Waikato Regional Council Technical Report 2012/33

Suspended sediment time trends in the Waipa River and Waitomo Stream

www.waikatoregion.govt.nz
ISSN 2230-4355 (Print)
ISSN 2230-4363 (Online)

Prepared by:
Jo Hoyle,
National Institute of Water & Atmospheric Research Ltd

For:
Waikato Regional Council
Private Bag 3038
Waikato Mail Centre
HAMILTON 3240

February 2013

Document #: 2234251

Approved for release by:
Reece Hill

Date February 2013

Disclaimer

This technical report has been prepared for the use of Waikato Regional Council as a reference document and as such does not constitute Council's policy.

Council requests that if excerpts or inferences are drawn from this document for further use by individuals or organisations, due care should be taken to ensure that the appropriate context has been preserved, and is accurately reflected and referenced in any subsequent spoken or written communication.

While Waikato Regional Council has exercised all reasonable skill and care in controlling the contents of this report, Council accepts no liability in contract, tort or otherwise, for any loss, damage, injury or expense (whether direct, indirect or consequential) arising out of the provision of this information or its use by you or any other party.

Suspended sediment time trends in the Waipa River and Waitomo Stream

Prepared for Waikato Regional Council

June 2012

Authors/Contributors:
Jo Hoyle

For any information regarding this report please contact:

Jo Hoyle
River Geomorphologist
Sediment Processes
+64-3-343 7810
j.hoyle@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
10 Kyle Street
Riccarton
Christchurch 8011
PO Box 8602, Riccarton
Christchurch 8440
New Zealand

Phone +64-3-348 8987
Fax +64-3-348 5548

NIWA Client Report No:	CHC2012-083
Report date:	June 2012
NIWA Project:	EVW12504

Contents

Executive summary **3**

1 Introduction **4**

1.1 Background 4

1.2 Drivers of changes in suspended sediment concentration 4

2 Methodology **10**

3 Results and Discussion **13**

3.1 Waipa 13

3.2 Waitomo 15

4 Conclusions **18**

5 Acknowledgements **19**

6 References **19**

Appendix A Plots of residuals over various time for testing time trends **20**

Tables

Table 1-1: Annual flow statistics for the Waipa at Otewa. 7

Table 1-2: Annual flow statistics for the Waitomo at Aranui Caves Bridge. 9

Table 3-1: Summary of time trends results for Waipa at Otewa. 15

Table 3-2: Summary of time trend results for Waitomo at Aranui Caves Bridge. 17

Figures

Figure 1-1: Hydrograph of the Waipa at Otewa. 6

Figure 1-2: Hydrograph of the Waitomo at Aranui Caves Bridge. 8

Figure 2-1: The suspended sediment concentration rating for Waipa at Otewa. 10

Figure 2-2: The suspended sediment concentration rating for Waitomo at Aranui Caves Bridge. 11

Figure 3-1: Specific annual sediment yields and three year running average yield between 1985 and 2011 for Waipa at Otewa. 13

Figure 3-2: SSC versus Q for three individual auto-sampled flood events in the Waipa, showing clockwise hysteresis. 14

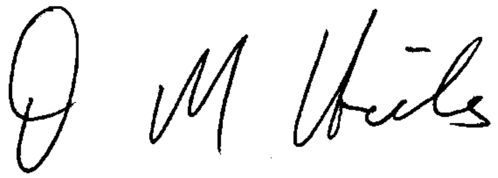
Figure 3-3: Specific annual sediment yields and three year running average yield between 1987 and 2011 for Waitomo at Aranui Caves Bridge. 15

Figure 3-4: SSC versus Q for three individual auto-sampled events in the Waitomo, showing no consistent hysteresis. 16

Figure A-1: Plot of Log_e(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment for the full period of data. 20

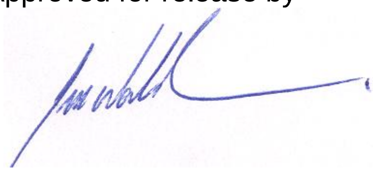
Figure A-2: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment for the decade before last. 20
Figure A-3: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment for the last decade. 21
Figure A-4: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment from 1990 to the end of 1995. 21
Figure A-5: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment from 1996 to the end of 2000. 22
Figure A-6: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment from 2001 to the end of 2005. 22
Figure A-7: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment from 2006 to the end of 2010. 23
Figure A-8: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment from 2011 to the end of 2012. 23
Figure A-9: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment for the full period of record. 24
Figure A-10: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment for the decade before last. 24
Figure A-11: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment for the last decade. 25
Figure A-12: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 1990 to the end of 1995. 25
Figure A-13: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 1996 to the end of 2000. 26
Figure A-14: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 2001 to the end of 2005. 26
Figure A-15: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 2006 to the end of 2010. 27
Figure A-16: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 2011 to the end of March 2012. 27
Figure A-17: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 1990 to the end of 1996. 28
Figure A-18: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 1997 to the end of 1998. 28
Figure A-19: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 1999 to the end of 2009. 29
Figure A-20: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 2010 to the end of March 2012. 29

Reviewed by



Murray Hicks

Approved for release by



Jeremy Walsh

Executive summary

Waikato Regional Council (WRC) commissioned NIWA to assess the Waipa and Waitomo datasets for evidence of a trend or change in sediment loads that can be related to catchment and bank recovery works.

Since sediment loads are highly dependent on river flows the approach used was to look for temporal change in the relationship between suspended sediment concentration (SSC) and discharge. This involved testing for a time trend in the residuals of a LOWESS fitted relationship between SSC and discharge derived from the full data set. This was carried out over varying time periods to see how time trends have shifted. The significance of each time trend was evaluated using the Student's t-test, testing the hypothesis that the coefficient on the linear relation was significantly different from zero at the 1 % and 5 % significance levels.

The results indicate that statistically significant time trends probably do exist for both the Waipa and Waitomo catchments. However, the Student's-t test assumes normal distribution of data, and therefore, results from significance tests where data is not normally distributed should be treated with caution.

In the Waipa, there was an increase in SSC leading up to 2000 and a decrease in SSC from 2000 through until at least the end of 2010. This indicates that the considerable effort that went into river rehabilitation works in the early 2000's (peaking in 2004/2005) have paid off. The data in the Waipa are slightly biased, as there has been a tendency in recent years for more sampling in the rising stage of events, relative to the falling stage, thereby misrepresenting SSC in recent years. This bias means that the downward trend in SSC is actually stronger than the data would indicate. We recommend that WRC revisit their autosampler operating schedule to improve future monitoring.

In the Waitomo, results are less clear and depend on the period of time selected for trend analysis. SSC was generally decreasing from 1990 through until the end of 1996, reflecting the success of efforts in the 1990's from the Waitomo Landcare Group. From 1997 to the end of 1998 there was an increase in SSC, reflecting the 1998 floods. There was little change from 1999 until 2006, an upward trend from 2006 until 2010 and a decrease from 2010 to 2012. However, there is no overall downward trend in SSC in the Waitomo in the last decade. This does not mean that rehabilitation efforts over the last decade have been ineffective, but may indicate that these efforts are being offset by other drivers increasing SSC within the catchment (such as intensification of landuse).

1 Introduction

1.1 Background

Waikato Regional Council (WRC) commissioned NIWA to assess the Waipa at Otewa dataset for evidence of a trend or change in sediment yields that can be related to catchment and bank recovery works.

While meeting with WRC staff in Hamilton in May, it became apparent that there are also concerns regarding trends in sediment yields in the Waitomo catchment, so an assessment of trends in the Waitomo catchment was added to the scope of this study.

Detecting time trends in suspended sediment yield due to changing sediment supply factors is complicated by hydrological variability. The erratic occurrence of rainstorms and floods can lead to factor-of-ten variability in annual sediment yields (for example in the Waipa at Otewa catchment between 1985 and 2011 the annual specific sediment yield ranged from 36 to 419 t/km^2) with the standard deviation of annual yields being very large in comparison with the mean (with a SD of 92 t/km^2 and a mean of 137 t/km^2 in the Waipa). The upshot is that with only a relatively short monitoring record, there is usually too much hydrologically driven variability to identify a supply related trend simply from annual loads.

A way forward is to remove the flow variability signal by looking for temporal change in the 'rating' relationship between suspended sediment concentration (SSC) and water discharge (Q). This assumes that the rating shifts are driven by changes in sediment supply (or availability).The suspended load in streams during storm runoff events also varies considerably as a result of variations in sediment supply by erosion processes (which tend to be very patchy in space and time); the phase relationship between sediment supply and the water runoff (typically this shows as a clockwise hysteresis in the SSC-Q relation); and entrainment, deposition, and dispersion processes within the flow.

Thus the approach we follow is to look at a time trend in SSC-Q residuals (occurring due to supply effects) but also to check that, if a hysteresis in the SSC-Q relation exists, time trends have not been biased by the sampling schedule (e.g. that not all sampling has been undertaken during rising stages in the first few years and all falling stages in the later years).

In this short report we start by outlining some of the drivers of changes in SSC that may cause a systematic deviation in observed SSC away from the rating. This is followed by a description of the methodology used to examine time trends in SSC. The results of the analysis for the Waipa and Waitomo are then presented, followed by some recommendations.

1.2 Drivers of changes in suspended sediment concentration

Active bank erosion and hillslope erosion are key sources of suspended sediment, and increased rates of erosion may be triggered by events such as floods or landslides or by progressive changes like intensification of landuse. While variation in discharge is incorporated in the SSC rating, large floods may result in elevated SSC even after discharge has receded. In contrast to these factors that increase SSC, SSC may also be systematically lowered as a result of remediation measures, such as bank protection works and riparian and/or hillslope planting. Often, a number of these influences on suspended sediment supply will occur concurrently. For example, intensification of landuse may offset (or be offset by) the benefits of remediation efforts. It is important to understand the history of activities and events in the Waipa and Waitomo in order to provide a context against which to assess time trends in suspended sediment in these catchments.

1.2.1 Waipa

There are a number of events that have occurred in the upper Waipa catchment that could be reflected in the SSC record at the Waipa at Otewa gauge. The most notable is the Tunawaea landslip. This was a block type failure that occurred in August 1991 on the Tunawaea stream just upstream of the confluence with the Waipa River (Jennings et al., 1993). This landslip formed a 70 m high dam which failed on the 22 July 1992 (Jennings et al., 1993; Webby and Jennings, 1994). The volume of sediment generated by this landslip was approximately 9 million m^3 (M. Duffy WRC, pers. comm., 7 May 2012). The grain size distribution of the slip material is unknown, but experience suggests that a substantial portion of the slip material may be fine sediment and susceptible to entrainment by suspension.

The downstream advection of the suspended load portion of the slip material would likely have occurred relatively quickly (within a few years), so we would expect to see a potential increase in the SSC-Q relation in the few years following the dam failure (to say late 1994). In addition to this short-term effect of the Tunawaea slip, the slower diffusion of the bed load portion of the slip material is also having secondary effects. For example, as the bedload component of the Tunawaea slip gradually works its way down the Waipa, the bed becomes locally raised, exacerbating bank and terrace erosion (observed by NIWA staff to be widespread in the upper Waipa). This has been most severe approximately 5-6 km downstream of the Tunawaea confluence where a reach, ~ 800 m long, is bordered on its right bank by a 16 m high terrace of Taupo Pumice (deposited by the Taupo eruption that occurred in 186 AD). In the period since the Tunawaea landslip the aggrading riverbed has allowed floods to undercut these terraces, eroding them back ~ 15-20 m, releasing an estimated 192,000-256,000 m^3 of additional sediment into the Waipa. Again, a substantial portion of this material would have been sufficiently fine to contribute to suspended load, which would have advected fairly rapidly downstream. The remaining bedload portion is now diffusing downstream with the bedload portion of the Tunawaea slip material. These secondary effects of the Tunawaea landslip have potential to contribute to an increase in the SSC-Q relation at least until the bed material slug has moved past the Waipa at Otewa gauge.

Analysis of aerial photographs indicates the presence of further landslips in the upper Waipa, upstream of the Tunawaea confluence. However, the timing and volume of material supplied from these landslips are unknown.

Figure 1-1 shows a hydrograph of the Waipa at Otewa (monitoring station 43481) for the full period over which flow data is available (May 1985 – May 2012). This hydrograph shows the timing of the floods that caused the Tunawaea landslip and landslip dam failure. These floods had peak discharges of 189 m^3/s and 203 m^3/s respectively, which are close to the mean annual flood (171 m^3/s; Table 1-1). The largest flood during this period of record occurred on 29 February 2004 and had a peak discharge of 442 m^3/s. A flood of this magnitude has a recurrence interval of around 50 years (using the non-linear transformation of Gringorten, 1963). Hicks and Basher (2008) showed that events greater than a 10 year recurrence interval tend to leave a sediment supply legacy. It is likely that it was this 2004 event that resulted in most of the Taupo Pumice terrace erosion.

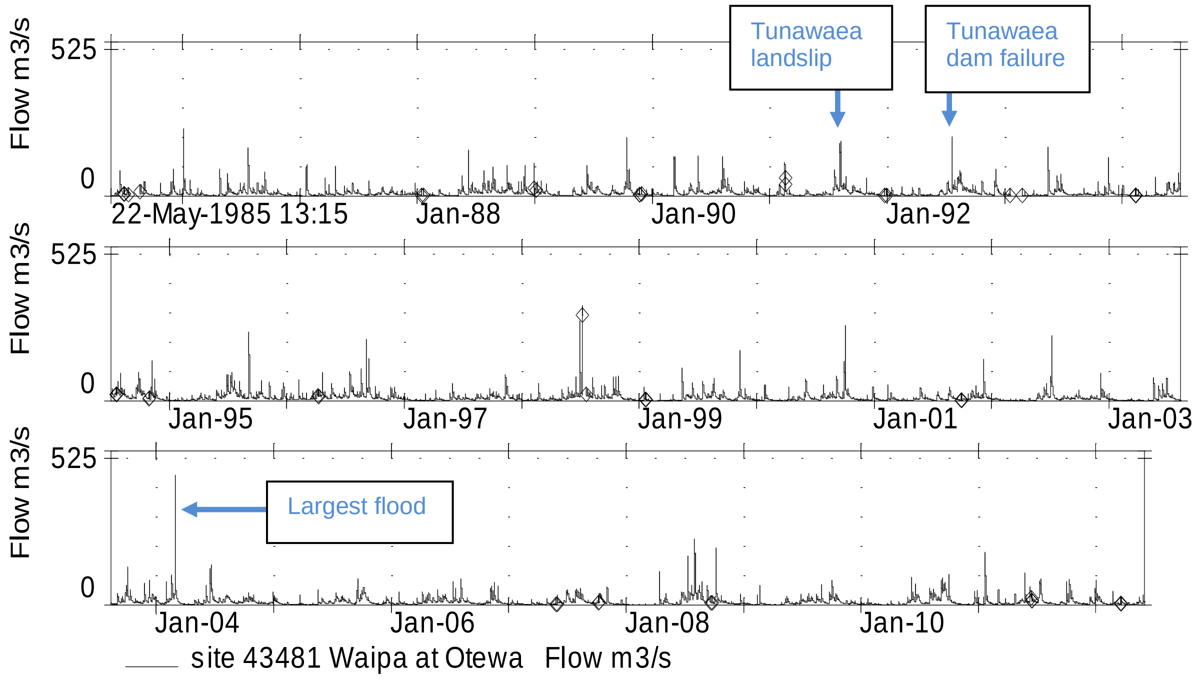


Figure 1-1: Hydrograph of the Waipa at Otewa. The flood events triggering the Tunawaea landslip and the landslip dam failure are identified (Q_{pk}'s of 189 and 203 m^3/s respectively). The largest flood event (Q_{pk} of 442 m^3/s) occurred on 29 February 2004. Note that the flood event in July 1998 is marked with a diamond, indicating that the continuous flow record was interrupted during this flood (leaving a gap in the data record). While the peak discharge recorded during this flood was 325 m^3/s, the flood peak may have been missed.

Offsetting the aforementioned factors which are expected to contribute to increasing suspended sediment loads, in the early 2000's $1 million was spent on riparian restoration work in the Waipa River. This largely involved willow planting on the active floodplain, designed to limit erosion of the Taupo Pumice terraces by floods. The majority of river works in the upper Waipa were completed in 2004/2005.

1.2.2 Waitomo

The Waitomo catchment has the highest specific annual average sediment yield of all the Waikato catchments investigated by Hoyle et al. (2011). This relates to its high mean annual rainfall (and runoff) and dominantly weak, volcaniclastic lithology (tephra, ash etc.).

Historically, suspended sediment in Waitomo Stream has contributed to the build-up of sediment in the Waitomo Caves and has affected the water quality and appearance of the water, some of which is abstracted for rural and town supplies. To reduce sediment loads and improve water quality, WRC helped form a Landcare Group involving the community and a range of national and local agencies, who together have put significant effort into erosion control in this catchment (R. Hill, pers comm., 7 May 2012). Between 1992 and 2002, the group funded more than 60 km of fencing in the catchment (catchment area of ~ 30 km^2) that excludes stock from 625 ha of native bush, 20 km of streams and wetlands and 350 ha of slip-prone land (McKerchar and Hicks, 2003). The group has also facilitated planting of

Table 1-1: Annual flow statistics for the Waipa at Otewa. Years marked with an * indicate that there are gaps in the flow record. Data highlighted in red indicates the events that triggered the Tunawaea landslip and landslip dam failure. Data highlighted in blue indicates the largest flood event during this period of record. The mean annual flood is 171 m^3/s.

			Minimum			Maximum		
Year	Mean	Coeff. of Var	Discharge (m^3/s)	Date	Time	Discharge (m^3/s)	Date	Time
*1985	11.771	1.03	2.332	22/05/85	13:15	94.661	2/12/85	22:45
1986	12.359	1.03	2.259	21/04/86	20:00	229.82	6/01/86	21:30
1987	9.8966	0.84	1.752	17/01/87	24:00	108.1	22/01/87	15:00
*1988	15.598	0.97	2.174	3/02/88	19:45	159.35	8/06/88	15:00
*1989	13.588	1.03	2.477	29/04/89	7:45	199.8	15/10/89	17:30
1990	14.441	0.98	2.698	8/03/90	23:15	139.44	25/05/90	10:00
*1991	12.803	1.24	2.685	24/01/91	2:30	189.14	9/08/91	17:00
1992	13.935	1.03	2.915	14/02/92	15:15	203.04	22/07/92	11:30
*1993	10.297	1.22	2.207	27/03/93	21:00	167.26	16/05/93	22:00
*1994	15.605	0.96	2.08	11/04/94	23:15	137.85	7/11/94	17:45
1995	14.987	1.12	2.042	20/02/95	21:00	235.97	7/09/95	5:15
*1996	17.745	0.85	3.914	10/11/96	19:30	211.85	5/09/96	7:55
1997	9.6137	0.89	2.083	3/04/97	18:00	90.844	13/11/97	10:05
*1998	14.725	1.26	2.786	31/12/98	21:25	324.72	9/07/98	22:35
*1999	11.507	1.11	1.712	24/02/99	20:30	173.69	11/11/99	7:35
2000	11.773	1.3	1.752	29/03/00	6:15	257.71	2/10/00	23:10
*2001	10.388	0.98	2.803	7/02/01	4:05	143.71	7/12/01	15:55
2002	10.785	1.28	1.939	22/04/02	8:15	224.43	7/07/02	11:30
2003	12.082	1.09	1.704	30/04/03	22:35	132.01	4/10/03	4:25
2004	14.992	1.39	2.214	25/04/04	0:45	442.4	29/02/04	4:35
2005	10.993	0.95	1.779	15/03/05	5:25	91.701	18/09/05	22:35
2006	12.727	0.83	2.384	20/03/06	18:55	91.977	7/08/06	1:45
*2007	10.202	0.96	1.883	12/03/07	21:35	62.744	5/11/07	12:00
*2008	15.108	1.51	1.239	17/03/08	19:30	225.49	31/07/08	13:05
2009	10.647	0.91	1.42	24/04/09	22:25	86.301	4/10/09	22:30
2010	13.298	1.2	1.635	5/04/10	18:35	105.22	1/10/10	5:45
*2011	12.472	1.17	2.046	17/01/11	19:40	179.83	23/01/11	19:05
*2012	9.203	0.95	2.784	26/04/12	21:15	85.742	1/01/12	18:50

riparian and retired land. Although we are uncertain of the nature and timing of erosion control efforts over the last decade (2002-2012), the popular perception is that the Waitomo Stream has cleaned up, with less desilting required in the Waitomo Caves and a reduction in treatment required for water supply.

A hydrograph for Waitomo at Aranui Caves Bridge (monitoring station 1943481) from October 1986 to May 2012 is presented in Figure 1-2, and flow statistics are presented in Table 1-2. Based on these data we would expect that SSC could have remained elevated in late 1998/1999 and 2004 due to the occurrence of large floods. The mean annual flood during this period was 27 m^3/s. Table 1-2 shows that peak discharges have exceeded this average for 7 years of the last decade, perhaps indicating a climatic trend, or at least interdecadal variability.

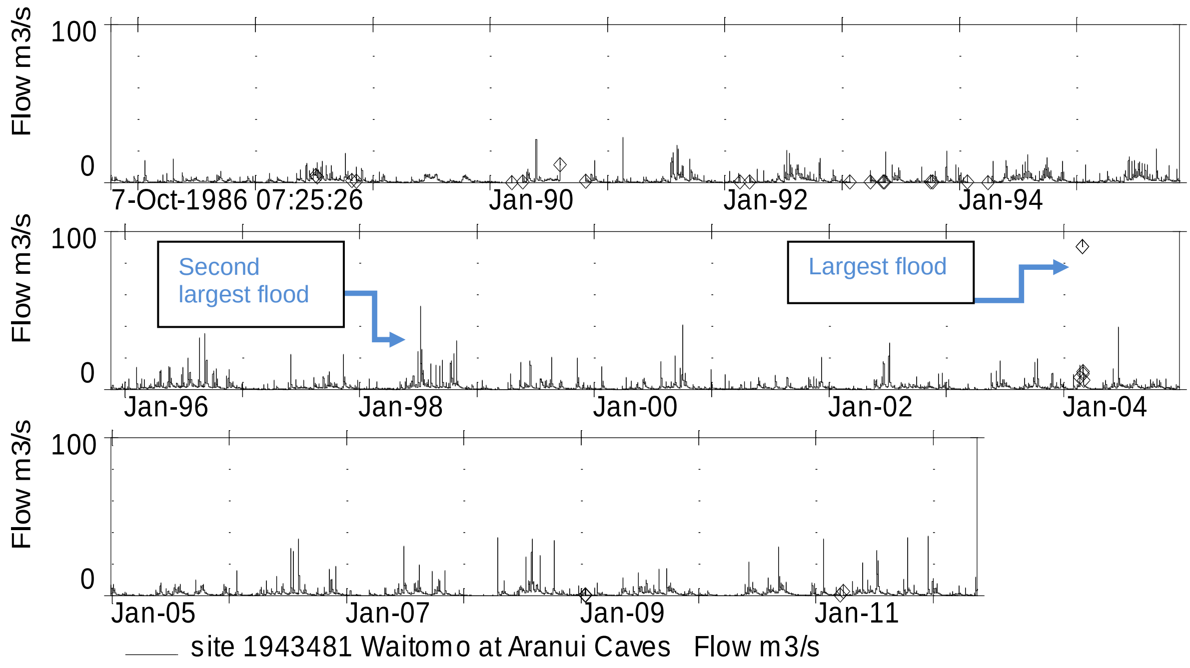


Figure 1-2: Hydrograph of the Waitomo at Aranui Caves Bridge. The largest and second largest floods during this period of record are indicated (Q_{pk}'s of 90 and 53 m^3/s respectively). Note that the largest flood event is marked with a diamond, indicating that the continuous flow record was interrupted during this flood (leaving a gap in the data record).While the peak discharge recorded during this flood was 90 m^3/s, the peak of the flood may have been missed.

Table 1-2: Annual flow statistics for the Waitomo at Aranui Caves Bridge. Years marked with an * indicate that there are gaps in the flow record. Data highlighted in blue indicates the largest flood event during this period of record; data highlighted in red indicates the second largest flood. The mean annual flood is 27 m^3/s.

			Minimum			Maximum		
Year	Mean	Coeff. of Var	Discharge (m^3/s)	Date	Time	Discharge (m^3/s)	Date	Time
*1986	1.2195	0.57	0.523	28/12/86	10:23	4.122	22/12/86	1:40
1987	1.3139	0.81	0.433	13/01/87	22:30	15.12	21/04/87	13:36
*1988	2.049	0.92	0.257	11/02/88	3:14	18.632	7/10/88	0:53
1989	1.4695	0.85	0.231	20/08/89	8:45	6.814	22/01/89	0:15
*1990	1.4816	1.06	0.111	24/02/90	5:49	27.619	25/05/90	7:42
1991	1.7587	1.24	0.304	26/12/91	21:15	28.846	18/02/91	6:10
*1992	2.0083	1	0.277	7/01/92	12:50	20.778	14/07/92	20:01
*1993	1.3826	1.13	0.518	7/05/93	20:30	20.401	21/11/93	14:50
*1994	2.3432	0.87	0.237	11/04/94	7:30	17.852	3/08/94	8:40
1995	2.0772	0.99	0.407	26/01/95	0:20	21.41	7/09/95	3:00
1996	2.393	0.99	0.492	6/02/96	15:20	35.583	5/09/96	3:40
1997	1.3509	1.07	0.357	5/04/97	18:10	22.576	31/05/97	8:30
1998	2.1875	1.51	0.392	22/04/98	18:10	52.7	9/07/98	20:10
1999	1.4945	1.12	0.311	5/04/99	18:10	20.814	21/08/99	11:05
2000	1.6087	1.42	0.327	29/03/00	5:00	41.213	2/10/00	21:00
2001	1.4786	0.98	0.431	11/02/01	1:00	20.582	7/12/01	12:45
2002	1.6558	1.16	0.348	23/04/02	0:00	29.52	7/07/02	11:15
2003	1.6053	1.08	0.281	14/05/03	18:00	19.579	13/10/03	16:25
*2004	1.8442	1.06	0.481	25/04/04	1:10	90.35	29/02/04	2:00
2005	1.4207	0.92	0.351	17/04/05	0:50	10.195	18/09/05	20:40
2006	1.8364	1.24	0.382	26/03/06	10:50	36.147	6/08/06	17:25
2007	1.5411	1.14	0.318	22/04/07	23:45	31.426	30/06/07	13:35
2008	1.9257	1.44	0.221	13/04/08	14:50	36.935	15/04/08	15:45
*2009	1.752	0.86	0.398	25/04/09	11:05	17.248	25/09/09	2:20
2010	1.6537	1.15	0.275	17/04/10	1:00	31.137	6/09/10	23:40
*2011	2.1139	1.34	0.464	25/04/11	0:20	37.864	17/12/11	19:20
*2012	1.0744	1.08	0.374	8/05/12	12:15	11.858	14/05/12	4:55

2 Methodology

For both the Waipa at Otewa and Waitomo at Aranui Caves Bridge sites a sediment concentration rating was established by plotting instantaneous SSC versus instantaneous water discharge (Q). A LOWESS (Locally-Weighted Scatterplot Smoothing) approach was used to fit the ratings for each catchment, with the LOWESS ratings represented by a series of power step-functions. As the data were transformed to their logarithms for curve-fitting, the LOWESS curve will generally need adjusting for log-transformation bias using the approach of Ferguson (1986). This adjustment scales with the exponential of the local standard error of the curve-fitting in log units, and was calculated during the LOWESS fitting process (in a process similar to that detailed by Hicks et al., 2000). While this adjustment was applied for the Waitomo site, visual assessment of the Waipa data and LOWESS rating curve indicated that the non-bias corrected rating was a better one for the Waipa site. The ratings for the Waipa and Waitomo are presented in Figures 2-1 and 2-2 respectively.

The ratings for each site were then applied to their full water discharge record, allowing integration of the sediment yield over the longest period possible for each site. Annual specific (normalised by catchment area) sediment yields were calculated to examine variability in sediment yield over time, even though these yields are largely controlled by annual variation in discharge.

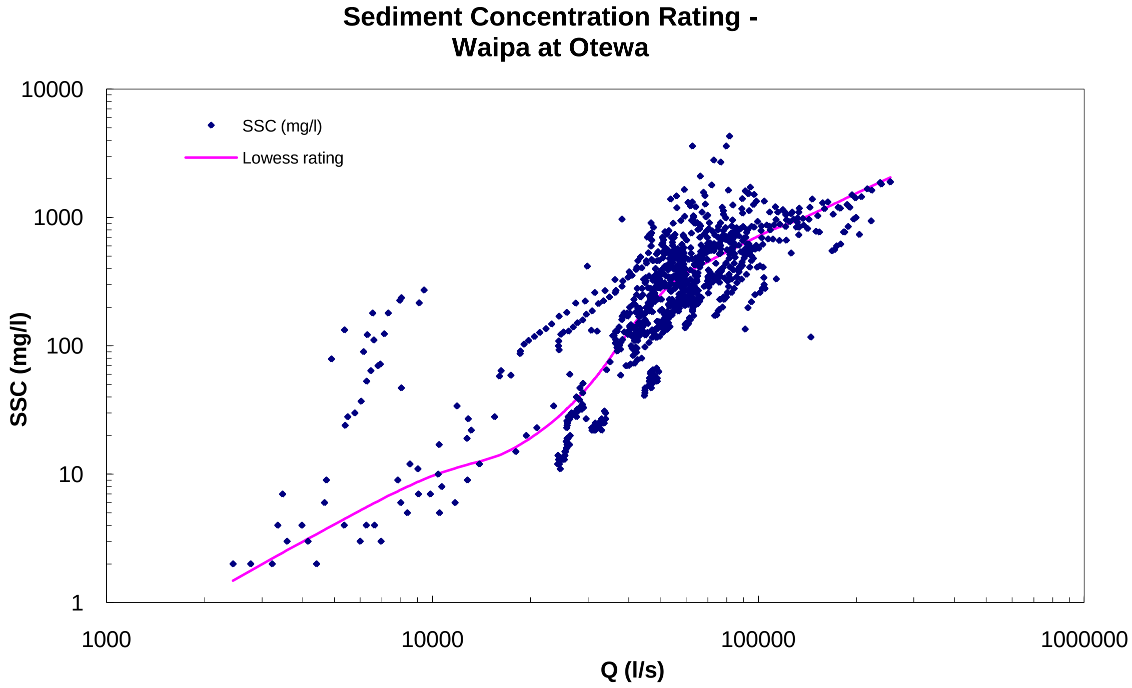


Figure 2-1: The suspended sediment concentration rating for Waipa at Otewa. The rating function for this site is a non-bias corrected LOWESS fit (smoothing factor 0.4).

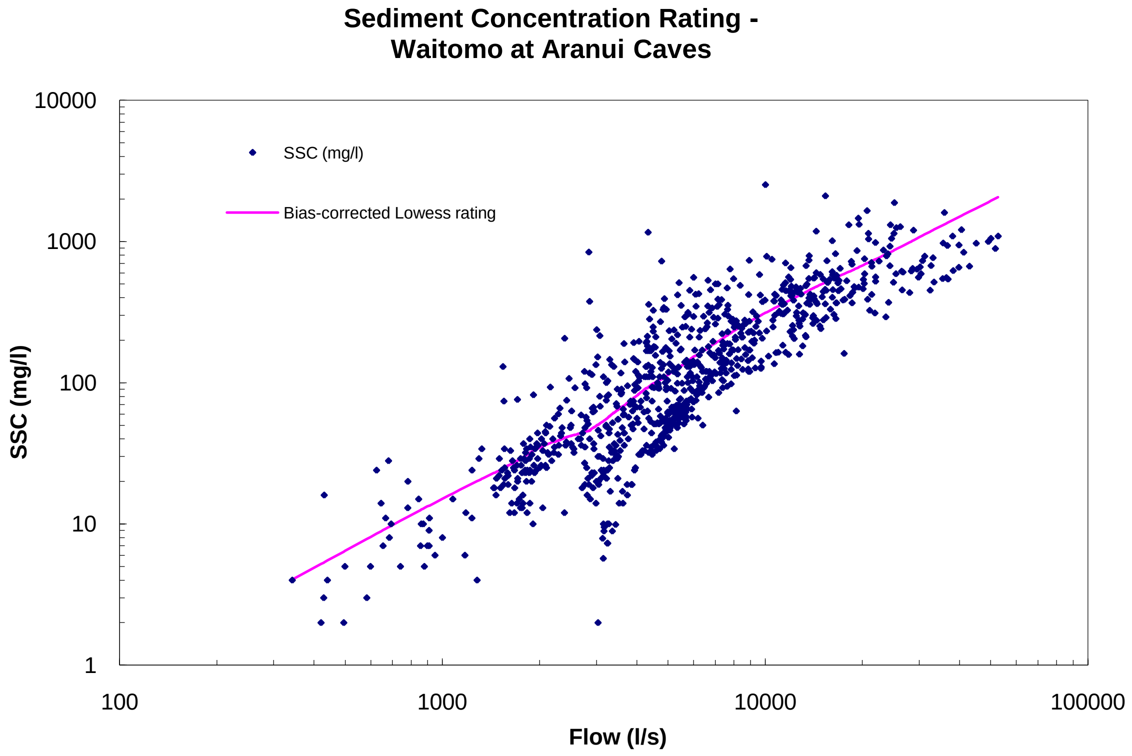


Figure 2-2: The suspended sediment concentration rating for Waitomo at Aranui Caves Bridge. This rating function is a bias-corrected LOWESS fit (smoothing factor 0.4).

In order to test for trends in SSC over time, independent of fluctuations in discharge, the residuals of the observed log SSC values compared to the log SSC values predicted by the LOWESS fit were plotted against time and a linear trendline was applied. The residuals of the 'actual plotted residuals' compared with the residuals predicted by the linear trendline were examined for normality, and the time trend was evaluated for significance. Time trends in the data were evaluated using the two tailed Student's t-test, testing the hypothesis that the coefficient on the linear relation was significantly different from zero at the 1 % and 5 % significance levels. A significant negative t-statistic indicates a reduction in SSC over the time period assessed, and a significant positive t-statistic indicates an increase in SSC over the time period assessed. Normality was evaluated with the Kolmogorov-Smirnov (K-S) and Chi^2 tests, where low significance levels (e.g. <0.01) indicate that there is a very low probability that the data are normally distributed. In some cases the K-S and Chi^2 tests disagreed, in which case normality is unclear.

While the Student's-t test assumes that the data are normally distributed, which is not always the case, it was still considered the best time trend test available for the data in question. Consideration was given to using the Mann- Kendall test, which is commonly used for examining time trends, however, this test requires that data are collected over uniform periods of time and, therefore, was considered inappropriate for our purposes.

Time trends were examined over a variety of time periods:

- the full period of data available for each site (1990 – 2012 in both cases)

- the last decade (2003 – 2012) and the previous decade (1993 – 2002)
- 5 yearly intervals from the beginning of the period of data (1990-1995, 1996-2000, 2001-2005, 2006-2010), finishing with the last 2 years (2011-2012)
- for the Waitomo, additional trend analysis was conducted for selected periods where visual analysis of the plot of residuals over time indicated potential trends.

3 Results and Discussion

3.1 Waipa

Figure 3-1 shows that between 1985 and 2011, specific annual sediment yields for the Waipa at Otewa have ranged from 36 to 419 t/km^2, with a mean of 137 t/km^2 and a standard deviation of 92 t/km^2. 2004 and 2008 had very large specific sediment yields (370 and 419 t/km^2 respectively), and by comparing these results with the annual peak discharge data in Table 1-1 we can see that these years also had large peak discharges (442 and 225 m^3/s respectively, and the 2008 data may have missed the peak as the data record is incomplete). However, fluctuations in discharge do not explain all the variability in sediment yields as 1998 was also a year with a high peak annual discharge (at least 325 m^3/s, as the record gap may have missed the flood peak), and yet the specific annual sediment yield is relatively low at 91 t/km^2. Also, yield depends on flow throughout the year, not just the peak annual discharge.

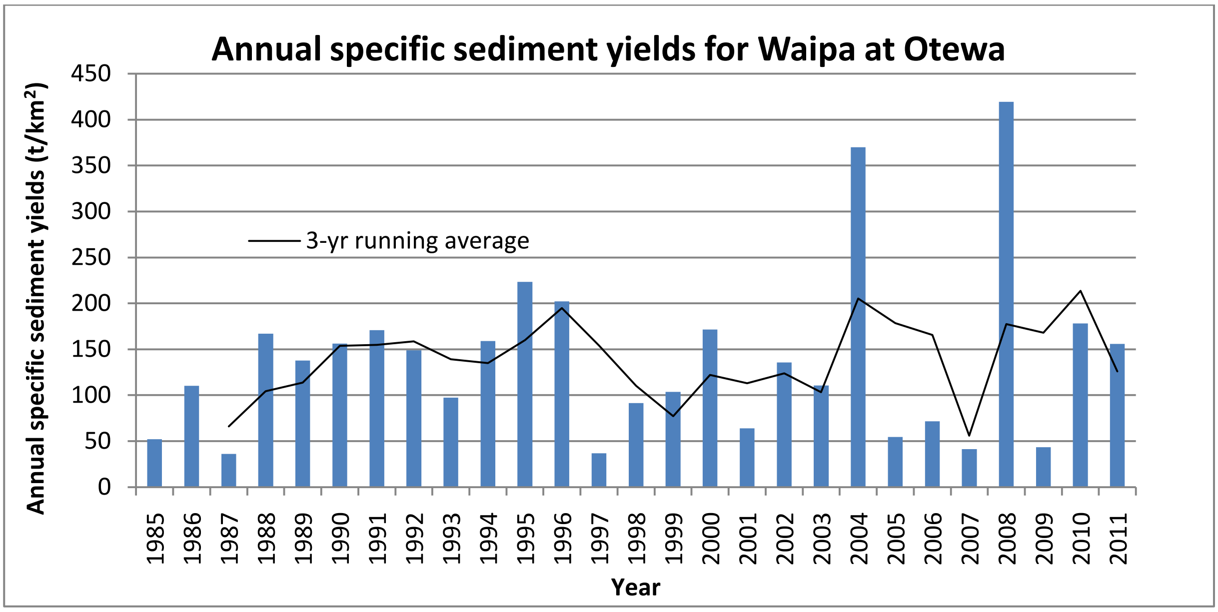


Figure 3-1: Specific annual sediment yields and three year running average yield between 1985 and 2011 for Waipa at Otewa.

Plotting SSC versus Q for each individual auto-sampled event in the Waipa (e.g. Figure 3-2) showed that the Waipa tends to exhibit a clockwise hysteresis (i.e. more sediment is carried on the rising limb relative to the falling limb). These plots also showed that auto-sampling of events early in the sediment monitoring programme (2000- 2007) tended to catch more of the falling limb than the rising limb (missing the start of events and therefore underestimating SSC). In more recent years (2008-2012) auto-sampling has tended to catch more of the rising limb than the falling limb, thereby overestimating SSC. This change in sampling introduces some bias to the time trends, as the residuals of observed SSC/predicted SSC will also be greater over more recent years. WRC may wish to revisit their autosampler operating schedule in the Waipa to improve monitoring of future events. Currently, the auto-samplers are capturing the start of events but are tending to run out of bottles too early. This may be remedied by increasing the time between samples so that both rising and falling stages can be captured without bias.

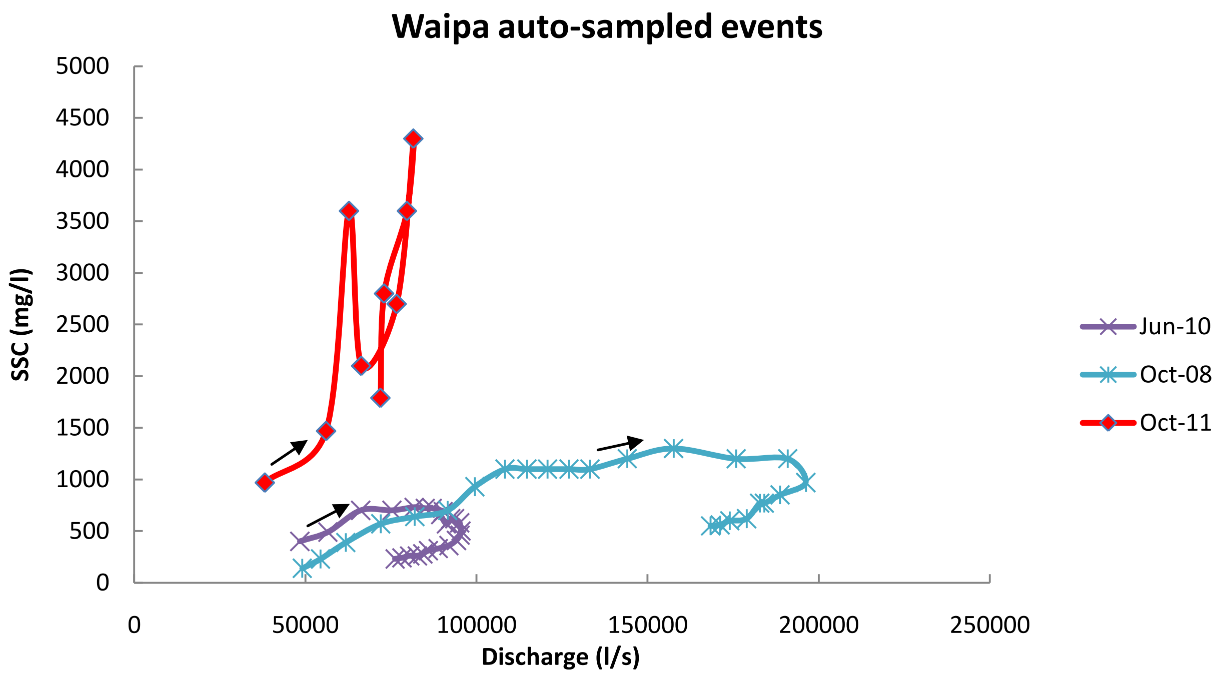


Figure 3-2: SSC versus Q for three individual auto-sampled flood events in the Waipa, showing clockwise hysteresis. Note that the arrows show the order of measurements. For these events there is also a bias towards data being collected on the rising limb (therefore overestimating SSC). This figure also highlights how much SSC can vary for a given discharge.

The results from the time trend tests for the Waipa are presented in Table 3-1, and the plots of residuals over time, from which these results are generated, are presented in Appendix A. Table 3-1 shows that over the full period of data (1990 – 2012) there has been a downward trend in SSC which is statistically significant at the 1 % level (but the data is not normally distributed). There is no significant time trend over the last decade or the preceding decade. Working through the data record in 5-yearly intervals shows that from 1990-1995 and from 1996-2000 there were significant increases in SSC. The upward trend in the first of these periods likely reflects the initial advection of suspended sediment from the Tunawaea slip material. The upward trend in the second period is more likely a reflection of increased bank erosion (and potentially the beginning of the Taupo Pumice terrace erosion), secondary effects of the Tunawaea slug. The trend then changed, with significant decreases in SSC between 2001-2005 and 2006-2010. The first of these periods aligns with the 2000-2004 river works programme, and also covers the 2004 flood, of which there is no apparent signature. The downward trend in the later period is significant despite the bias towards sampling on the rising stage over the last few years of this period. This ten year downward trend is a strong indication of the success of the erosion control efforts in this river. There was no significant trend in 2011, but this may be due to it being too short a period to test for a time trend.

Table 3-1: Summary of time trends results for Waipa at Otewa. Outlining the period of data included in each time trend test, whether the data is normally distributed (based on p value from Kolmogorov-Smirnov and Chi^2 tests), the t-statistic from the two tailed Student's-t test and the significance level of the Student's-t test results.

	from	to	Normal distribution	K-S p	Chi^2 p	t statistic	significant?
Full data period	6/08/1990	1/01/2012	no	<0.01	<0.01	-9.459	Yes at 1%
10 yr periods	2/03/1993	8/12/2002	no	<0.01	<0.01	1.505	No
	21/05/2003	1/01/2012	yes	>0.2	0.518	-1.834	No
5 yr periods	6/08/1990	20/12/1995	yes	>0.2	0.105	2.257	Yes at 5%
	2/04/1996	30/12/2000	no	<0.01	<0.01	3.389	Yes at 1%
	12/02/2001	12/10/2005	no	<0.01	<0.01	-11.970	Yes at 1%
	20/07/2006	1/10/2010	maybe	>0.2	<0.01	-7.952	Yes at 1%
	5/03/2011	1/01/2012	no	<0.05	<0.01	0.008	No

3.2 Waitomo

Figure 3-3 shows that between 1987 and 2011 specific annual sediment yields for Waitomo at Aranui Caves Bridge have ranged from 61 to 461 t/km^2, with a mean of 158 t/km^2 and a standard deviation of 98 t/km^2. The highest annual specific sediment yield in this period occurred in 1998, which was also the year with the second largest peak discharge during this period (Q_{pk} 53 m^3/s;Table 1-2). The year with the largest peak discharge was 2004 (Q_{pk} 90 m^3/s) and yet the specific annual sediment yield for 2004 is relatively low at 165 t/km^2. As in the Waipa, fluctuations in annual peak discharge do not tell the whole story. Sediment yields are accumulated across the full flow record and, therefore, depend on the full flow-duration distribution as well as sediment supply.

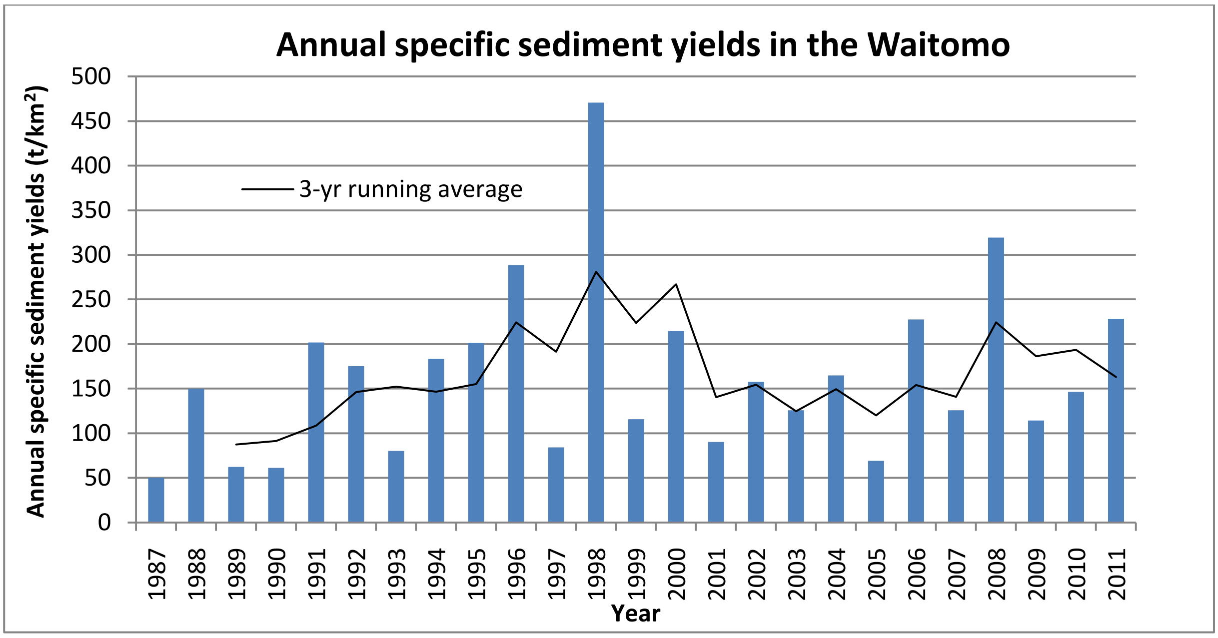


Figure 3-3: Specific annual sediment yields and three year running average yield between 1987 and 2011 for Waitomo at Aranui Caves Bridge.

Plotting SSC versus Q for individual auto-sampled events in the Waitomo (e.g. Figure 3-4) indicates that there is no consisent hysteresis (i.e. the SSC sampled on the rising limb is not consistently greater or less than that on the falling limb). This means that, in terms of looking at time trends, it is less important to consider bias in the sampling schedule for this river.

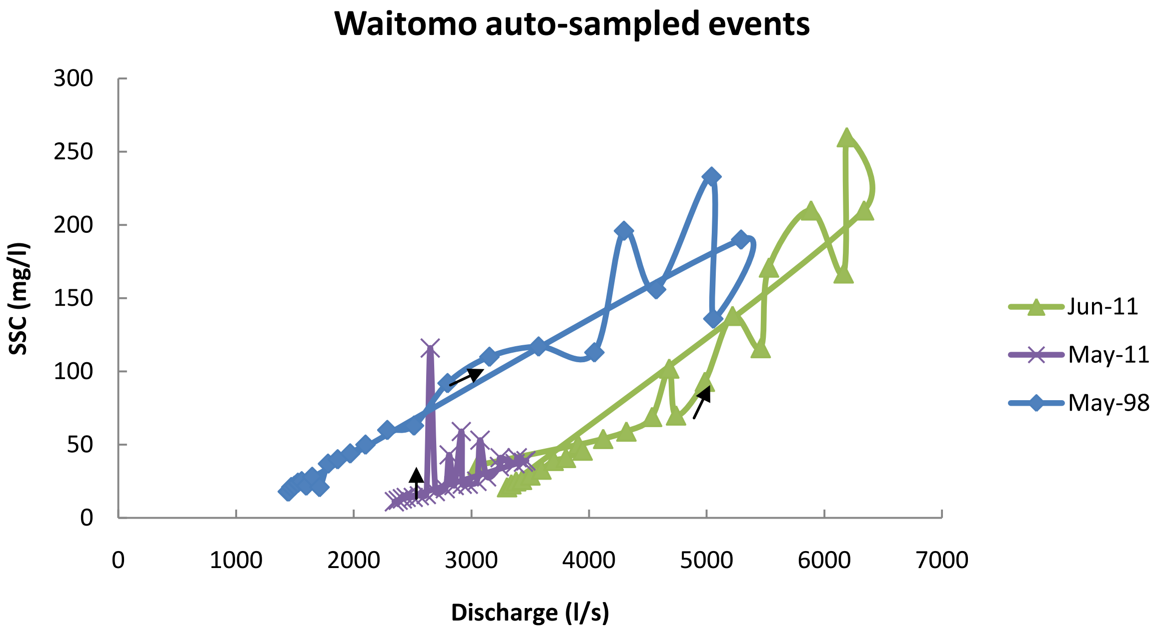


Figure 3-4: SSC versus Q for three individual auto-sampled events in the Waitomo, showing no consistent hysteresis. Note arrows show the order of measurements.

The results from the time trend tests for the Waitomo are presented in Table 3-2, and the plots of residuals over time, from which these results are generated, are presented in Appendix A. Note that there were very few measurements taken from 2001 to 2008. Table 3-2 shows that over the full period of data (1990 – 2012) there is no statistically significant trend in SSC. There is also no significant time trend over the 1992-2002 decade or over the 2003-2012 decade. We know that considerable effort went into catchment erosion control between 1992-2002, but unfortunately the effects of this are not apparent in the decadal time trend analysis. Analysing the data at 5-yearly intervals shows that from 1990-1995 there was a significant decrease in SSC, from 1996-2000 there was no significant trend and from 2001-2004 there were insufficient data to test for a trend (only 3 measurements in 5 years). From 2006-2010, and again from 2011 to March 2012, there were significant increases in SSC.

These results concur with the findings of McKerchar and Hicks (2003), who found that SSC declined by approximately 40 %, for a given flow, between 1990-200. The greatest reduction occurred over 1990-1994, and there was no trend from 1997-2000.

Visual analysis of Waitomo residuals over the full data period (Appendix A) indicated that time trends may be significant over periods different to those discussed above. Analysis of these selected periods showed that from 1990-1996 there was a significant decrease in SSC. There was a significant increase in SSC from 1997-1998, which suggests a response to the 1998 floods, which produced exceptionally large sediment loads. Together, these results indicate that the catchment restoration efforts of the 1990's were effective at reducing

SSC. While the trends are less apparent after 1996, suspended sediment loads from the 1998 floods would likely have been much higher without the Waitomo Landcare programme. Over the following eleven years from 1999 to 2009 there was no significant trend (although very little data were collected for 5 of these years). It is likely that there are insufficient data to pick up any signature of the 2004 event. From 2010- March 2012 there has been a significant decrease in SSC. This decrease in recent years concurs with the anecdotal observations and reduced maintenance work required in the caves.

Table 3-2: Summary of time trend results for Waitomo at Aranui Caves Bridge. Outlining the period of data included in each time trend test, whether the data is normally distributed (based on p value from Kolmogorov-Smirnov and Chi^2 tests), the t-statistic from the two tailed Student's-t test and the significance level of the Student's-t test results.

	from	to	Normal distribution	K-S p	Chi^2 p	t statistic	significant?
Full data period	7/08/1990	4/03/2012	no	<0.05	<0.01	1.204	No
10 yr periods	30/03/1993	10/12/2001	no	<0.05	<0.01	1.461	No
	1/03/2004	4/03/2012	maybe	>0.2	<0.01	-1.500	No
5 yr periods	7/08/1990	12/12/1995	yes	>0.2	0.515	-3.511	Yes at 1%
	11/01/1996	3/10/2000	no	<0.05	<0.01	0.715	No
	10/12/2001	21/06/2004	only three measurements, insufficient data				
	20/07/2006	20/12/2010	maybe	>0.2	<0.01	3.307	Yes at 1%
	29/01/2011	4/03/2012	maybe	>0.2	<0.01	2.728	Yes at 1%
Selected periods	7/08/1990	26/11/1996	yes	>0.2	0.564	-2.749	Yes at 1%
	7/01/1997	8/12/1998	no	<0.15	<0.01	5.364	Yes at 1%
	13/01/1999	19/11/2009	yes	>0.2	0.092	-1.209	No
	28/01/2010	4/03/2012	no	<0.01	<0.01	-5.600	Yes at 1%

4 Conclusions

This study indicates that statistically significant time trends do exist for both the Waipa and Waitomo catchments. Having said this, the Student's-t test assumes normal distribution of data, which is often not the case, and therefore, results from significance tests where data is not normally distributed (Tables 3-1 and 3-2) should be treated with caution.

The keys results for the Waipa are that there was an increase in SSC leading up to 2000 and a decrease in SSC from 2000 through until at least the end of 2010. Relating these results to what we know of catchment drivers of SSC indicates that the considerable effort that went into river rehabilitation works in the early 2000's (peaking in 2004/2005) have paid off. The downward trend in SSC is apparent despite a slight bias towards sampling in the rising stage of events in the Waipa since around 2008, thereby underestimating the SSC reduction in recent years. We recommend that WRC revisit their sampling schedule to try and remove this bias from future monitoring.

The key results from the Waitomo are that SSC was generally decreasing from 1990 through until the end of 1996, reflecting the success of efforts in the 1990's from the Waitomo Landcare group. Results from 1997 onwards vary depending on how time is broken up for analysis. In summary, results indicate that from 1997 to the end of 1998 there was an increase in SSC, reflecting the 1998 floods. There has been little change from 1999 until 2006, and an upward trend in SSC from 2006 until 2010. Results from 2010 to 2012 are somewhat conflicting, with a significant decrease overall, but a significant increase in the last year. Overall, there is no downward trend in SSC in the Waitomo in recent years. However, this does not mean that rehabilitation efforts over the last decade have been unsuccessful. It may be that these efforts are being offset by other drivers increasing SSC within the catchment.

5 Acknowledgements

We thank WRC for supplying data for this study. We also appreciate WRC staff providing their time and insight during our recent visit to the WRC office and the field trip into the Waipa catchment.

6 References

Ferguson, R.I. (1986). River loads underestimated by rating curves. *Water Resources Research 22(1)*: 74-76.

Gringorten, I.I. (1963). A plotting rule for extreme probability paper. *Journal of Geophysical Research 68*: 813-814.

Hicks, D.M.; Basher, L.R. (2008). The signature of an extreme erosion event on suspended sediment loads: Motueka River catchment, South Island, New Zealand. *In*: Sediment Dynamics in Changing Environments. IAHS Publ. 325.

Hoyle, J.; Hicks, M.; Roulston, H. (2011). Sampled suspended sediment yields from the Waikato region. NIWA Client Report CHC2011-135. Prepared for Waikato Regional Council.

Jennings, D.N.; Webby, M.G.; Parkin, D.T. (1993). Tunawaea Landslide Dam: Part 2 – Hazard Assessment. In: Proceedings of IPENZ Annual Conference 1993, Hamilton. 649-659.

McKerchar, A.; Hicks, M. (2003). Suspended sediment in Waitomo Stream. NIWA Client Report CHC2003-014. Prepared for Waikato Regional Council.

Webby, M.G.; Jennings, D.N. (1994). Analysis of dam break flood caused by failure of Tunawaea landslide dam. Proceedings, I.E. Aust. Conference on Hydraulics in Civil Engineering, Brisbane, Australia: 163-168.

Appendix A Plots of residuals over various time for testing time trends

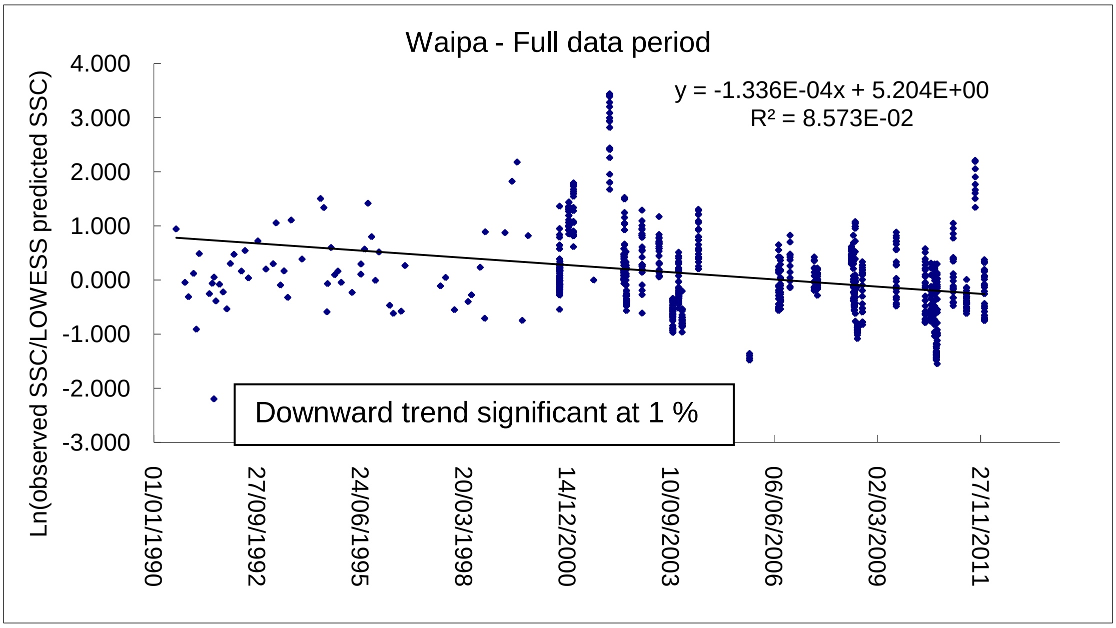


Figure A-1: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment for the full period of data. Data not normally distributed.

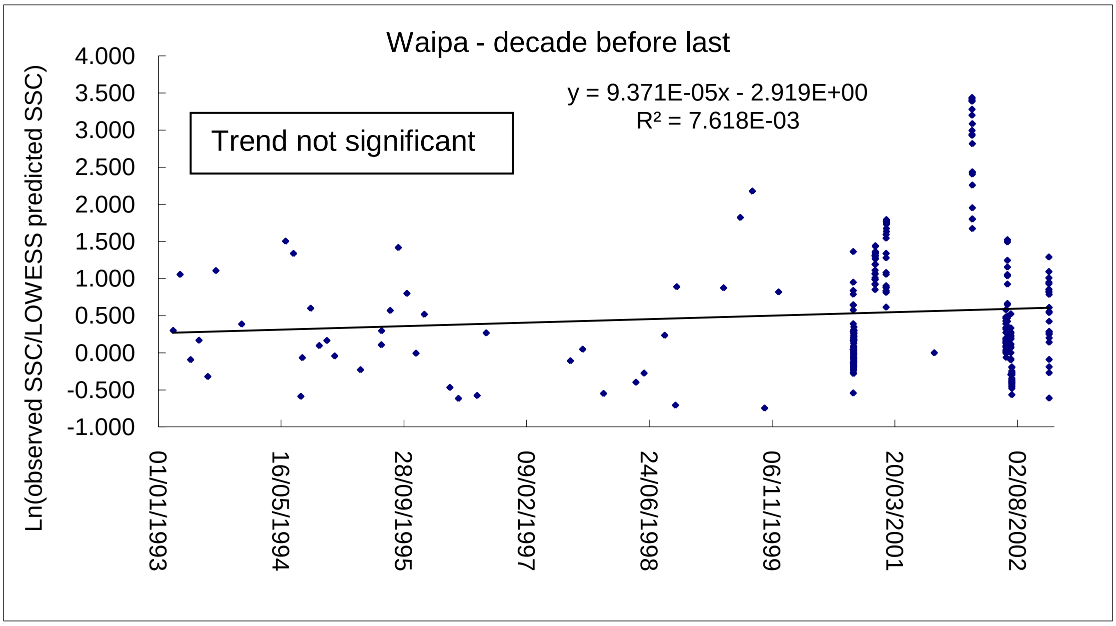


Figure A-2: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment for the decade before last. Data not normally distributed.

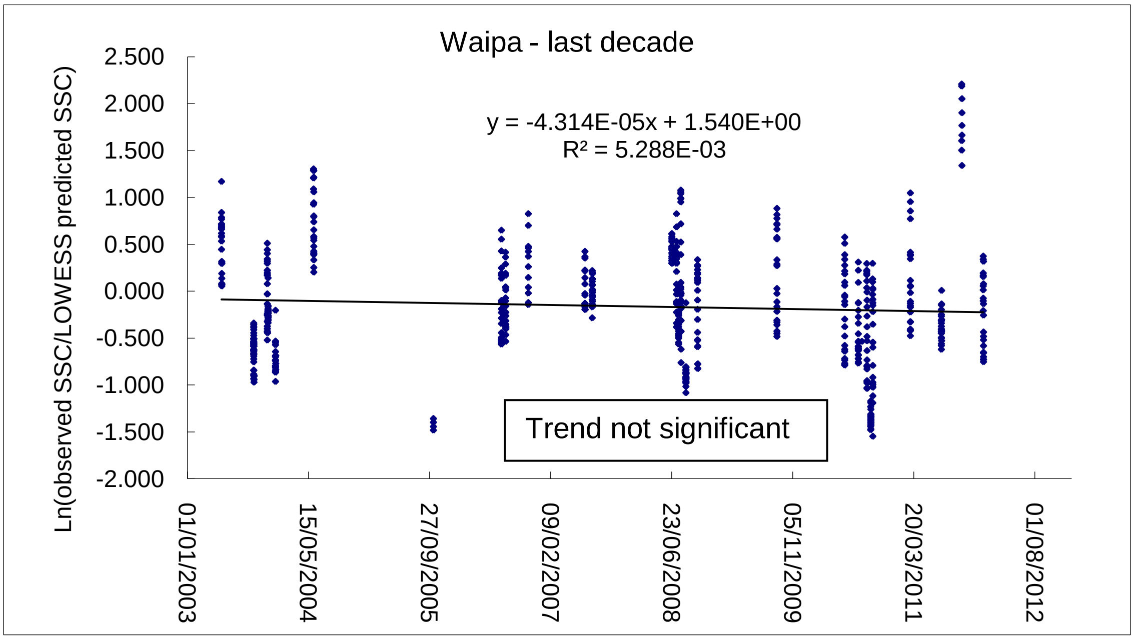


Figure A-3: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment for the last decade. Data normally distributed.

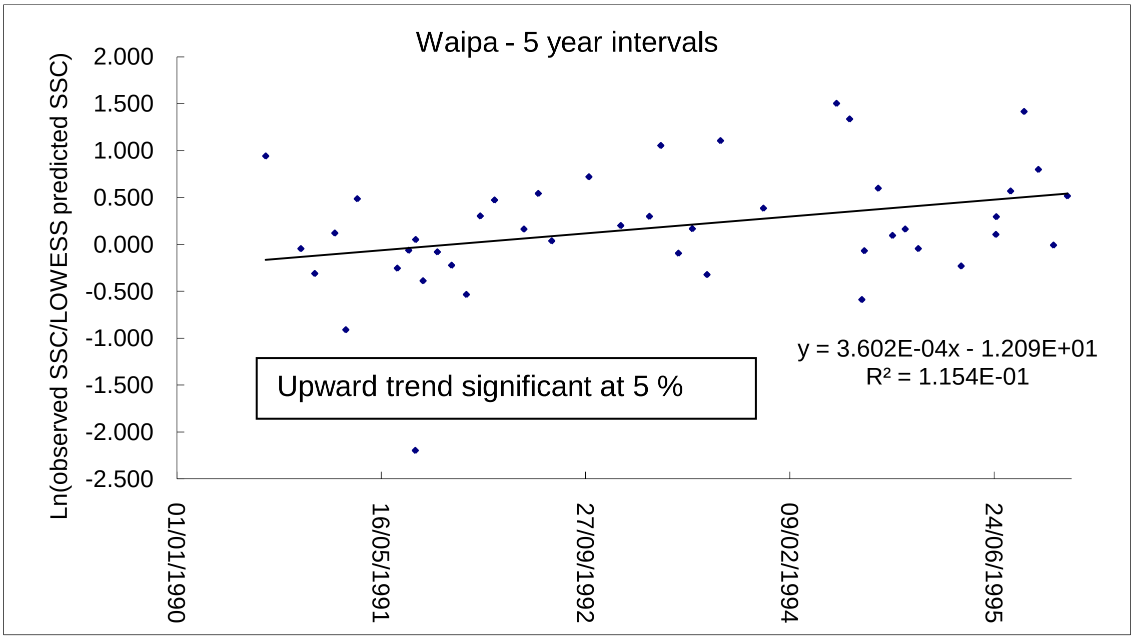


Figure A-4: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment from 1990 to the end of 1995. Data normally distributed.

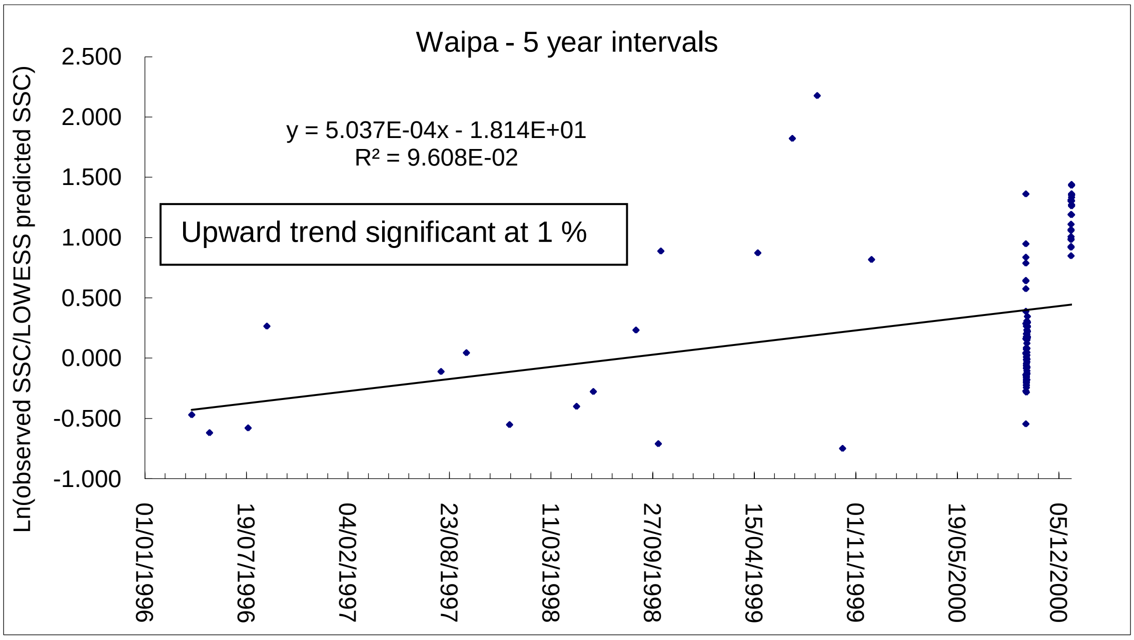


Figure A-5: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment from 1996 to the end of 2000. Data not normally distributed.

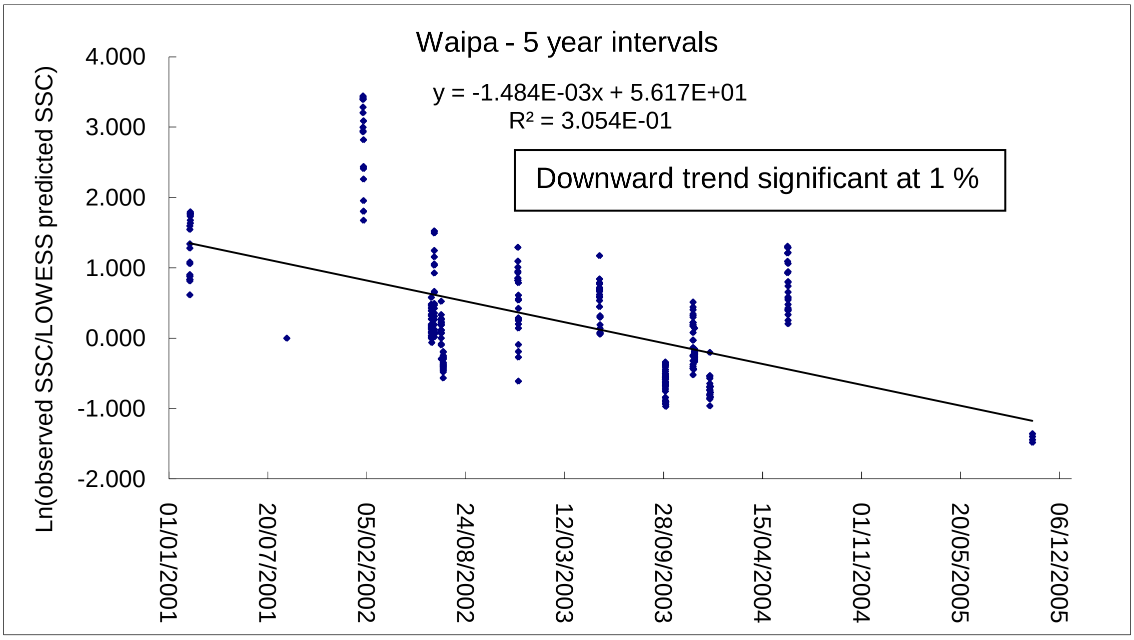


Figure A-6: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment from 2001 to the end of 2005. Data not normally distributed.

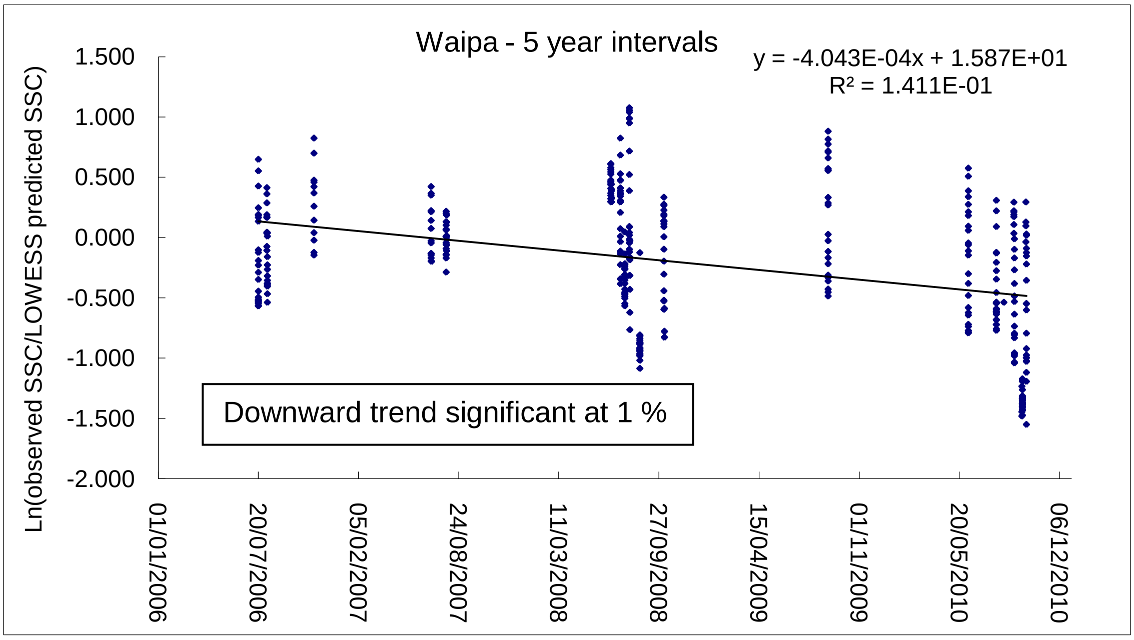


Figure A-7: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment from 2006 to the end of 2010. Data may be normally distributed (K-S and Chi^2 tests disagree).

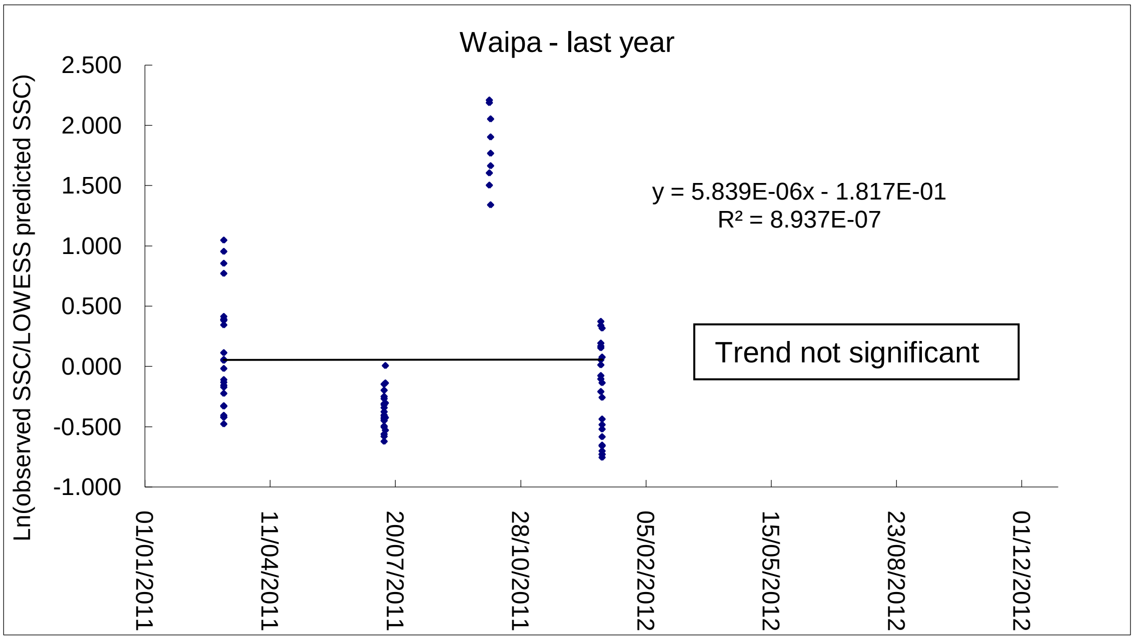


Figure A-8: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waipa catchment from 2011 to the end of 2012. Data not normally distributed.

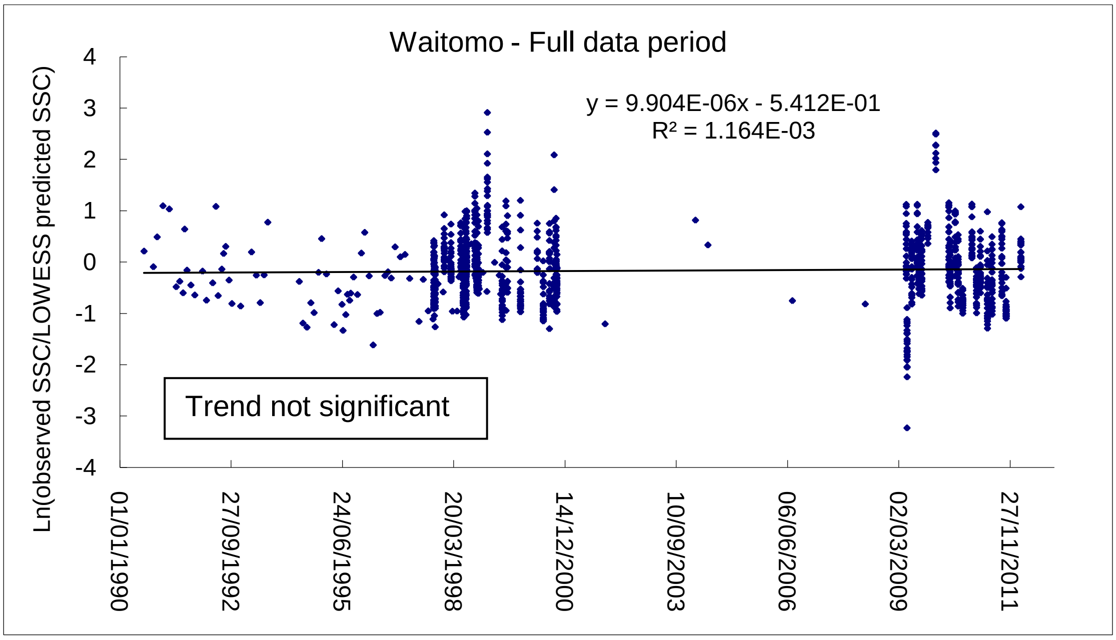


Figure A-9: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment for the full period of record. Data not normally distributed. Note the scarcity of data between 2001 and 2009.

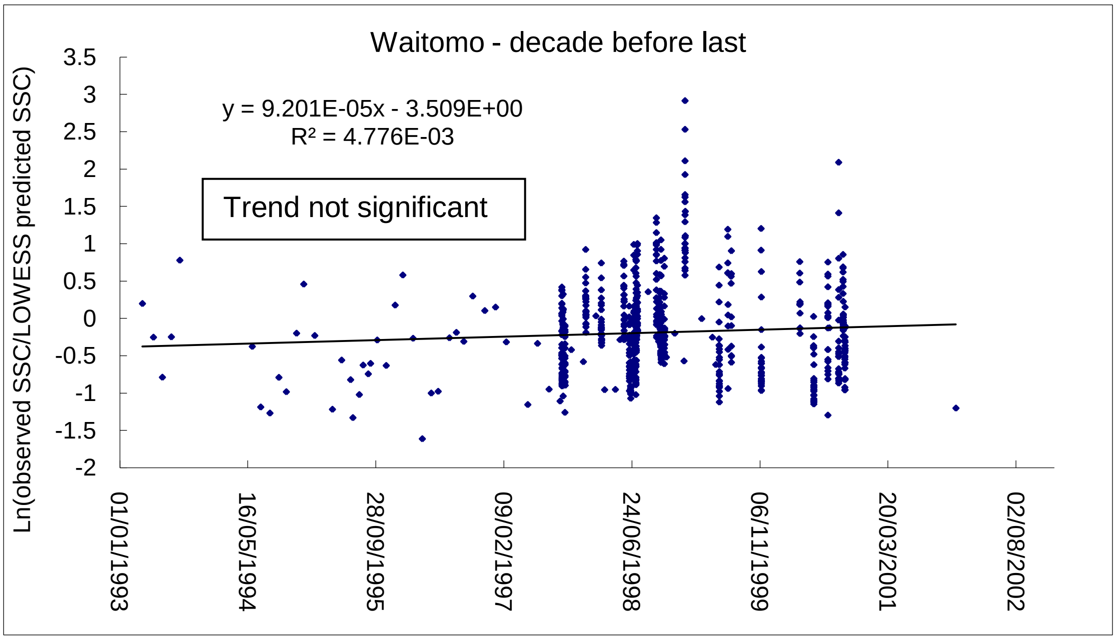


Figure A-10: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment for the decade before last. Data not normally distributed.

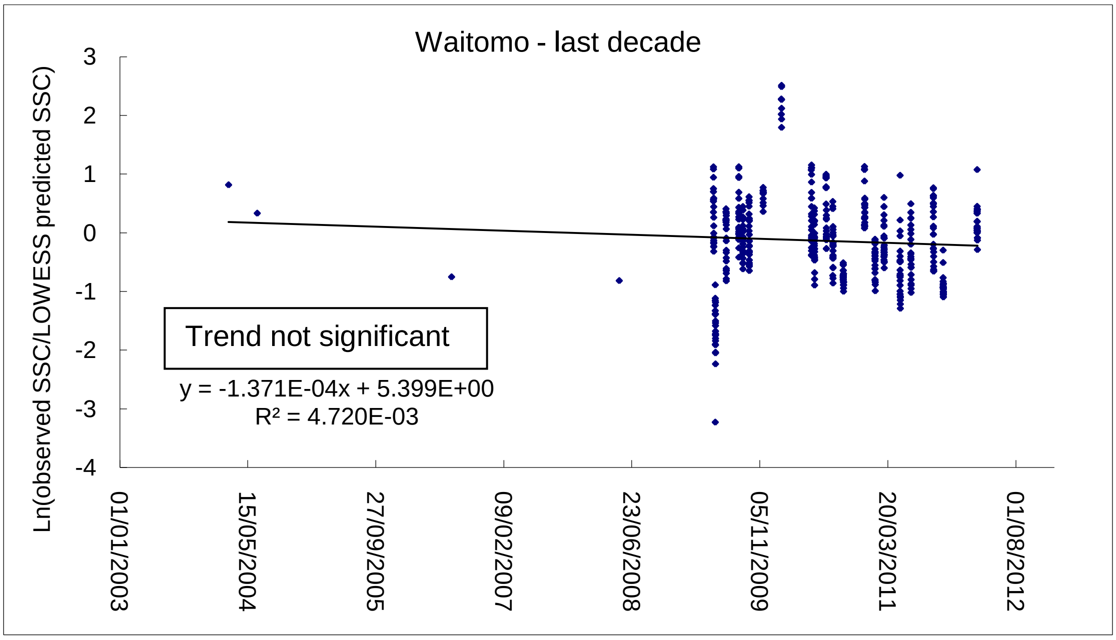


Figure A-11: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment for the last decade. Data may be normally distributed (K-S and Chi^2 tests disagree).

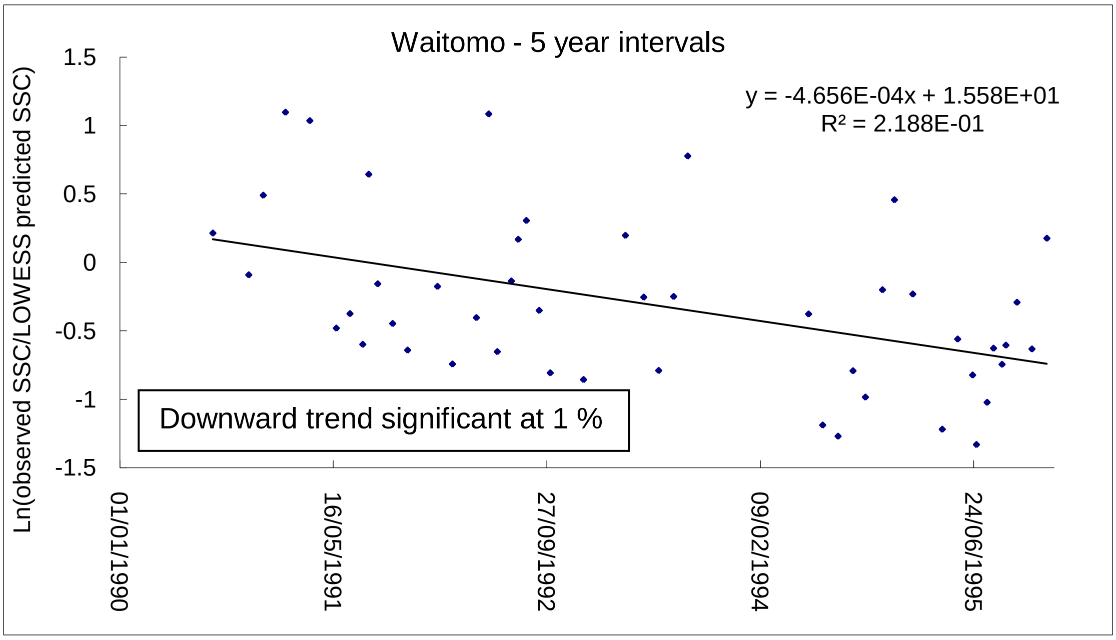


Figure A-12: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 1990 to the end of 1995. Data normally distributed.

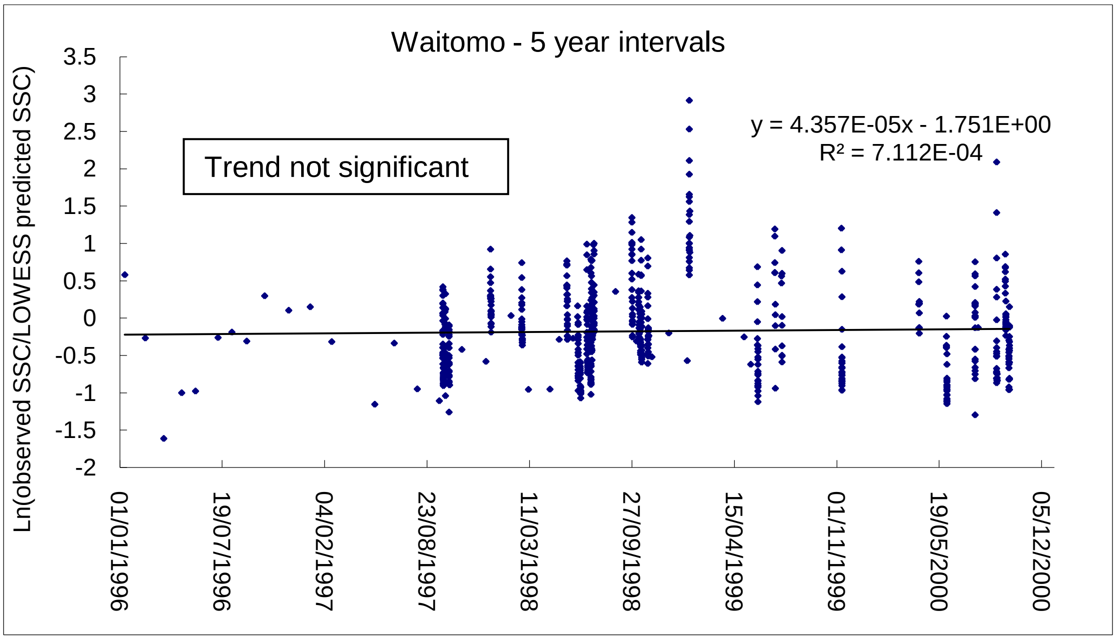


Figure A-13: Plot of Log_e(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 1996 to the end of 2000. Data not normally distributed.

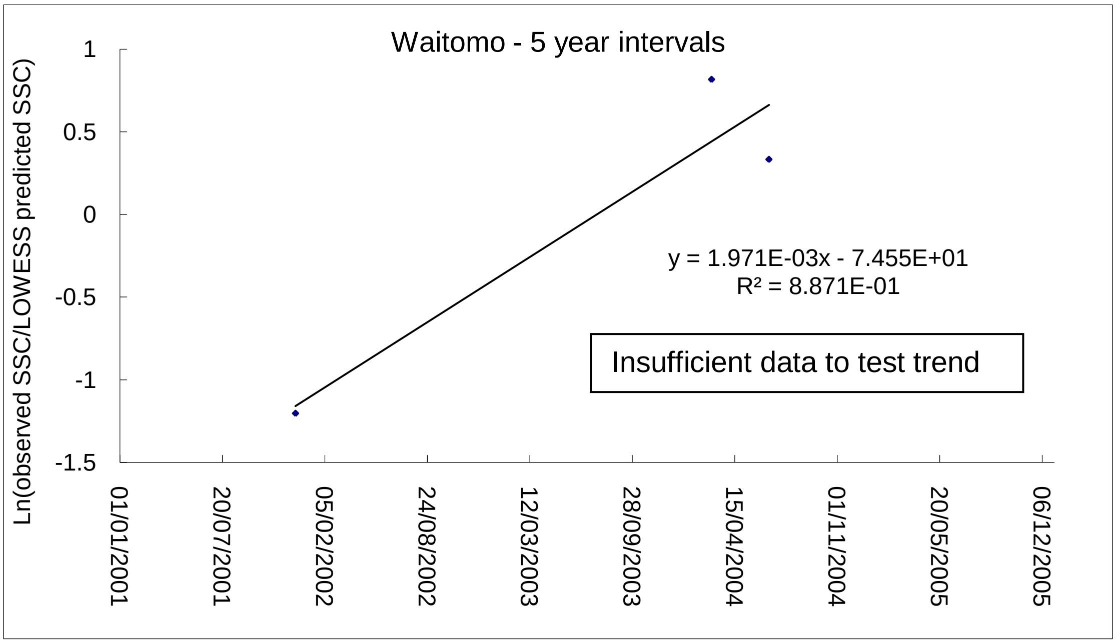


Figure A-14: Plot of Log_e(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 2001 to the end of 2005.

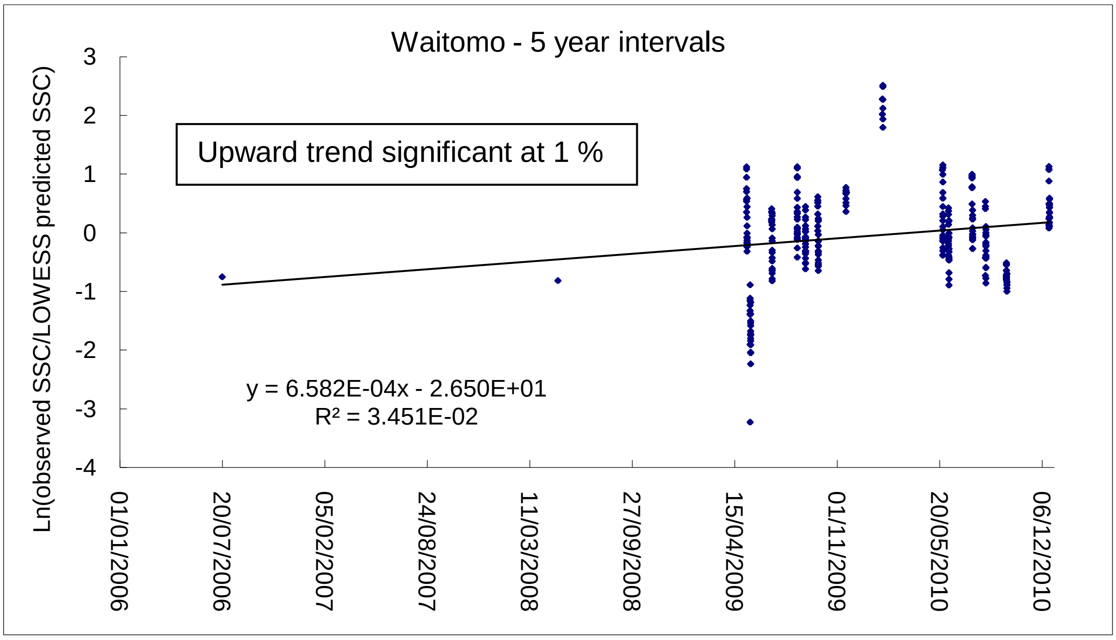


Figure A-15: Plot of Log_e(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 2006 to the end of 2010. Data may be normally distributed (K-S and Chi^2 tests disagree).

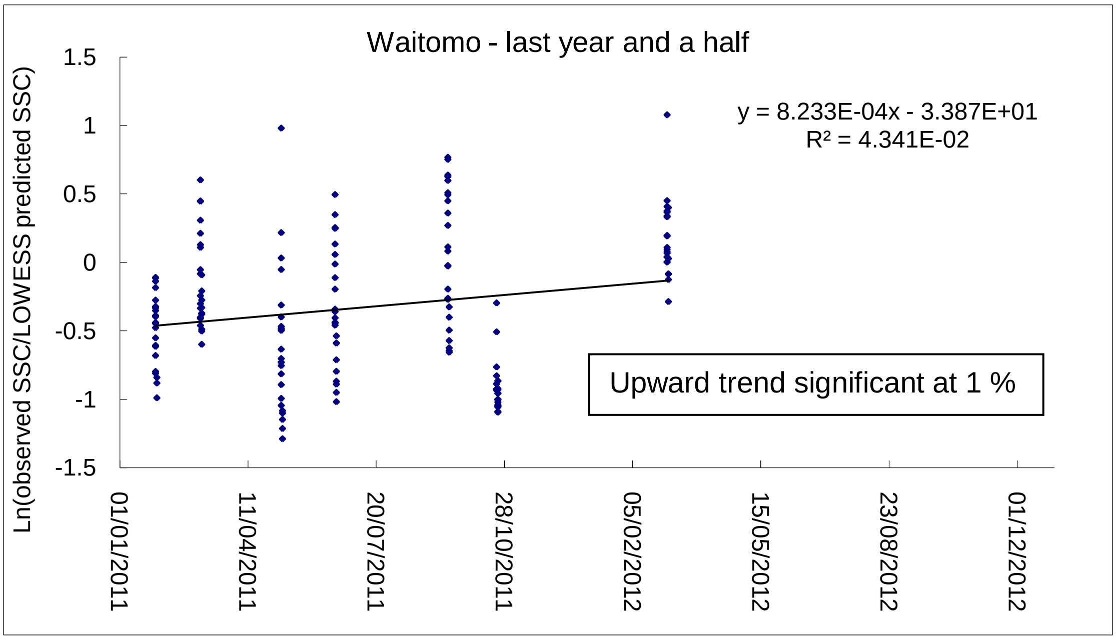


Figure A-16: Plot of Log_e(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 2011 to the end of March 2012. Data may be normally distributed (K-S and Chi^2 tests disagree).

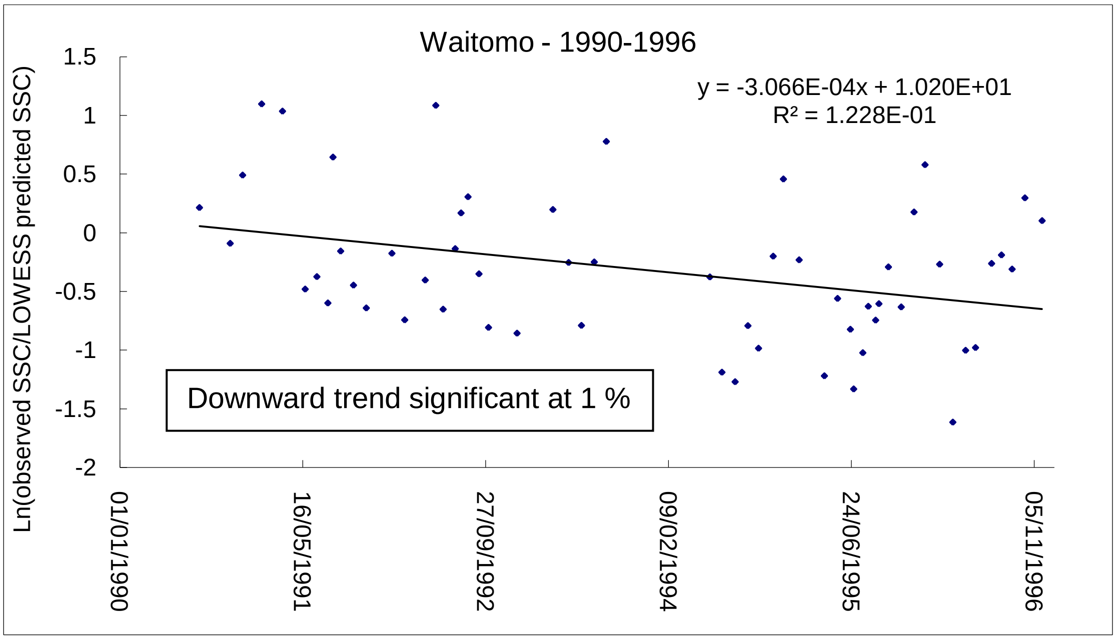


Figure A-17: Plot of Log_e(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 1990 to the end of 1996. Data normally distributed.

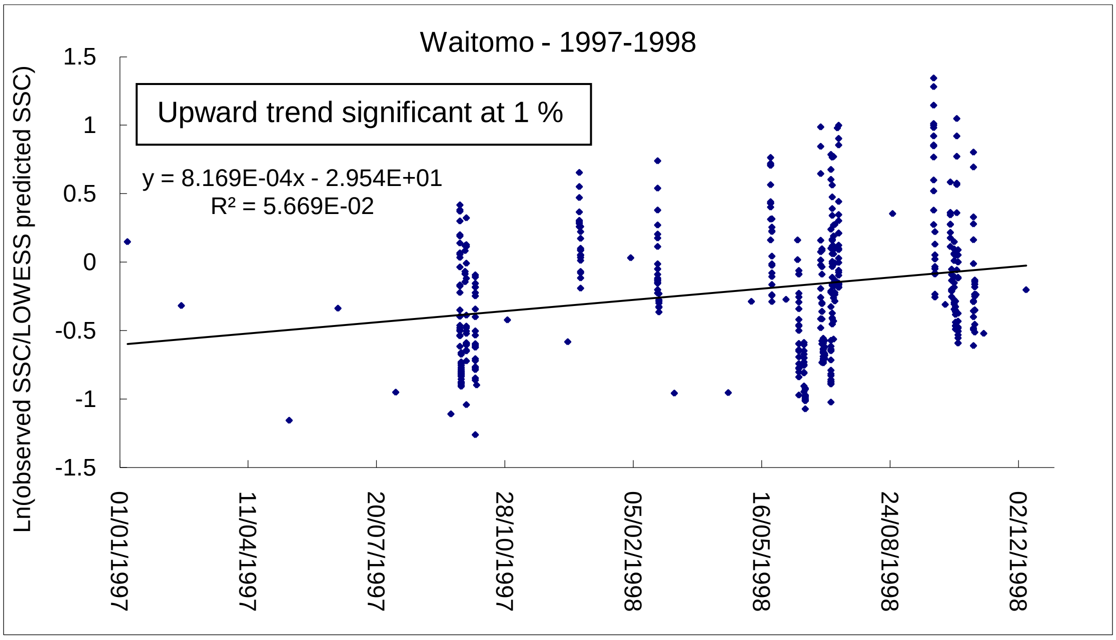


Figure A-18: Plot of Log_e(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 1997 to the end of 1998. Data not normally distributed.

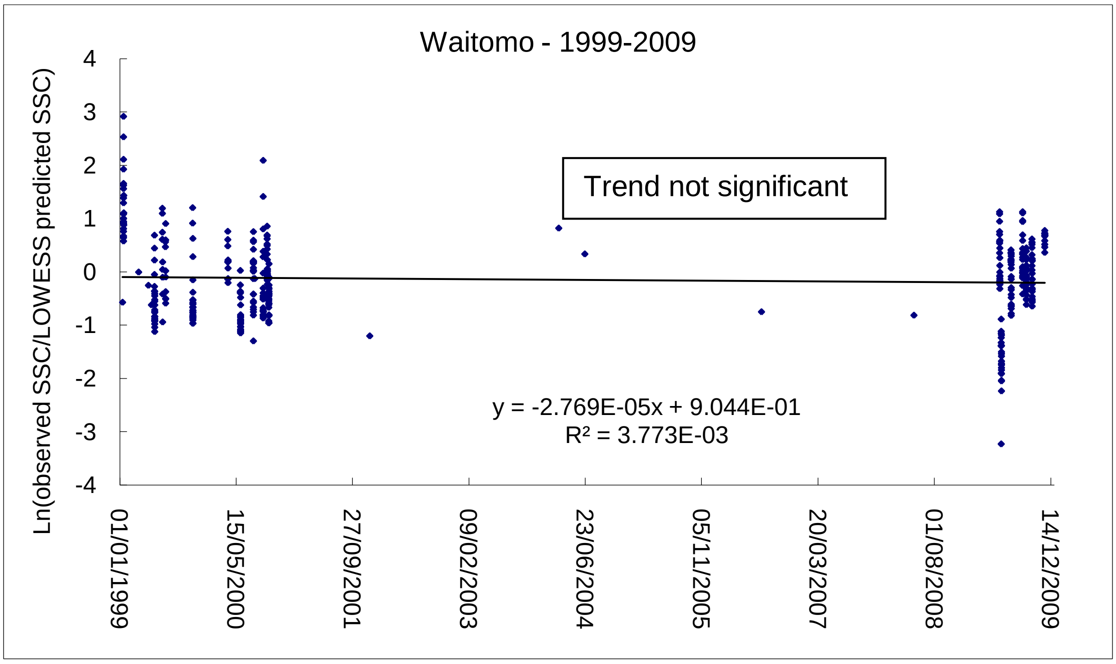


Figure A-19: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 1999 to the end of 2009. Data normally distributed.

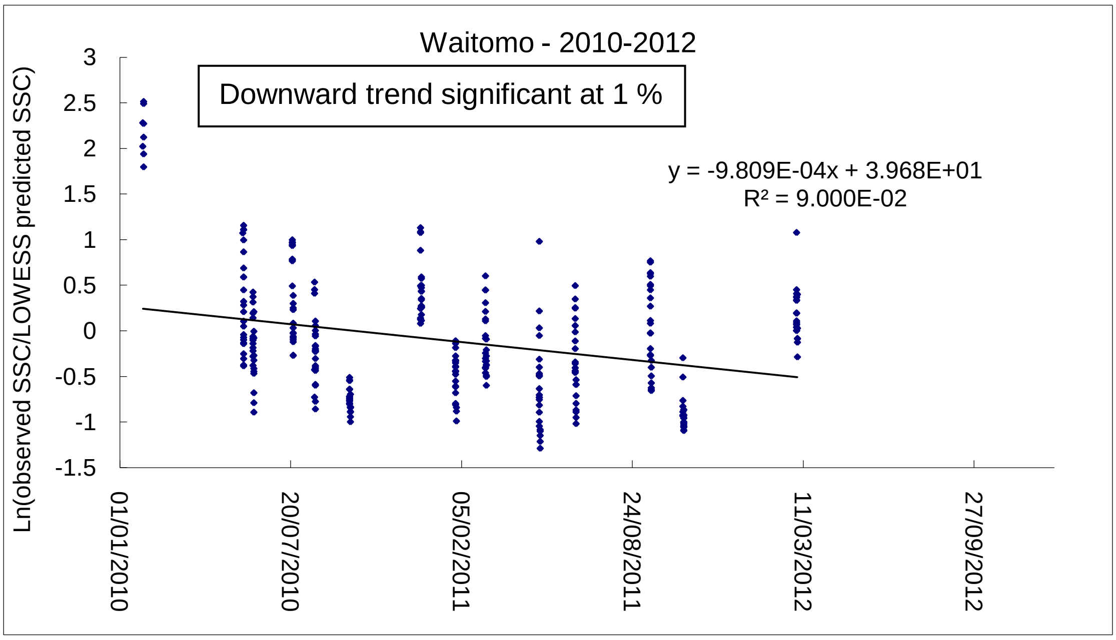


Figure A-20: Plot of Log$_e$(observed SSC/LOWESS predicted SSC) residuals over time for the Waitomo catchment from 2010 to the end of March 2012. Data not normally distributed.