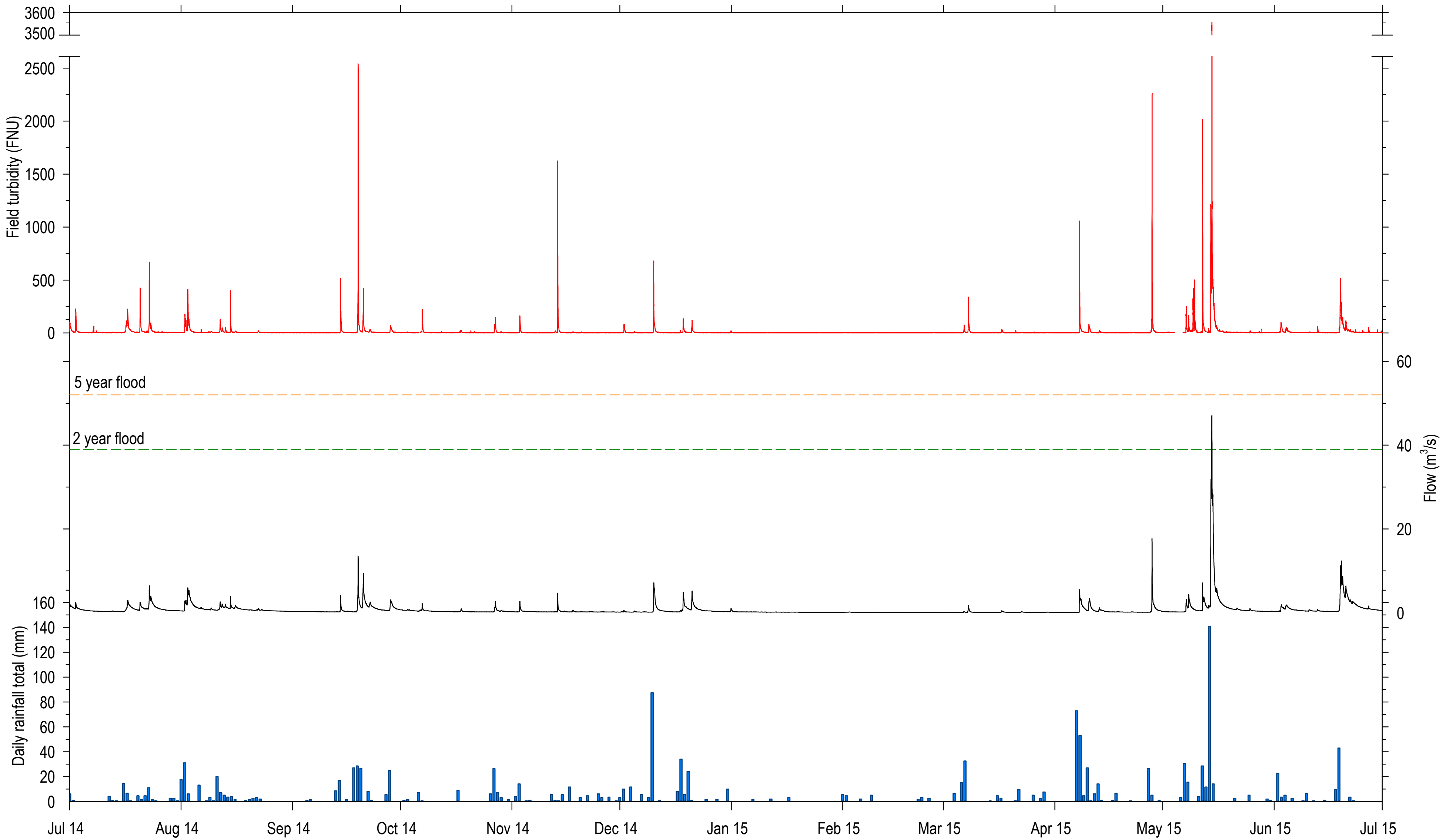
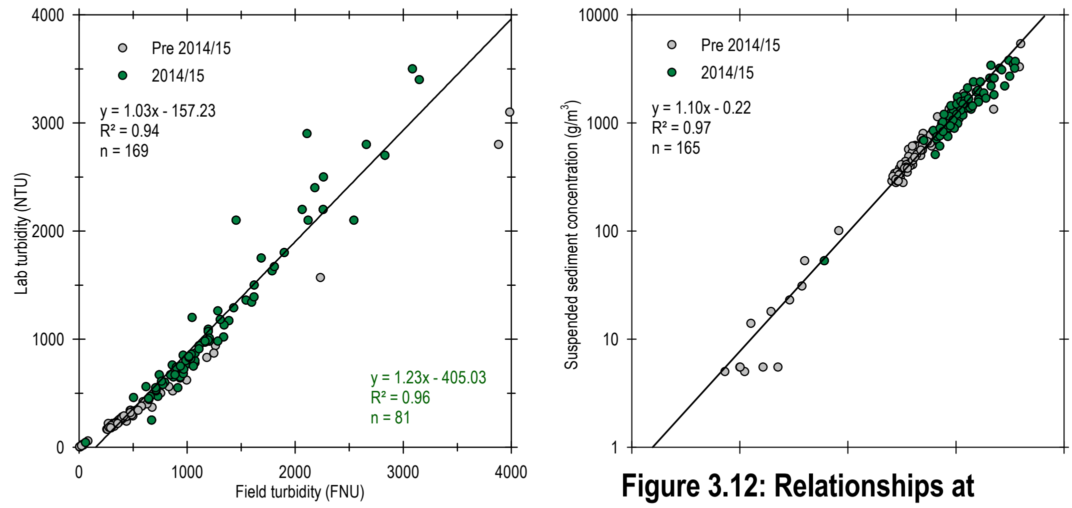


Figure 3.11: Plots of (continuous) turbidity and flow at the Pauatahanui Stream monitoring site and total daily rainfall at Battle Hill Park between 1 July 2014 and 30 June 2015

(a) Field vs lab turbidity

The relationship between field and lab turbidity is shown in Figure 3.12 and indicates that the field sensor was working well during the 2014/15 monitoring period.



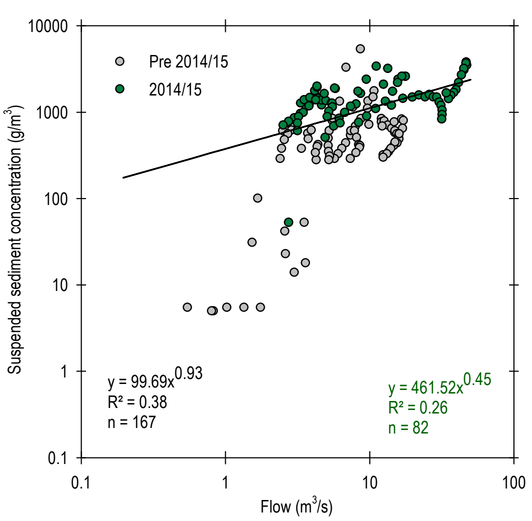


Figure 3.12: Relationships at Pauatahanui Stream between lab turbidity and field turbidity (top left), suspended sediment concentration (SSC) and field turbidity (top right), and SSC and flow (bottom left). Note the log scale on the SSC-turbidity and SSC-flow graphs. The text in green is for the 2014/15 monitoring period whilst the text in black is for all data collected to date

(b) SSC, field turbidity and flow

There was a strong linear relationship (R^2=0.86, not shown) between field turbidity and SSC at Pauatahanui Stream over the 2014/15 monitoring period (Figure 3.10). This relationship is further improved (R^2=0.97) when combined with the data collected prior to 2014/15.

The highest SSC recorded in the 2014/15 monitoring period was 3,800 g/m^3 during the 4-year return period event on 14 May 2015. This sample was taken following 63 mm of rainfall recorded at Battle Hill Park in the preceding six hours. A further 22 stream samples recorded SSC over 1,000 g/m^3 during this event. The highest SSC result recorded at this site to date is 5,400 g/m^3 during a <1-year return period event on 20 September 2013.

The relationship between SSC and flow at this site is highly variable (R^2=0.38) (Figure 3.12).

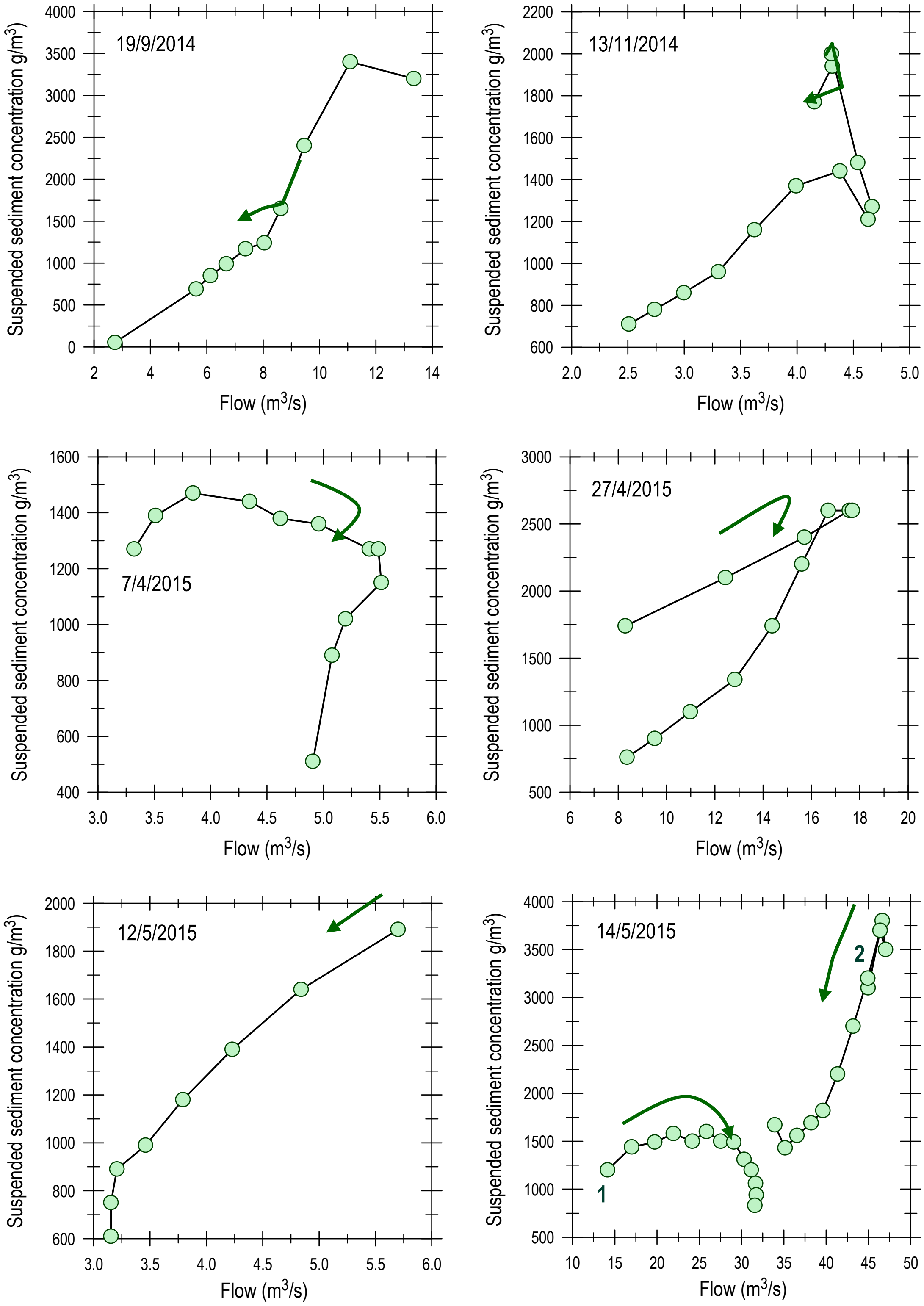


Figure 3.13: SSC and flow showing hysteresis patterns during the flood events with ≥ 3 samples collected from Pauatahanui Stream in 2014/15. Arrows and lines connecting the dots on the hysteresis plots show the sequence of sample collection. Note the plot for 14 May 2015 contains two separate sequences (numbered in order) where samples were collected.

The flood events sampled on 13 November 2014 and 7, 27 April 2015 all display clockwise hysteresis with SSC higher on the rising limb compared to the same flow on the falling limb (Figure 3.13). Furthermore, all the events prior to 2014/15 (six events: 11 and 20 September, 9, 15 and 31 October, and 3 January 2014 – not shown) show similar patterns of hysteresis with SSC peaking before flow has peaked, suggesting sediment exhaustion in this stream catchment. The events on 19 September 2014 and 12 May 2015 only have samples for the falling limb while the event on 14 May 2015 had a five hour gap between sampling sequences (with the second sequence part of the same event but a result of a second higher peak in flow).

3.3.3 Sediment yield calculations

(a) Annual specific suspended sediment yield

The estimated annual suspended sediment yields for the Pauatahanui Stream catchment are summarised in Table 3.8. The annual yields for 2013, 2014 and the first half of 2015 were 0.35, 0.18 and 0.60 t/ha/yr, respectively. For comparison, the estimates of catchment sediment yield predicted using the CLUES model for the same catchment was 1.94 t/ha/yr as a worst-case-scenario assuming no mitigation and 0.53 t/ha/yr with sediment mitigation and best management practices (Green et al. 2014).

Table 3.8: Estimated annual specific sediment yields for the Pauatahanui Stream catchment from 12 June 2013 to 30 June 2015. Note the calculations do not account for data lost during the year

Year	Total time monitored	Period data lost (%)	Total sediment load (kt)	t/ha/yr
2013	202 days 10 hrs 15 mins	15 days 14 hrs 40 mins (8%)	1.31	0.348
2014	365 days	57 days 6 hrs 30 mins (16%)	0.68	0.181
2015	181 days	2 days 8 hrs 55 mins (1%)	2.24	0.596
Total	*748 days 10 hrs 5 mins*	*75 days 6 hrs 5 mins (10%)*	*4.23*	*1.125*

(b) Event suspended sediment yield

Event-specific suspended sediment yields were calculated for events ≥1-year return period and the results summarised in Table 3.9. The yields for the first two events listed in Table 3.9 likely underestimate the actual yield given the sensor failed during the early stages of the events missing the periods of highest sediment concentration.

Table 3.9: Event sediment yields for Pauatahanui Stream floods with ≥ 1 year return period from 12 June 2013 to 30 June 2015

Year	Events (≥ 1year return period)	Duration (time)	Lost data (time)	Maximum turbidity (FNU)	Total sediment load (t)	t/ha	Maximum flow (m^3/s)	Flood return period
2013	16–25/06/2013	9 days, 9 hrs 30 mins	2 days 2 hrs 5 mins	1,723	527.1	0.140	37.6	1 year
	14–17/10/2013	3 days 4 hrs 25 mins	1 day 4 hrs 15 mins	634	123.9	0.033	15.9	1 year
	31/10/2013–02/11/2013	8 days 23 hrs 50 mins	-	647	173.8	0.046	17.2	1 year
2015	27–29/04/2015	2 days 9 hrs 25 mins	-	2,262	151.8	0.040	17.7	1 year
	14–18/05/2015	3 days 23 hrs 50 mins	-	3,553	1,730	0.460	47.1	2 years

The contribution of all flood events to the total sediment load is shown in Figure 3.14. The event on 14 May 2015 (Figure 3.15) produced the most amount of sediment. Approximately 1,730 t of sediment flowed down the stream in the nearly four days that flows remained elevated. This was 77% of the total sediment load calculated for the first six months of 2015.

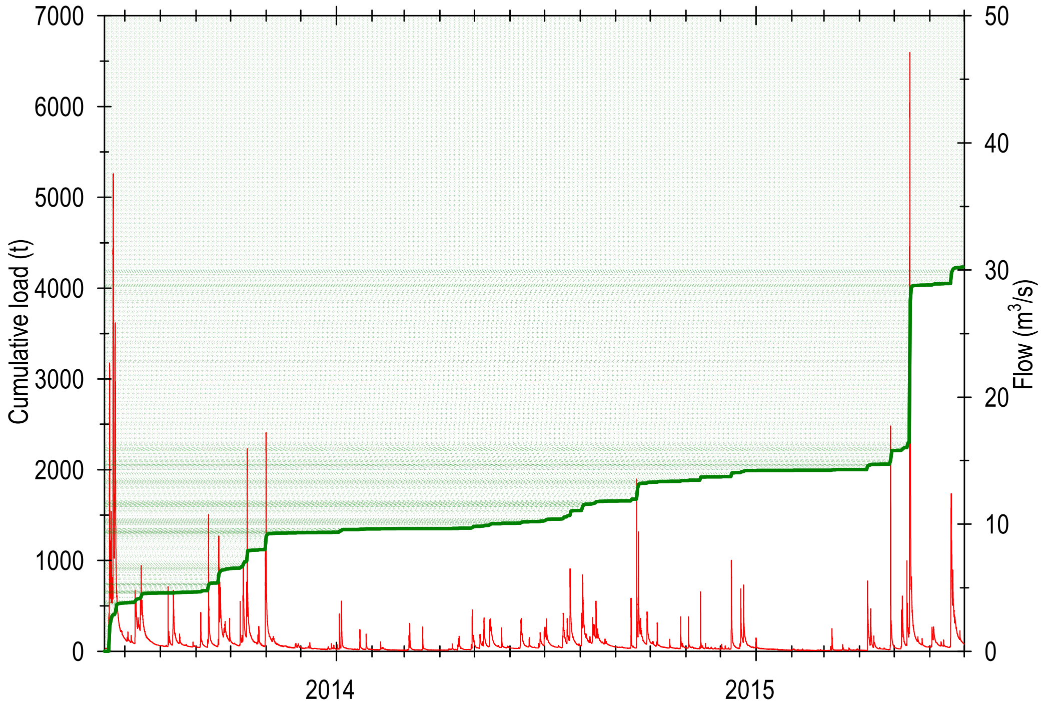


Figure 3.14: Cumulative sediment load (green line) versus stream flow (red line) in the Pauatahanui Stream from 13 June 2013 to 30 June 2015

Figure 3.15: Pauatahanui Stream monitoring site during the 14 May 2015 event (top) and at low flow (bottom)

4. Discussion

Following the installation of continuous turbidity sensors in late 2012, more than 200,000 turbidity readings and almost 600 discrete water samples have been collected across the three stream sites monitored. This represents a significant advancement in our ability to characterise the quantity of sediment entering Porirua Harbour from the surrounding land. The quality and continuity of data has improved throughout the monitoring period with the quantity of lost data due to malfunction or fouling reducing from 57 days in 2013 to 7 hours in 2015.

The highest turbidity values in 2014/15 were similar across all three monitoring sites and ranged between 3,131 FNU[4] at the Horokiri site and 3,553 FNU at the Pauatahanui site. The maximum suspended sediment concentration (SSC) was recorded in the Porirua Stream during the 20-year return period event on 14 May 2015 (5,800 g/m^3). This same event generated maximum SSC of 3,000 g/m^3 and 2,400 g/m^3 in the Pauatahanui and Horokiri streams, respectively.

Sufficient data have now been collected to permit calculations of annual sediment yields for the three stream catchments. For the 2013 calendar year, total sediment yields were ~0.25, 0.5 and 0.35 t/ha/yr for Porirua, Horokiri and Pauatahanui streams, respectively. In 2014, the sediment yields were less with an estimated 0.13, 0.23 and 0.18 t/ha/yr for the same stream catchments. In stark contrast, the sediment yields for the first six months of 2015 were high with an estimated 0.51, 1.2 and 0.6 t/ha/yr for Porirua, Horokiri and Pauatahanui streams, respectively. It is important to note that these provisional calculations underestimate the annual yields as they do not account for periods of missing data.

The differences in calculated annual sediment yields are driven mainly by the frequency and magnitude of rainfall with 2013 and 2014 being relatively benign years with respect to wet weather events. The significant wet weather event on 14 May 2015[5], however, contributed more than three quarters of the total sediment load for the first six months of 2015 and more sediment than the combined loads for 2013 and 2014. This highlights the significant sediment inputs these large wet weather events contribute to the harbour and the value of continuous monitoring to characterise the temporal nature of these inputs.

Continuous turbidity monitoring will continue in 2015/16 with the addition of sediment gaugings and concurrent particle size analyses across a range of wet weather events at the three monitoring sites. The results of these gaugings and analyses will be used to determine how representative the instream turbidity sensor location is of sediment concentrations across the width of the stream.

Further consideration will also be given to estimating the degree of uncertainty in our estimates of event-based and annual sediment loads and developing methods for estimating loads when equipment fails. A review of how the

[4] Derived data (see Figure 3.6).
[5] Reported in more detail in Harkness (2015).

turbidity monitoring programme conforms to the NEMS (2013) for turbidity recording will be undertaken with particular consideration to the assignment of quality codes to field turbidity data.

Acknowledgements

Wendy Purdon carried out the essential task of installing the turbidity sensors and autosamplers at all three monitoring sites. Her ongoing maintenance and development of these sites has been crucial to ensuring the quality of the continuous data is high and reducing the frequency of sensor malfunctions.

Dr Andrew Hughes (NIWA) provided valuable advice at the inception of this monitoring programme as well as ongoing support and data scrutiny.

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References

Davies-Colley RJ and Smith DG. 2001. Turbidity, suspended sediment and water clarity: A review. *Journal of the American Water Resources Association*. Vol. 37, No. 9: 1,085-1,101.

Duan M. 1983. Smearing estimate: A non-parametric retransformation method. *Journal of American Statistical Association* 78: 605-610.

Green MO, Stevens L and Oliver MD. 2014. *Te Awarua-o-Porirua Harbour and catchment sediment modelling: Details of the CLUES and source-to-sink models*. Greater Wellington Regional Council, Publication No. GW/ESCI-T-14/132, Wellington.

Harkness M. 2015. *Hydrology State of the Environment monitoring programme: Annual data report, 2014/15.* Greater Wellington Regional Council, Publication No. GW/ESCI-T-15/151, Wellington.

Hicks DM. 2009. *Analysis of suspended sediment data from upper Lee River, Nelson.* NIWA Client Report CHC2009-179 prepared for Tasman District Council.

Maidment DR. 1993. *Handbook of hydrology*. McGraw-Hill Inc., New York.

Morar SR, Oliver MD and Purdon W. 2015. *Te Awarua-o-Porirua Harbour catchment turbidity monitoring: Results of continuous turbidity monitoring, 2012–2014.* Greater Wellington Regional Council, Publication No. GW/ESCI-T-15/20, Wellington.

National Environmental Monitoring Standards (NEMS). 2013. *Turbidity recording: Measurement, processing and archiving of turbidity data*. Version 1.0.

Appendix 1: Laboratory and field methods

Core water quality variables measured/analysed at each site are presented in Table A1.1. Manual water samples are collected via hand or a standard sample pole approximately 200 mm below the water surface within 0.6 m of turbidity sensor. Autosampler samples are collected from an intake hose attached to the bottom of the turbidity sensor housing. Samples requiring laboratory analysis are placed in chilli bins with ice and couriered overnight to RJ Hill Laboratories in Hamilton.

Table A1.1: Field and analytical water quality methods and detection limits

Variable	Sample type	Method	Detection limit(s)
Field turbidity	In-stream sensor	Hach Solitax T-line sensor (ISO7027 compliant) with SC 200 module. Campbell Scientific OBS-3+ sensor	0.001– 4,000 FNU
Lab turbidity	Water sample collected manually or by autosampler	Analysis using a Hach 2100N, Turbidity sensor. APHA 2130 B 22nd Ed. 2012.	0.05 NTU
Suspended sediment concentration (SSC)	Water sample collected manually or by auto-sampler	Filtration using Advantec GC-50 or equivalent 125mm 1 –12 diameter filters (nominal pore size 1.2 – 1.5µm), gravimetric determination. Entire sample filtered (includes aliquot previously sub-sampled for turbidity [when in autosampler bottle] and returned to bottle). No correction for density. ASTM D3977-97 (Modified).	10 g/m^3