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Sampled suspended sediment yields from the Waikato region

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Executive summary

Measurements of suspended sediment yields during storms at 23 sites in the Waikato region were analysed to determine mean annual sediment yields and event sediment yields. The mean annual yields were estimated using two approaches: (i) by developing suspended sediment concentration vs. water discharge ratings and combining these with the water discharge record; (ii) by developing event sediment yield vs. event hydrological magnitude (peak discharge or quickflow) ratings and combining these with either a peaks-over-threshold series of peak discharges or with the total event quickflow series, each extracted from the discharge record. The mean annual yields calculated using these approaches were also checked against results derived using the SEDRATE software.

During their respective periods of data collection, the basin specific mean annual sediment yields (averaged from the estimates from the two analysis approaches where available) were:

Mangaonua at Dreadnought	8.5 t/km^2/y (29.9 yrs flow data)
Waikato at Hamilton Traffic Bridge	8 t/km^2/y (34 yrs flow data)
Mangapu River at SH3 Bridge u/s of Mangaokewa confl.	71 t/km^2/y (10.8 yrs flow data)
Mangatutu Stream at Walker Road Bridge	37 t/km^2/y (7.2 yrs flow data)
Waitoa at Mellon Road	12 t/km^2/y (25.3 yrs flow data)
Matahuru Stream at Myjers	188 t/km^2/y (5.1 yrs flow data)
Waihou at Okauia	51 t/km^2/y (29.3 yrs flow data)
Opitonui River at d/s of Awaroa confl.	126 t/km^2/y (19.4 yrs flow data)
Waipa at Otewa	175 t/km^2/y (25.9 yrs flow data)
Waipa at Otorohanga	97 t/km^2/y (30.1 yrs flow data)
Oraka at Pinedale	41 t/km^2/y (31.8 yrs flow data)
Piako at Paeroa Tahuna Road Bridge	20 t/km^2/y (38.6 yrs flow data)
Waikato at Rangiriri	21 t/km^2/y (46.0 yrs flow data)
Tapu at Tapu-Coroglen	29 t/km^2/y (19.8 yrs flow data)
Tauranga-Taupo at Te Kono Slackline	78 t/km^2/y (34.7 yrs flow data)
Waihou at Te Aroha Bridge	57 t/km^2/y (46.4 yrs flow data)
Mangaokewa at Te Kuiti Pumping Station	54 t/km^2/y (27.6 yrs flow data)
Waingaro at Ruakiwi Road	85 t/km^2/y (9.6 yrs flow data)
Matahuru at Waiterimu Road	51 t/km^2/y (26.9 yrs flow data)
Waitomo at Aranui Caves Bridge	230 t/km^2/y (24.0 yrs flow data)
Whakapipi at SH22 Bridge	43 t/km^2/y (27.3 yrs flow data)
Wharekawa at Adams Farm Bridge	40 t/km^2/y (19.6 yrs flow data)
Waipa at Whatawhata	60 t/km^2/y (38.4 yrs flow data)

Annual yields vary substantially about the mean annual yield due to inter-annual weather variation. Over all catchments, the standard deviation in annual yield averaged 47% of the mean annual yield.

A correlation and multiple-regression analysis indicated that the variation in specific sediment yield (*SSY*) in the dataset is due mainly to catchment runoff (or rainfall, which is highly correlated with runoff), mean slope, and land-cover. Other factors being equal, sediment yields were lower from forested catchments compared with catchments in pasture or horticulture. The tendency for forest land-cover to be associated with steeper, wetter terrain and for pasture to be associated with flatter, drier country serves to reduce the range of sediment yields over the region. While there were indications of a lithology influence, with

higher yields from catchments formed in erodible Tertiary sedimentary rocks or tephra, this was not statistically significant. An empirical model predicting specific sediment yield is:

$SSY_{(t/km^2/y)} = 0.42\ RS + 1.70\ \%all\text{-}pasture - 137$

where R is runoff (mm/y), S is catchment mean slope, *%all-pasture* is the percentage of the catchment area in grassland or horticulture, and the standard error of the estimate is 42 $t/km^2/y$.

Event-yield magnitude-frequency relations developed for the auto-sampled sites showed generally that the catchments with higher (or lower) mean annual yields have systematically higher (or lower) yields over all return periods. The mainly forested Wharekawa and Opitonui catchments on the Coromandel Peninsula were exceptions, showing relatively lower yields from common events (return period of about 1 year and less) and relatively higher yields from less common events. This behaviour likely reflects limited sediment sources during smaller, more frequent events in these catchments.

Yield estimates derived from previous studies of some of the study catchments agree acceptably well with those of the present study, allowing that the present analysis has the benefit of longer spans of flow record and increased numbers of suspended sediment samples.

A similar study of sediment yields from nine catchments in Auckland’s Waitemata Formation terrain showed much the same range in specific sediment yields as found across the Waikato region. The variation in yield across the Auckland region was due mainly to catchment rainfall (or runoff), mean slope, and land-cover, which also aligns with the results from the Waikato sites.

It is recommended that the sediment yield results from this study are combined with those from other Waikato catchments and from the Auckland region to calibrate an empirical model for predicting sediment yield that is sensitive to spatially-distributed characteristics of catchment hydrology, slope, land-cover, and lithology.

1 Introduction

1.1 Background and purpose

Sustainable management of the Waikato region's land and aquatic environment requires ongoing monitoring of various environmental parameters. Sediment in receiving-water bodies is of concern, thus monitoring of sediment loads and yields is required to identify and quantify its sources, manage its effects, and to measure trends and the effectiveness of management measures. Since it is a prohibitive undertaking to continuously monitor sediment in every basin across the region, an alternative is to develop an understanding of how sediment yields vary with differing landuse and basin hydrological and physical characteristics. From this, sediment yield on a regional basis can be proxied by monitoring landuse and hydrological parameters such as rainfall or runoff.

Towards this understanding, this report presents results from sediment yield studies at 23 catchments under various landuses in the Waikato region (Figure 1-1, Table 1-1). Catchment areas range from 20.5 to 12421 km^2.

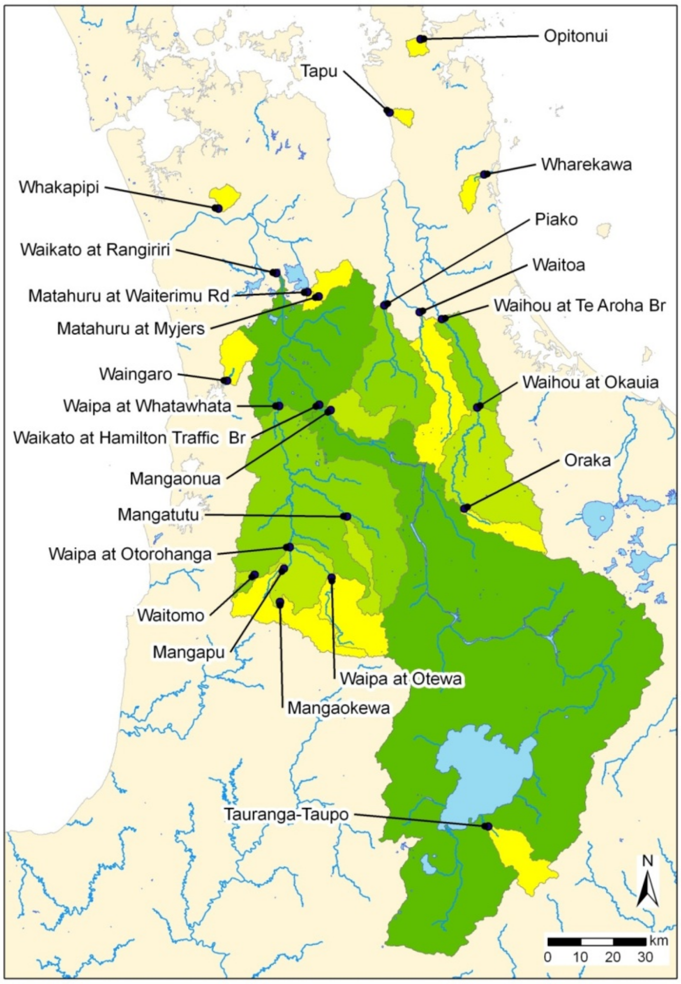

Figure 1-1: Study catchment locations within the Waikato region.

1.2 Objectives

The objectives of the study are to:

- Determine mean annual sediment yield over the period of flow record for each of the 23 basins.
- Collate or extract information on catchment slope, land-cover, landuse, and mean annual rainfall, and report with sediment yield results for each of the 23 basins.
- Provide a preliminary analysis of relationships between mean annual sediment yield and event sediment yield in terms of catchment characteristics, including rainfall, runoff, slope, landuse, and lithology.

1.3 Catchment locations

The locations of the flow recorders for each catchment are provided in Table 1-1.

Table 1-1: NZTM coordinates of flow recorders in each catchment. The sampling method is listed as either M, denoting manual sampling, or A denoting auto-sampling.

Catchment	Sampling	Flow Recorder No.	Easting	Northing
Mangaonua at Dreadnought	M	1543497	2715375	6374751
Waikato at Hamilton Traffic Br	M	43466	2711800	6376400
Mangapu River at SH3 Br u/s Mangaokewa confl	A	1043444	2701061	6326277
Mangatutu Stream at Walker Rd Br	A	1943459	2720300	6342200
Waitoa at Mellon Rd	M	9179	2742600	6404700
Matahuru Stream at Myjers	A	3043490	2711644	6409530
Waihou at Okauia	M	9224	2760200	6375600
Opitonui River at d/s Awaroa confl	A	11310	2742873	6488366
Waipa at Otewa	A	43481	2715700	6323500
Waipa at Otorohanga	M	43468	2702900	6332900
Oraka at Pinedale	M	1009213	2756300	6344600
Piako at Paeroa Tahuna Rd Br	M	9140	2731800	6406800
Waikato at Rangiriri	M	43420	2698700	6416700
Tapu at Tapu-Coroglen	M	9701	2733364	6465803
Tauranga-Taupo at Te Kono	M	1543413	2763600	6247300
Waihou at Te Aroha Br	M	9205	2749400	6402600
Mangaokewa at Te Kuiti Pumping Stn	M	1643462	2699840	6316096
Waingaro at Ruakiwi Road	A	42601	2683700	6383700
Matahuru at Waiterimu Rd	A	43489	2708300	6410900
Waitomo at Aranui Caves	A	1943481	2692077	6324406
Whakapipi at SH22-Tuakau	M	1643457	2681052	6436497
Wharekawa at Adams Farm Br	A	12509	2762313	6446823
Waipa at Whatawhata	M	43433	2699600	6376000

1.4 Catchment characteristics

This section outlines key characteristics specific to each of the catchments examined in this report. GIS techniques have been used to calculate catchment area and extract representative measures of catchment lithology, landuse, slope, mean annual rainfall and runoff.

The boundary shape-files for most of the catchments were provided by Environment Waikato, the remaining catchments were generated by NIWA. This was done by using a geometric network to delineate the upstream catchment from the flow recorder sites provided. The geometric network has been created from NIWA's 'River network' that was derived from a Digital Elevation Model generated using LINZ topographical contours. The catchment boundaries are defined as the contributing area upstream of the flow recorder relevant to each catchment (Table 1-1). The catchment areas are given in Table 1-2.

Table 1-2: Catchment characteristics.

Site	Catchment area (km^2)	Catchment Slope (m/m) min	max	mean	STD	Mean Annual Rainfall (mm/yr)	Mean Annual Runoff (mm/yr)
Mangaonua at Dreadnought	166	<0.01	2.01	0.25	0.19	1167.0	409
Waikato at Hamilton Traffic Br	8230	<0.01	4.73	0.08	0.11	1509.0	994
Mangapu River at SH3 Br u/s Mangaokewa confl	150.7	<0.01	1.61	0.21	0.16	1745.4	1078
Mangatutu Stream at Walker Rd Br	123	<0.01	3.41	0.26	0.21	1692.8	1044
Waitoa at Mellon Rd	409	<0.01	7.67	0.28	0.20	1177.2	448
Matahuru Stream at Myjers	82.6	<0.01	7.67	0.25	0.20	1293.4	579
Waihou at Okauia	816	<0.01	6.00	0.43	0.26	1505.2	1036
Opitonui River at d/s Awaroa confl	29	<0.01	2.73	0.27	0.22	1966.9	1192
Waipa at Otewa	317	<0.01	4.91	0.11	0.12	1789.3	1277
Waipa at Otorohanga	919	<0.01	2.24	0.42	0.21	1671.6	1020
Oraka at Pinedale	136	<0.01	2.52	0.36	0.24	1508.0	651
Piako at Paeroa Tahuna Rd Br	534	<0.01	3.16	0.19	0.20	1134.6	415
Waikato at Rangiriri	12421	<0.01	3.16	0.19	0.21	1506.6	933
Tapu at Tapu-Coroglen	26.4	<0.01	6.51	0.18	0.20	1903.7	1121
Tauranga-Taupo at Te Kono	199	<0.01	17.14	0.18	0.19	2020.2	1550
Waihou at Te Aroha Br	1137	<0.01	4.45	0.33	0.18	1528.4	1131
Mangaokewa at Te Kuiti Pumping Stn	173.2	<0.01	2.60	0.30	0.21	1635.0	953
Waingaro at Ruakiwi Rd	117	<0.01	17.14	0.20	0.19	1499.2	737
Matahuru at Waiterimu Rd	105	<0.01	2.60	0.24	0.19	1209.9	579
Waitomo at Aranui Caves Br	20.5	<0.01	1.52	0.07	0.10	2171.0	1800
Whakapipi at SH22 Br	48.9	<0.01	1.77	0.33	0.18	1275.6	576
Wharekawa at Adams Farm Br	46.5	<0.01	1.21	0.11	0.11	2040.8	1232
Waipa at Whatawhata	2826	<0.01	2.81	0.36	0.22	1617.4	976

Catchment slope data (Table 1-2) were calculated by creating a slope surface in ArcGIS using the Digital Elevation Model provided by Environment Waikato. A cell size of 10m X 10m was preserved during this process. Slope has been calculated as rise/run, (i.e. a slope of 1 equals 45^o). Zonal statistics (mean, maximum, minimum and standard deviation) were generated from this slope surface for each study catchment. The digital elevation model supplied by Environment Waikato was sourced from Terralink International Limited, 2007, and is copyright reserved.

Mean annual rainfall data (Table 1-2) were provided by Environment Waikato. These data are based on the period 1981 – 2010 and were generated using the method of Tait et al. (2006).

Mean annual runoff (Table 1-2) was calculated based on the mean water discharge over the period of the flow record (in m^3/s), divided by the catchment area (in m^2), and multiplied by the number of seconds in a year. This is multiplied by 1000 to give runoff in mm/year.

Catchment lithology data (Table 1-3) have been calculated from the Land Resource Inventory (LRI) for NIWA's River network. For this project, lithology was accumulated downstream from this river network database for each of the study catchments. The lithology classes were then calculated as percentages of the total catchment area. The classes used in Table 1-3 are based on the NZLRI Edition 2 and the class abbreviations are defined in Table 1-4.

Catchment land-cover data have been calculated from the Land Cover DataBase 2 (LCDB2, 2000/2001) for NIWA's River network. For this project, land-cover was accumulated downstream from this river network database for each of the study catchments. The land-cover classes were then calculated as percentages of the total catchment area. The LCDB land-cover classes present were then grouped as follows:

- **Exotic forest** – Minor shelterbelts, major shelterbelts, afforestation (imaged), afforestation (not imaged post LCDB1), pine forest open canopy, pine forest closed canopy
- **Harvested Forest** – Forest harvested
- **Horticulture** – short rotation cropland, vineyard, orchard and other perennial crops
- **Native forest** – Broadleaved indigenous hardwoods, deciduous hardwoods
- **Pasture/grassland** – Alpine grass/herbfield, high producing exotic grassland, low producing grassland, tall tussock grassland, depleted grassland, herbaceous freshwater vegetation
- **Urban** – built up area, urban parkland open space, surface mine, dump, transport infrastructure
- **Scrub/ Shrub** – flaxland, fernland, gorse and or broom, manuka and or kanuka, subalpine shrubland, mixed exotic shrubland, matagouri, grey scrub
- **Other** – river lakeshore gravel and rock, landslide, alpine gravel and rock, permanent snow and ice, lake and pond, river.

Table 1-3: Catchment lithology (based on LRI Edition 2). Abbreviations explained in Table 1-4.

	Lithology (% catchment area)																			
Site	ng	rm	kt	mo	lp	tp	ft	la	vo	vu	pt	al	us	mm	mb	mj	sm	ac	gw	mx
Mangaonua at Dreadnought	0	0	0	9	0	0	0	0	0	0	3	2	76	0	0	0	0	10	0	0
Waikato at Hamilton Traffic Br	4	0	39	26	1	19	0	0	2	0	1	0	4	0	0	0	0	4	0	0
Mangapu River at SH3 Br u/s Mangaokewa confl	0	0	0	56	0	0	0	0	0	0	0	13	0	8	0	16	0	1	2	3
Mangatutu Stream at Walker Rd Br	0	0	0	80	0	0	0	0	8	0	0	8	0	0	0	0	0	3	0	0
Waitoa at Mellon Rd	0	0	0	38	0	0	0	0	1	0	0	8	52	0	0	0	0	0	0	0
Matahuru Stream at Myjers	0	0	0	22	0	0	0	0	0	0	0	8	0	0	0	0	0	70	0	0
Waihou at Okauia	0	0	0	78	0	0	0	0	3	0	0	3	17	0	0	0	0	0	0	0
Opitonui River at d/s Awaroa confl	0	0	0	5	0	0	0	0	19	72	0	3	0	0	0	0	0	0	0	0
Waipa at Otewa	0	0	20	73	0	4	0	0	0	0	0	2	0	0	0	0	0	2	0	0
Waipa at Otorohanga	0	0	9	68	0	2	0	0	0	0	0	10	0	2	0	6	0	2	0	1
Oraka at Pinedale	0	0	0	94	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0
Piako at Paeroa Tahuna Rd Br	0	0	0	49	0	0	0	0	3	0	8	9	20	0	0	0	0	11	0	0
Waikato at Rangiriri	2	0	27	35	0	13	0	0	2	0	3	3	7	0	0	1	0	6	0	0
Tapu at Tapu-Coroglen	0	0	0	0	0	0	0	0	95	0	0	3	0	0	0	0	0	2	0	0
Tauranga-Taupo at Te Kono Slackline	0	0	44	13	0	17	0	0	0	0	0	0	0	0	0	0	0	26	0	0
Waihou at Te Aroha Br	0	0	0	64	0	0	0	0	5	0	0	4	26	0	0	0	0	0	0	0
Mangaokewa at Te Kuiti Pumping Stn	0	0	10	76	0	2	0	0	0	0	0	1	0	0	0	4	0	4	1	1
Waingaro at Ruakiwi Rd	0	0	0	20	0	0	0	0	0	0	0	2	1	1	2	6	1	64	0	4
Matahuru at Waiterimu Rd	0	0	0	27	0	0	0	0	0	0	0	8	4	0	0	0	0	60	0	0
Waitomo at Aranui Caves Br	0	0	0	93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5
Whakapipi at SH22 Br	0	0	0	63	0	0	0	0	21	0	4	5	0	0	0	0	7	0	0	0
Wharekawa at Adams Farm Br	0	0	0	62	0	0	0	0	37	0	0	1	0	0	0	0	0	0	0	0
Waipa at Whatawhata	0	0	3	64	0	1	0	0	4	0	3	11	6	1	0	2	0	4	0	1

Table 1-4: Lithology classes present in the study catchments. Based on NZLRI Edition 2.

Item Code	Rock type class
Igneous Rocks: (i) extremely weak to weak	
ng	Ngauruhoe Tephra
rm	Rotomahana mud
kt	Kaharoa & Taupo ashes
mo	Ashes older than Taupo
lp	Pumiceous lapilli
tp	Taupo and Kaharoa breccia and pumiceous alluvium
ft	Quaternary breccias older than Taupo breccias
la	Lahar deposits
vu	Extremely weak altered volcanics
Igneous Rocks: (ii) weak to extremely strong	
vo	Lavas and welded ignimbrites
Sedimentary Rocks: (i) very loose to compact	
pt	Peat
al	Undifferentiated floodplain alluvium
us	Unconsolidated sands and gravels
Sedimentary Rocks: (ii) very compact to weak	
mm	massive mudstone
mb	Bedded mudstone
mj	Jointed mudstone or siltstone
sm	massive sandstone
ac	crushed argillite
mx	sheared mixed lithologies
Sedimentary Rocks: (iii) moderately strong to extremely strong	
gw	greywacke

The grouped land-covers present in each catchment are listed in Table 1-5.

Table 1-5: Landuse in the study catchments. Based on LCDB2.

	Land-cover (% catchment area)							
Site	Exotic Forest	Harvested Forest	Horti-culture	Native forest	Pasture/ grass land	Urban	Scrub/ Shrub	Other
Mangaonua at Dreadnought	0.6	0.2	4.2	5.0	86.3	2.4	1.2	0.0
Waikato at Hamilton Traffic Br	24.4	5.6	0.5	18.1	36.3	1.0	4.7	9.2
Mangapu River at SH3 Br u/s Mangaokewa confl	2.1	1.2	0.0	7.7	86.8	0.5	1.7	0.0
Mangatutu Stream at Walker Rd Br	1.5	0.5	0.6	41.5	54.9	0.1	0.9	0.0
Waitoa at Mellon Rd	0.7	0.2	4.0	2.7	90.5	1.8	0.1	0.0
Matahuru Stream at Myjers	2.0	0.0	0.0	6.2	90.6	0.0	1.1	0.1
Waihou at Okauia	19.0	1.7	1.0	20.8	55.5	0.7	1.0	0.0
Opitonui River at d/s Awaroa confl	45.5	16.7	0.0	34.5	2.7	0.0	0.7	0.0
Waipa at Otewa	8.3	0.4	0.0	46.6	42.6	0.1	1.6	0.3
Waipa at Otorohanga	2.7	0.7	0.2	17.7	75.8	0.7	1.8	0.3
Oraka at Pinedale	47.6	2.9	0.0	18.7	29.3	0.1	1.4	0.0
Piako at Paeroa Tahuna Rd Br	0.8	0.1	1.1	4.7	91.5	1.2	0.5	0.1
Waikato at Rangiriri	17.3	4.0	0.4	17.1	49.4	1.4	3.9	6.4
Tapu at Tapu-Coroglen	1.4	0.2	0.0	84.1	4.1	0.2	9.9	0.1
Tauranga-Taupo at Te Kono Slackline	25.3	0.3	0.0	67.5	1.9	0.3	4.5	0.2
Waihou at Te Aroha Br	14.7	1.3	1.0	23.1	58.2	0.7	0.8	0.1
Mangaokewa at Te Kuiti Pumping Stn	6.2	2.2	0.0	13.7	73.6	0.7	3.5	0.0
Waingaro at Ruakiwi Rd	8.0	9.5	0.2	12.2	63.2	0.2	6.7	0.0
Matahuru at Waiterimu Rd	2.3	0.0	0.0	7.1	89.3	0.0	1.3	0.0
Waitomo at Aranui Caves Br	11.2	1.0	0.0	23.3	59.9	0.0	4.6	0.0
Whakapipi at SH22 Br	0.6	0.0	18.6	6.1	64.1	10.2	0.3	0.0
Wharekawa at Adams Farm Br	40.8	2.6	0.0	53.1	1.4	0.0	2.2	0.0
Waipa at Whatawhata	4.7	1.0	0.0	21.5	69.7	0.8	1.8	0.2

1.5 Data availability for sediment yield analysis

Figure 1-2 and Table 1-6 present the periods of flow and sediment concentration data for each of the study catchments.

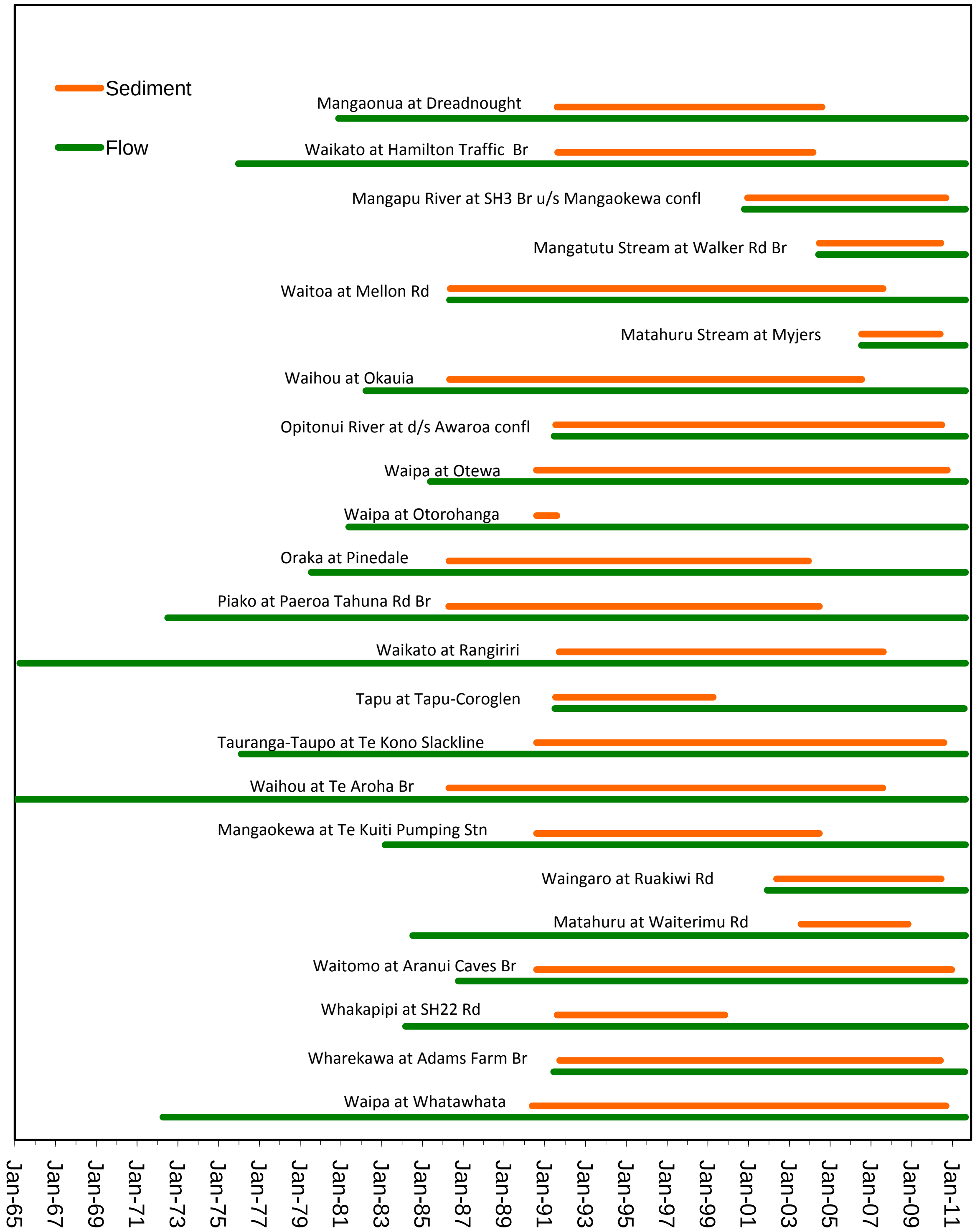

Figure 1-2: Periods of time over which sediment concentration and flow data are available for each catchment.

Table 1-6: Data availability for the study sites. The second column shows the number of years of flow record, excluding gaps, and the number of runoff events for which there is sediment concentration data adequate for determining event sediment yield. The span of record indicates the beginning and end dates of data collection (or if end date is August 2011, the most recent data used in this study).

Site	No. years/events	Span of record	
Mangaonua at Dreadnought			
Sediment Data	None	Aug-91	Aug-04
Flow Data	29.87	Nov-80	Aug-11
Waikato at Hamilton Traffic Bridge			
Sediment Data	None	Aug-91	Mar-04
Flow Data	33.98	Dec-75	Aug-11
Mangapu River at SH3 Br u/s Mangaokewa confluence			
Sediment Data	46	Dec-00	Sep-10
Flow Data	10.85	Oct-00	Aug-11
Mangatutu Stream at Walker Rd Bridge			
Sediment Data	34	Jun-04	Jun-10
Flow Data	7.21	Jun-04	Aug-11
Waitoa at Mellon Rd			
Sediment Data	None	May-86	Aug-07
Flow Data	25.27	May-86	Aug-11
Matahuru Stream at Myjers			
Sediment Data	22	Jul-06	May-10
Flow Data	5.06	Jul-06	Aug-11
Waihou at Okauia			
Sediment Data	None	May-86	Jul-06
Flow Data	29.31	Mar-82	Aug-11
Opitonui River at d/s Awaroa confluence			
Sediment Data	60	Jul-91	Jun-10
Flow Data	19.41	Jun-91	Aug-11
Waipa at Otewa			
Sediment Data	25	Aug-90	Oct-10
Flow Data	25.95	May-85	Aug-11
Waipa at Otorohanga			
Sediment Data	None	Aug-90	Aug-91
Flow Data	30.07	May-81	Aug-11
Oraka at Pinedale			
Sediment Data	None	Apr-86	Dec-03
Flow Data	31.77	Jul-79	Aug-11
Piako at Paeroa Tahuna Rd Bridge			
Sediment Data	None	Apr-86	Jun-04
Flow Data	38.59	Jul-72	Aug-11

Site	No. years/events	Span of record	
Waikato at Rangiriri			
Sediment Data	None	Sep-91	Aug-07
Flow Data	46.03	Apr-65	Aug-11
Tapu at Tapu-Coroglen			
Sediment Data	None	Jul-91	Apr-99
Flow Data	19.77	Jul-91	Aug-11
Tauranga-Taupo at Te Kono Slackline			
Sediment Data	None	Aug-90	Aug-10
Flow Data	34.73	Feb-76	Aug-11
Waihou at Te Aroha Bridge			
Sediment Data	None	Apr-86	Aug-07
Flow Data	46.36	Jan-65	Aug-11
Mangaokewa at Te Kuiti Pumping Stn			
Sediment Data	None	Aug-90	Jun-04
Flow Data	27.58	Mar-83	Aug-11
Waingaro at Ruakiwi Rd			
Sediment Data	41	May-02	Jun-10
Flow Data	9.64	Nov-01	Aug-11
Matahuru at Waiterimu Rd			
Sediment Data	18	Jul-03	Oct-08
Flow Data	26.86	Jul-84	Aug-11
Waitomo at Aranui Caves Bridge			
Sediment Data	35	Aug-90	Dec-10
Flow Data	24.00	Oct-86	Aug-11
Whakapipi at SH22 Bridge			
Sediment Data	None	Aug-91	Nov-99
Flow Data	27.30	Mar-84	Aug-11
Wharekawa at Adams Farm Bridge			
Sediment Data	17	Sep-91	Jun-10
Flow Data	19.58	Jun-91	Aug-11
Waipa at Whatawhata			
Sediment Data	None	May-90	Sep-10
Flow Data	38.39	Apr-72	Aug-11

2 Analysis Methods

Two approaches were used to establish mean annual sediment yields for the catchments in this investigation. The first was to establish a 'sediment concentration rating' relationship between instantaneous suspended sediment concentration and water discharge. The second was to determine an 'event yield rating' relationship between individual event sediment yields and event hydrological magnitude (indexed by event peak discharge or quickflow). This second approach could only be applied to the nine auto-sampled sites, with data collected at adequate intervals across individual events. The sediment concentration ratings and the event ratings were then applied across the full flow record to compute annual and mean annual sediment yields. Further details on each approach are given below.

2.1 The sediment concentration rating approach

For each site a sediment concentration rating was established by plotting instantaneous suspended sediment concentration (SSC) versus instantaneous water discharge (Q). This rating was then applied to the full water discharge record allowing integration of the sediment yield over the longest period possible for each site. The sediment yield was also integrated during quickflow periods only, as defined in section 2.2, to establish the proportion of the sediment load that is carried during storm events.

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 was adjusted 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). An example LOWESS-fit rating curve for Waitomo at Aranui Caves Bridge site is shown in Figure 2-1. Approximating the bias-adjusted LOWESS curves with step-functions simplifies the calculation of yields and induces no significant error.

In all cases, the residuals of the observed log SSC values compared to the log SSC values predicted by the LOWESS fit were examined for normality and for any time trend. Normality was evaluated with the Kolmogorov-Smirnov test at the 5% significance level, while a time-trend was evaluated using a Student's t-test, testing the hypothesis that the coefficient on a linear relation between log(observed/predicted event yield) was significantly different from zero at the 5% significance level. No trend is indicated if the coefficient is not significantly different from zero.

The mean annual yields were also calculated using the SEDRATE software, again using LOWESS to fit the relationship and adjusting for log-transformation bias. While the SEDRATE analysis is less detailed than the approach described above, it nonetheless provides a cross-check on the results.

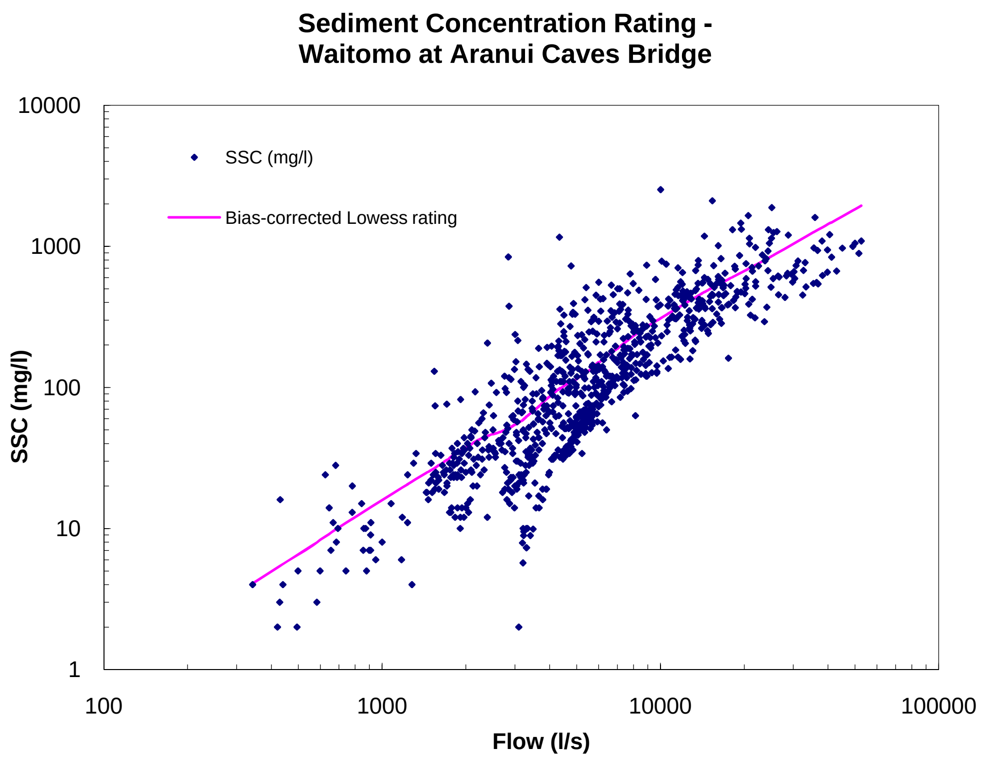

Figure 2-1: Example of a suspended sediment concentration rating from Waitomo at Aranui Caves Bridge catchment. The rating function is a bias-corrected LOWESS fit.

2.2 The storm event sediment yield rating approach

The aim of this approach was to accurately measure the sediment yield from storm runoff events with adequate data, and from these determine relationships between storm sediment yield and an appropriate index of event hydrological magnitude (such as peak flow or quickflow runoff).

For each of the catchments with auto-sampled sediment concentration records (Mangapu River at SH3 Bridge upstream Mangaokewa confluence, Mangatutu Stream at Walker Road Bridge, Matahuru Stream at Myjers, Opitonui River at downstream Awaroa confluence, Waipa at Otewa, Waingaro at Ruakiwi Road, Matahuru at Waiterimu Road, Waitomo at Aranui Caves Bridge, Wharekawa at Adams Farm Bridge), individual storms with sufficient sediment concentration data were identified. Typically, we then added synthetic SSC data points to the beginning and end of the events, since the auto-samplers usually missed sampling these. The synthetic SSC values we assigned to the start and end of events were based on an appreciation of the typical concentrations at the tails of storm events at a given site.

The times for the beginning and end of events were based on the beginning and end of quickflow. Quickflow is the part of the water runoff from a rainstorm that moves quickly through a basin; the remainder of the runoff, termed the ‘delayed flow’, arrives in the stream channels more slowly after moving through the ground and other areas of temporary storage. Following the procedure of Hewlett and Hibbert (1967), hydrographs were examined to assess the typical quickflow separation slope for each site. Also, a minimum value of quickflow runoff of 1 mm was set for each site in order to discard tiny quickflow “events” generated by noise in the stage record. This approach provides an objective, repeatable way of identifying the beginning and end of storm events and for deciding whether a multi-peak hydrograph represents one event or several. The same approach was used for generating series of events when the event ratings were applied to determine mean annual sediment yields. The quickflow separation slopes for each site are included with the sediment concentration ratings in Table 3-1.

The sediment yield over discrete events was computed by direct integration of the sediment concentration and discharge records using the PSIM module of the TIDEDA hydrological software package. The PSIM module was also used to extract various hydrological measures of each event, including the peak discharge.

For each catchment, the event sediment yields were plotted against peak discharge (l/s), quickflow runoff (mm), and total runoff (mm). The storm sediment yields generally correlated best with the storm peak discharge, as has been found in previous studies of a similar nature (Hicks, 1990). The exceptions were Mangatutu at Walker Road Bridge, Mangapu River at SH3 Bridge upstream Mangaokewa confluence and Waipa at Otewa, which correlated best with quickflow. In each case, the event yield vs. peak discharge or quickflow relationship was represented best by a power-law regression. The power-fit regressions were adjusted for log-bias using the bias-correction factor of Duan (1983), which gave essentially the same correction as did Ferguson’s (1986) method. The event yield vs. peak discharge or quickflow rating relationships established for each catchment were then used to estimate the yields from all events over the duration of the flow record, providing average annual sediment yield estimates.

An example event yield rating is shown below for the Waitomo at Aranui Caves Bridge site (Figure 2.2).

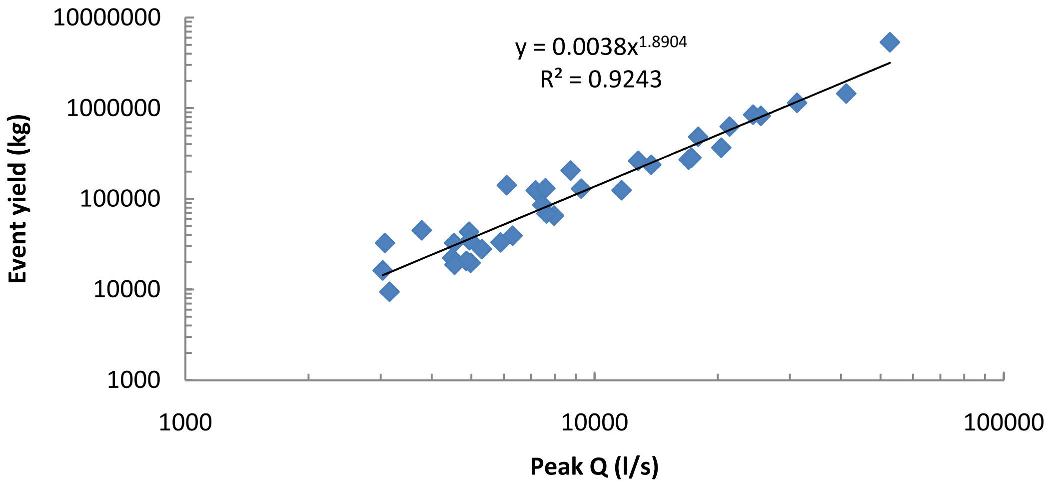

Figure 2-2: Example of an event yield rating from Waitomo at Aranui Caves Bridge catchment. This rating has a power relationship.

In all cases, the residuals of the observed log event yield values minus the predicted log event yield values were examined for normality (using the Kolmogorov-Smirnov test at the 5% significance level) and trends over peak discharge or quickflow (depending on variable used in the rating relationship) and time were examined using the Student's t-test at the 5% significance level. Residuals were all normally distributed and, on this basis, a standard factorial error of the estimate was determined.

The percentage uncertainty on the mean annual yield, e_y, due to the rating fit was estimated by summing the squares of the error of the estimate of each event yield, thus:

$$e_y = 100\left(\sum_i ((\exp[t \bullet s(1+1/n+(X_i-\overline{X_j})^2/\sum_j (X_j-\overline{X_j})^2)]-1)\bullet Y_i)^2\right)^{0.5} / \sum_i Y_i$$

Equation 1

where s is the standard error of the regression estimate (in log units), X_i is the log of peak flow or quickflow (whichever is used in the rating), X_j are the log-X values used to define the rating, $\overline{X_j}$ is the mean X_j, n is the number of data points used to define the rating, Y_i is the rating-calculated yield of the ith event, and t is the Student's t value (set equal to 1 for the standard error and > 2 for the 95% confidence error, depending on the value of n). This assumes that the residuals of the rating (in log space) are normally distributed and that errors of sequential events are independent.

2.3 Determining magnitude-frequency relationships for event sediment yields

The event sediment yields generated from the flow record and event yield ratings, as described in section 2.2, were used to produce event-yield magnitude-frequency plots. Past experience has shown that these often contain useful information on the relative importance of events of different return period (e.g., monthly compared with annual events) and also sometimes show a landuse effect (Hicks, 1994).

As far as possible, the same 20-year reference period (1 August 1991 to 1 August 2011) was used for this analysis. Figure 1-2 shows that this spans the flow record from the Opitonui, Waipa at Otewa, Matahuru, Waitomo, and Wharekawa sites. The other event-sampled sites (Managapu, Mangatutu, Matahuru, Waingaro) had shorter records, so for these all of the record up to 1 August 2011 was used. The procedure followed a 'peaks-over threshold' approach and involved ranking the calculated event yields, truncating the series to include only the 12 X n largest events (where n is the record length in years), then assigning each event a recurrence interval (in years) using the simple formula $T = n/m$ (where m is event rank). Thus, for example, the largest event had a return period of 20 years, and the smallest had a return period of 0.083 years (i.e., 1 month). The return period was also transformed to the extreme-value reduced variate, yT, where $yT = -\ln(-\ln(1-1/T'))$, where $T' = 12 \times T$ is the return period on a monthly basis. Previous studies (e.g., Hicks et al., 2004) indicate that this transformation often produces a linear relationship between log (event yield) and yT.

3 Results

3.1 Rating relationships

The sediment concentration ratings are summarised in Table 3-1 along with measures of the uncertainty in the relationship, the trend in the residuals (observed SSC / predicted SSC) over time, whether or not the residuals are normally distributed, the quickflow separation slope, and the log-transformation bias correction factor averaged over the discharge range[1]. The individual rating plots are provided in Appendix A.

The event yield ratings are summarised in Table 3-2 along with measures of the uncertainty in the relationship and any trend in the residuals (observed event yield/predicted event yield) over time and with increasing peak discharge or quickflow (depending on the variable used in the rating relationship). The event sediment yield rating plots are provided in Appendix B.

Many of the ratings appeared to have significant time trends, although the direction of trend varied from site to site. This may possibly reflect changes in landuse, but can also be influenced by sediment supply variations stemming from large storms. Results where the residuals are not normally distributed flag uncertainty as to whether the inferred trend is reliable.

3.2 Sediment yields

The average annual specific sediment yields (t/km^2/yr) derived from the sediment concentration rating approach, the event-yield rating approach (where possible), and the estimate from SEDRATE are listed for each catchment in Table 3-3. The yield results (averaged over the concentration rating and event-yield rating approaches where both are available) are plotted on the top plot of Figure 3-1. The yields agree reasonably well across the three approaches, although the sediment concentration rating approach tends mostly to give a higher result than the event-yield approach. In part, this appears to be because the event-yield approach (which defines events in terms of discrete quickflow events that exceed a threshold quickflow runoff) ignored sediment carried by the delayed flow (i.e., on event recessions after the cessation of quickflow) and also ignored the sediment load carried by very small events (typically with return periods less than 1 month). A measure of this effect was found by using the sediment concentration rating approach to total just the sediment load carried during quickflow events. The proportion of the load carried during quickflow varied from 64% to 97% (Table 3-3). While this accounts for much of the difference among yield estimates at some sites (e.g., Waitomo at Aranui Caves, Matahuru at Myjers), at other sites the difference appears to be due more to sampling error in the rating relations (which tends to be larger for the sediment concentration ratings). For example, it may be that the sediment concentration rating approach is inclined to overestimate the load during high winter base flows.

Because both the approaches for estimating yields have advantages and disadvantages, where both are calculated we suggest taking the average of the two results as representative, with the standard deviation of the two results being indicative of the uncertainty (last column, Table 3-3). For catchments with data insufficient for the event yield

[1] The average bias-correction factor is included simply to indicate the magnitude of the adjustment applied. In actuality, the rating functions incorporate an adjustment that is conditional on the discharge.

Table 3-1: Sediment concentration ratings for each catchment. Also listed are the overall regression coefficient of determination (R^2), standard factorial error (SFE), and the average bias correction factor (BCF) incorporated in each set of rating step-functions. It is also stated whether or not the residuals are normally distributed and whether there is an increasing, decreasing, or neutral trend in the residuals over time.

Sites	SSC (mg/l) vs Q (l/s) ratings SSC (mg/l) =	Quickflow separation slope (ml/s²/km²)	R^2	SFE	Avg BCF	Residuals normally distrib.	Time trend
Mangaonua at Dreadnought Culvert	For Q<2000: $0.0358Q^{0.742}$ For Q >2000: $0.0121Q^{0.883}$	0.0221	0.62	1.64	1.14	Yes	Decr
Waikato at Hamilton Traffic Road Bridge	For Q<318000: $1.066Q^{0.144}$ For Q<360000: $2.45E^{-18}Q^{3.350}$ For Q<450000: $6.12E^{-13}Q^{2.378}$ For Q<620000: $2.680E^{-8}Q^{1.557}$ For Q>620000: $0.140Q^{0.397}$	0.0048	0.36	1.79	1.20	Yes	Decr
Mangapu at SH3	For Q<9000: $1.1739Q^{0.000533}$ For Q>9000: 142	0.0280	0.16	2.12	N/A	No	Decr
Mangatutu at Walker Road Bridge	For Q<7500: $0.006Q^{0.901}$ For Q<13000: $2.29E^{-9}Q^{2.565}$ For Q<17000: $1.19E^{-4}Q^{1.419}$ For Q>17000: $0.006Q^{1.016}$	0.0169	0.67	1.79	1.19	No	Incr
Waitoa at Mellon Road Recorder	For Q<2300: $0.012Q^{0.872}$ For Q<4300: $0.001Q^{1.186}$ For Q<7700: $0.050Q^{0.723}$ For Q<250000: $2.399Q^{0.289}$ For Q>250000: $0.337Q^{0.483}$	0.00816	0.63	1.88	1.22	Yes	Decr
Matahuru at Myjers	For Q<4000: $0.259Q^{0.828}$ For Q<5700: $0.014Q^{1.182}$ For Q<8500: $0.005Q^{1.305}$ For Q>8500: $0.755Q^{0.745}$	0.0202	0.61	1.62	1.13	Yes	Incr
Waihou at Okauia	For Q<25000: $7.15E^{-5}Q^{1.257}$ For Q<31000: $6.13E^{-14}Q^{3.318}$ For Q<55000: $3.79E^{-7}Q^{1.806}$ For Q>55000: $1.81E^{-5}Q^{1.452}$	0.0091	0.84	1.73	1.16	Yes	Decr
Opitonui at d/s Awaroa Confluence	For Q<4500: $0.010Q^{0.997}$ For Q<12000: $0.002Q^{1.160}$ For Q<24600: $0.516Q^{0.589}$ For Q>24600: $0.002Q^{1.136}$	0.157	0.65	2.00	1.27	No	Incr
Waipa at Otewa	For Q<10500: $5.24E^{-5}Q^{1.318}$ For Q<18000: $0.008Q^{0.781}$ For Q<31000: $1.93E^{-8}Q^{2.096}$ For Q<53000: $4.42E^{-15}Q^{3.574}$ For Q>53000: $0.001Q^{1.142}$	0.0314	1.023	2.16	1.38	No	Decr
Waipa at SH3 Bridge Otorohanga	For Q<32000: $1.91E^{-5}Q^{1.381}$ For Q<73000: $1.47E^{-4}Q^{1.185}$ For Q>73000: $1.14E^{-6}Q^{1.618}$	0.0303	1.01	1.24	1.03	Yes	Incr
Oraka at Pinedale	For Q<2700: $5.02E^{-11}Q^{3.387}$ For Q<4100: $1.49E^{-15}Q^{4.707}$ For Q<5300: $0.013Q^{1.121}$ For Q>5300: $3.55E^{-6}Q^{2.081}$	0.0041	1.09	1.84	1.23	Yes	Decr
Piako at Paeroa-Tahuna Road	For Q<6000: $0.079Q^{0.640}$ For Q<12000: $0.005Q^{0.964}$ For Q<25000: $0.680Q^{0.434}$	0.01943	0.63	1.94	1.25	Yes	Decr

Sites	SSC (mg/l) vs Q (l/s) ratings SSC (mg/l) =	Quickflow separation slope (ml/s²/km²)	R^2	SFE	Avg BCF	Residuals normally distrib.	Time trend
Bridge	For Q>25000: $0.122Q^{0.604}$						
Waikato at Rangiriri Bridge	For Q<466000: $0.003Q^{0.680}$ For Q<730000: $1.33E^{-5}Q^{1.097}$ For Q>730000: $6.47E^{-9}Q^{1.662}$	0.0021	0.42	1.72	1.17	Yes	Neutral
Tapu at Tapu-Coroglen Road	For Q<700: $0.444Q^{0.230}$ For Q<2400: $1.46E^{-4}Q^{1.454}$ For Q>2400: $0.017Q^{0.839}$	0.0793	0.91	2.41	1.55	No	Decr
Tauranga Taupo at Te Kono Slackline	For Q<11000: $0.055Q^{0.460}$ For Q<17000: $1.25E^{-8}Q^{2.105}$ For Q<35000: $1.08E^{-10}Q^{2.592}$ For Q>35000: $1.90E^{-7}Q^{1.878}$	0.0476	0.94	1.72	1.17	Yes	Incr
Waihou at Te Aroha	For Q<42000: $7.58E^{-5}Q^{1.266}$ For Q<74000: $7.454Q^{0.18}$ For Q<122000: $0.041Q^{0.649}$ For Q>122000: $8.47E^{-4}Q^{0.981}$	0.0055	0.37	1.73	1.17	Yes	Decr
Mangaokewa at Te Kuiti Pumping Station	For Q<3600: $0.008Q^{0.879}$ For Q<13000: $0.005Q^{1.215}$ For Q>13000: $4.53E^{-5}Q^{1.469}$	0.0245	0.94	1.65	1.14	Yes	Decr
Waingaro at Ruakiwi Road	For Q<7000: $0.004Q^{1.052}$ For Q<14600: $7.69E^{-6}Q^{1.765}$ For Q>14600: $2.36E^{-4}Q^{1.408}$	0.0378	0.96	1.49	1.08	No	Incr
Matahuru at Waiterimu Road	For Q<7100: $0.039Q^{0.915}$ For Q<8600: $2.87E^{-7}Q^{2.248}$ For Q>8600: $2.041Q^{0.506}$	0.0219	0.34	1.56	1.10	Yes	Incr
Waitomo at Aranui Caves Bridge	For Q<2400: $0.003Q^{1.238}$ For Q<9000: $0.001Q^{1.356}$ For Q>9000: $0.008Q^{1.142}$	0.0567	0.80	1.92	1.24	No	Decr
Whakapipi at SH22 Bridge	For Q<800: $4.359Q^{0.011}$ For Q<1900: $7.78E^{-5}Q^{1.643}$ For Q>1900: $8.98E^{-4}Q^{1.319}$	0.0552	0.74	1.81	1.21	Yes	Decr
Wharekawa at Adams Farm Bridge	For Q<4800: $0.019Q^{0.752}$ For Q<9000: $0.003Q^{0.951}$ For Q<19400: $0.370Q^{0.438}$ For Q<30000: $8.93E^{-7}Q^{1.748}$ For Q>30000: $0.030Q^{0.736}$	0.0775	0.84	1.71	1.16	No	Incr
Waipa at SH23 Bridge Whatawhata	For Q<44000: $1.71E^{-4}Q^{1.076}$ For Q<69000: $1.07E^{-5}Q^{1.335}$ For Q<102000: $0.200Q^{0.453}$ For Q<210000: $2.53E^{-5}Q^{1.231}$ For Q>210000: $0.065Q^{0.590}$	0.0265	0.81	1.84	1.22	Yes	Decr

Table 3-2: Event yield ratings determined for the catchments with automatically sampled sediment concentration. Ratings are based either on peak discharge (Q_{pk}) or quickflow (QF), depending on which had the strongest relationship, and the coefficients shown are not bias corrected. The overall regression coefficient of determination (R^2), standard factorial error (SFE), and bias correction factor (BCF) for each relationship are provided. The direction of any trends in the residuals over Q_{pk} or QF and over time are also stated.

Sites	Event yield (Y) ratings Q_{pk} (l/s) or QF (mm) Y (kg) =	R^2	SFE	BCF	Trend in residuals over Q_{pk} or QF	Trend in residuals time
Mangapu at SH3	$38672QF^{0.8314}$	0.72	1.48	1.09	Decr	Decr
Mangatutu at Walker Road Bridge	$16728QF^{0.9092}$	0.75	1.56	1.09	Decr	Neutral
Matahuru at Myjers	$0.0175Q_{pk}^{1.8364}$	0.91	1.41	1.06	No	Incr
Opitonui at d/s Awaroa Confluence	$0.0246Q_{pk}^{1.4926}$	0.83	1.71	1.16	No	Decr
Waipa at Otewa	$34709QF^{1.3584}$	0.93	1.48	1.07	No	Decr
Waingaro at Ruakiwi Road	$0.0011Q_{pk}^{1.9446}$	0.87	1.54	1.07	Decr	Decr
Matahuru at Waiterimu Road	$0.2086Q_{pk}^{1.4977}$	0.86	1.29	1.03	Neutral	Neutral
Waitomo at Aranui Caves Bridge	$0.0038Q_{pk}^{1.8904}$	0.92	1.52	1.08	No	Neutral
Wharekawa at Adams Farm Bridge	$0.0044Q_{pk}^{1.6122}$	0.89	1.67	1.14	Decr	Incr

rating approach, the average annual specific sediment yield calculated from the sediment concentration rating approach may still be compared with the estimate from SEDRATE.

These yield results (based on the average of the two approaches where possible) range from 8 t/km^2/yr at the Mangaonua at Dreadnought and Waikato at Hamilton Traffic Road Bridge catchments up to 230 t/km^2/y at the Waitomo at Aranui Caves site. For most sites the yield falls in the range 40-100 t/km^2/y (Figure 3-1). Waitomo at Aranui Caves, Matahuru at Myjers (188 t/km^2/y), and Waipa at Otewa (175 t/km^2/y) all have noticeably higher yields.

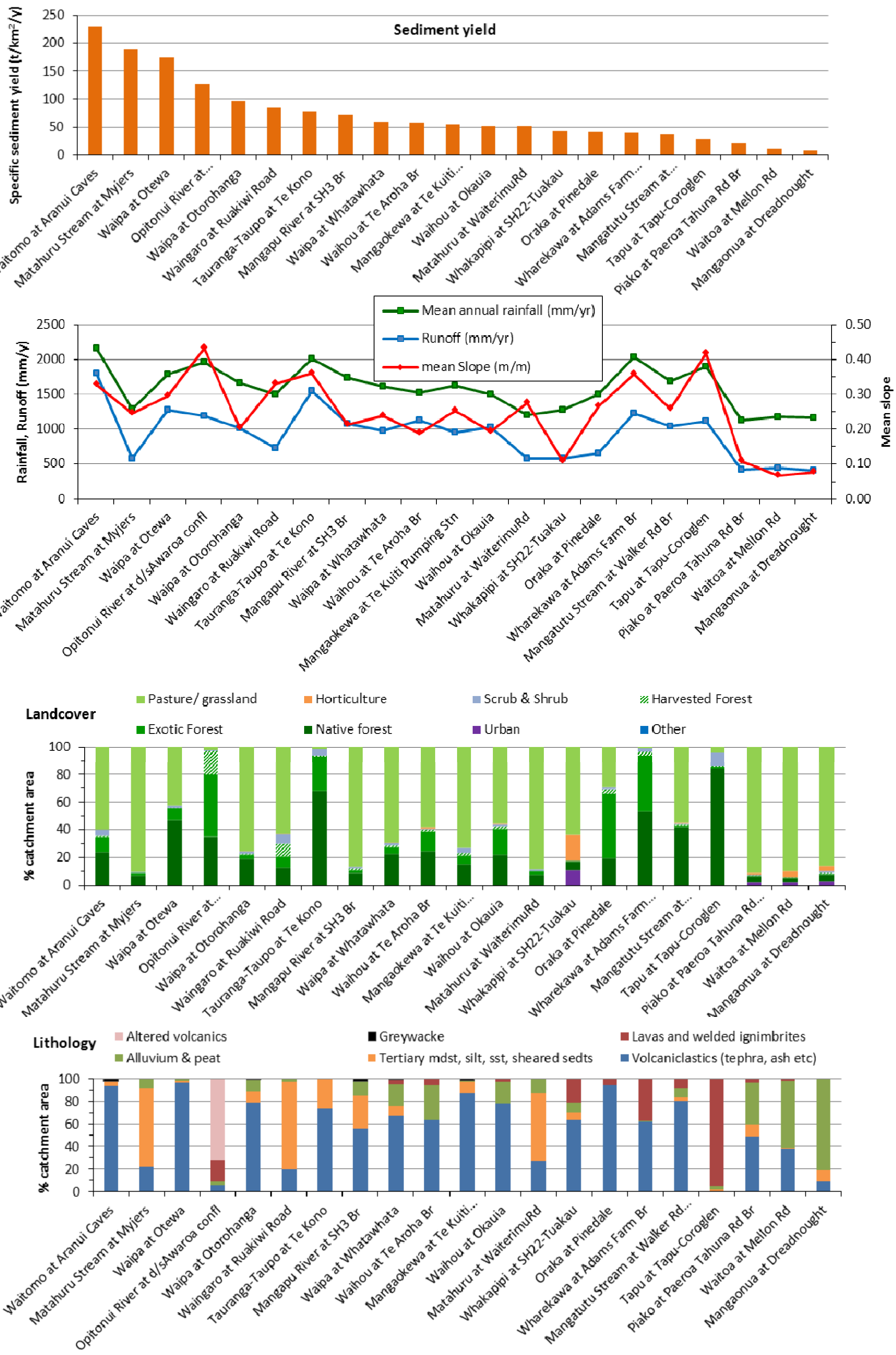

Figure 3-1: Specific sediment yield vs. catchment characteristics. Includes catchment mean annual rainfall and runoff, mean slope, and % area by land-cover and lithology. Sites are ordered (left to right) by decreasing sediment yield.

Table 3-3: Catchment characteristics and mean annual specific sediment yield estimates. Event yield based estimates are not available at all sites. Values in brackets show % uncertainty. All yields incorporate adjustment for log-transformation bias.

Site	Catchment Area (km^2)	Years of Flow data	Dominant Lithology	Dominant Landuse	Mean slope (m/m)	Mean Annual Rainfall (mm)	Specific Annual Average Sediment Yield (± standard deviation of specific annual sediment yields)			Event yield rating approach ($t/km^2/yr$) (95% CI error)	Averaged yield over the two methods ($t/km^2/yr$) (standard deviation between methods as % of average)
							Sedrate ($t/km^2/yr$)	Sediment concentration rating approach ($t/km^2/yr$)	% during quickflow		
Mangaonua at Dreadnought	166	29.87	Very loose to compact sedimentary	Pasture/ grassland	0.25	1167.0	8	8.5 ± 4.2	67%		8.5
Waikato at Hamilton Traffic Br	8230	33.98	Extremely weak to weak volcanics	Pasture/ grassland	0.08	1509.0	10	8.0 ± 2.7	78%		8.0
Mangapu River at SH3 Br u/s Mangaokewa confl	150.7	10.85	Extremely weak to weak volcanics	Pasture/ grassland	0.21	1745.4	93	82.8 ± 30.5	97%	60.1 ± 17.6 (14.2%)	71.5 (22%)
Mangatutu Stream at Walker Rd Br	123	7.21	Extremely weak to weak volcanics	Pasture/ grassland	0.26	1692.8	44	38.3 ± 12.0	90%	36.4 ± 5.9 (22%)	37.3 (3.5%)
Waitoa at Mellon Rd	409	25.27	Very loose to compact sedimentary	Pasture/ grassland	0.28	1177.2	14	11.8 ± 4.7	77%		11.8
Matahuru Stream at Myjers	82.6	5.06	Very compact to weak sedimentary	Pasture/ grassland	0.25	1293.4	186	221.6 ± 93.7	91%	155.4 ± 77.4 (46.8%)	188.5 (25%)
Waihou at Okauia	816	29.31	Extremely weak to weak volcanics	Pasture/ grassland	0.43	1505.2	49	51.2 ± 17.3	64%		51.2
Opitonui River at d/s Awaroa confl	29	19.41	Extremely weak to Weak volcanics	Exotic Forest	0.27	1966.9	166	125.5 ± 85.6	94%	126.2 ± 71.2 (26.6%)	125.8 (0.4%)
Waipa at Otewa	317	25.95	Extremely weak to weak volcanics	Exotic vegetation	0.11	1789.3	134	155.0 ± 91.9	92%	195.4 ± 66.6 (13%)	175.2 (16%)
Waipa at Otorohanga	919	30.07	Extremely weak to weak volcanics	Pasture/ grassland	0.42	1671.6	100	96.8 ± 58.6	89%		96.8

Oraka at Pinedale	136	31.77	Extremely weak to weak volcanics	Exotic Forest	0.36	1508.0	38	40.9 ± 22.2	71%		40.9
Piako at Paeroa Tahuna Rd Br	534	38.59	Extremely weak to weak volcanics	Pasture/ grassland	0.19	1134.6	21	20.2 ± 8.7	83%		20.2
Waikato at Rangiriri	12421	46.03	Extremely weak to weak volcanics	Pasture/ grassland	0.19	1506.6	21	20.6 ± 5.6	86%		20.6
Tapu at Tapu-Coroglen	26.4	19.77	Lavas and welded ignimbrites	Broad leafed indigenous & Deciduous Hardwoods	0.18	1903.7	27	28.6 ± 16.9	96%		28.6
Tauranga-Taupo at Te Kono Slackline	199	34.73	Extremely weak to weak volcanics	Broad leafed indigenous & Deciduous Hardwoods	0.18	2020.2	96	77.9 ± 63.5	95%		77.9
Waihou at Te Aroha Br	1137	46.36	Extremely weak to weak volcanics	Pasture/ grassland	0.33	1528.4	53	57.3 ± 13.7	67%		57.3
Mangaokewa at Te Kuiti Pumping Stn	173.2	27.58	Extremely weak to weak volcanics	Pasture/ grassland	0.30	1635.0	52	54.5 ± 30.6	90%		54.5
Waingaro at Ruakiwi Rd	117	9.64	Very compact to weak sedimentary	Pasture/ grassland	0.20	1499.2	103	98.5 ± 44.4	96%	71.5 ± 31.2 (21.9%)	85.0 (22%)
Matahuru at Waiterimu Rd	105	26.86	Very compact to weak sedimentary	Pasture/ grassland	0.24	1209.9	61	60.5 ± 24.9	86%	41.4 ± 22.6 (12.9%)	51.0 (26%)
Waitomo at Aranui Caves Br	20.5	24.00	Extremely weak to weak volcanics	Pasture/ grassland	0.07	2171.0	198	286.1 ± 98.4	90%	173.7 ± 64.1 (14.1%)	229.9 (35%)
Whakapipi at SH22 Br	48.9	27.30	Extremely weak to weak volcanics	Pasture/ grassland	0.33	1275.6	41	42.7 ± 31.8			42.7
Wharekawa at Adams Farm Br	46.5	19.58	Extremely weak to weak volcanics	Broad leafed indigenous & Deciduous Hardwoods	0.11	2040.8	39	36.2 ± 21.5	92%	43.5 ± 22.6	39.9 (13%)
Waipa at Whatawhata	2826	38.39	Extremely weak to weak volcanics	Pasture/ grassland	0.36	1617.4	63	59.6 ± 20.7			59.6

3.3 Annual yield variability

An appreciation of the annual variability in sediment yield to be expected from year-to-year variability in weather can be seen from Figure 3-2. This shows the specific annual yields over the 46 calendar years of flow record at the Waihou at Te Aroha Bridge site as estimated with the sediment concentration rating. The specific annual yield ranges from 12 to 83 t/km^2, with a mean of 38 t/km^2, a standard deviation of 14 t/km^2, and the standard error of the mean is 2 t/km^2.

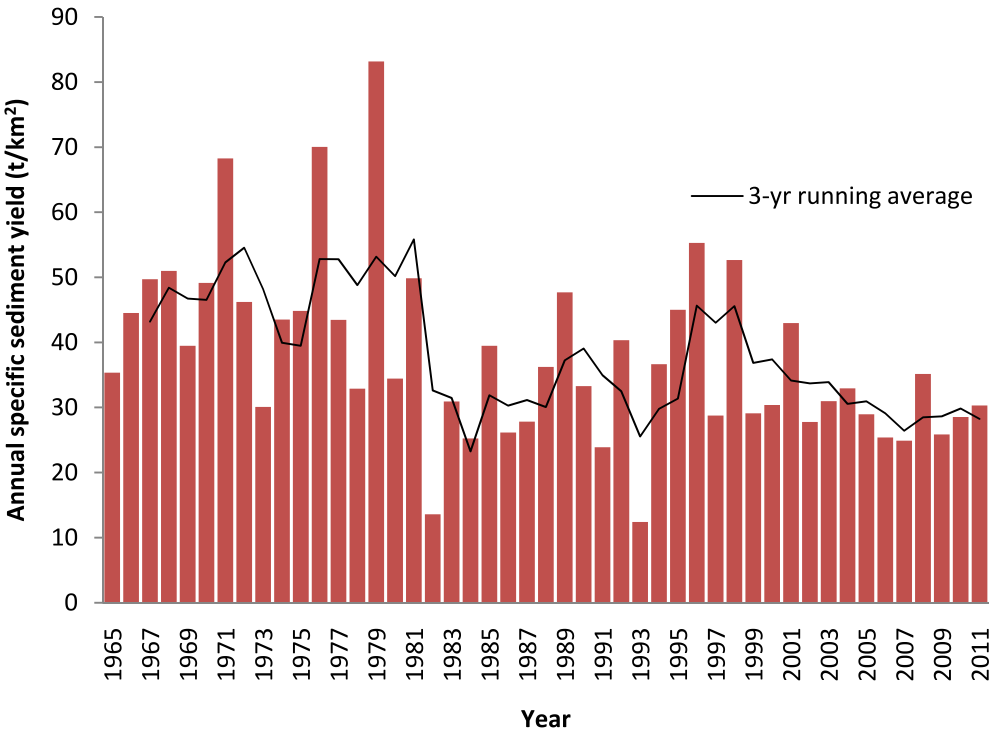

Figure 3-2: Specific annual sediment yields and three year running average yield between 1965 and 2011 at Waihou at Te Aroha Bridge.

The standard deviation of annual yields for all 23 catchments is listed in Table 3-3. The coefficient of variation (i.e., standard deviation / mean) averages 47% and ranges up to 74%. The extent of this hydrologically-driven annual variability indicates that yield estimates among catchments with short record periods (e.g., Mangatutu, Matahuru, Waingaro – refer Figure 1-2) should be compared with caution.

3.4 Event yield magnitude-frequency relations

Figure 3-3 shows the event specific yield magnitude-frequency relations developed for the auto-sampled sites. Generally, the catchments with higher mean annual yields show higher yields over all return periods. Wharekawa and Opitonui are exceptions, showing relatively lower yields from common events (return period of about 1 year and less) and higher yields from less common events. Both of these are forested catchments on the Coromandel Peninsula and are formed in relatively erosion-resistant volcanic rock, and this behaviour probably reflects limited sediment sources during the smaller events.

Figure 3-4 re-plots the data in Figure 3-3 with the event yields normalised by the mean annual yield and the return period transformed to the extreme-value reduced variate, *yT*. This more clearly shows the spread of event yield for a given return period. Also, it shows the curves for all sites crossing at *yT* = 2.1 (which corresponds approximately to 10 months) and when the event yield equals approximately 0.2 X the mean annual yield. The reason for this is not clear, but it hints at an approach for estimating the event-yield distribution for any Waikato catchment, given an estimate of its mean annual sediment yield and if the slope of the curves in Figure 3-4 can be related to catchment physical characteristics or climatic features.

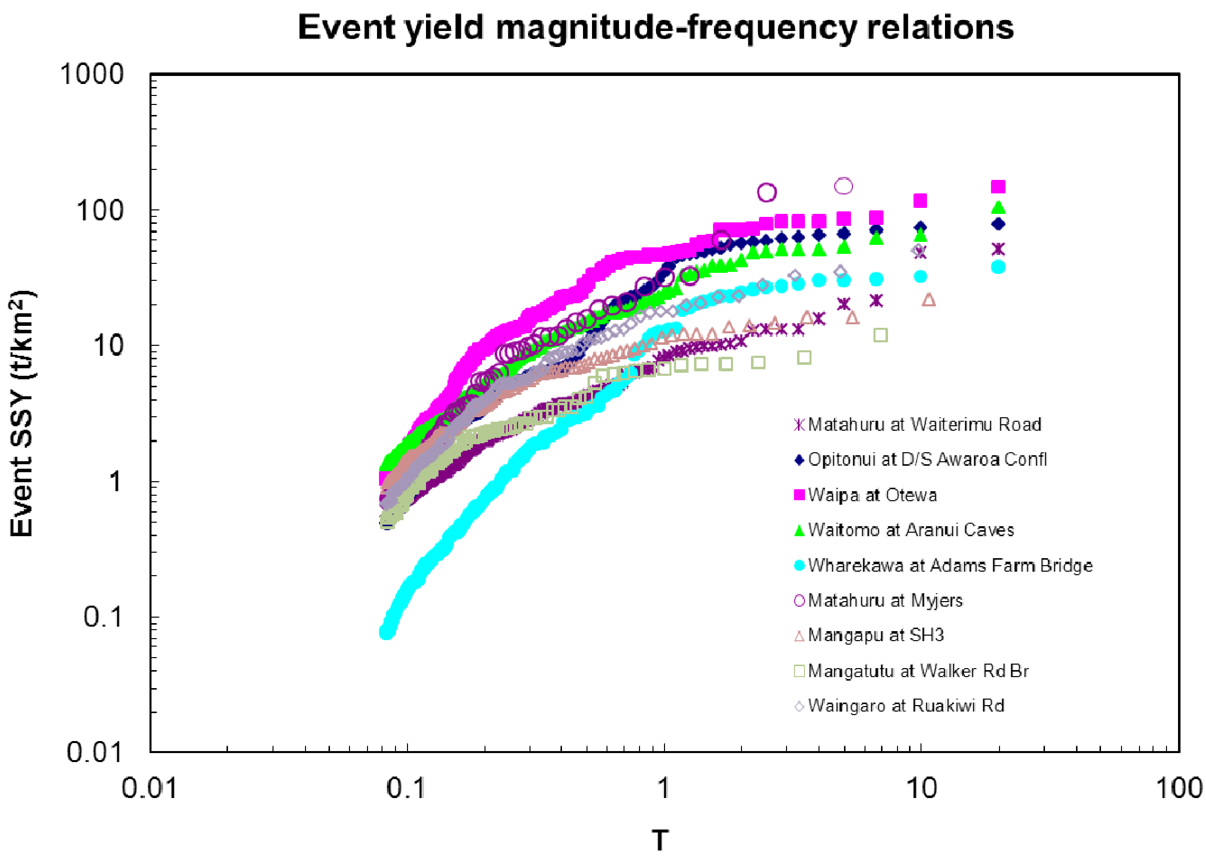

Figure 3-3: Event-yield magnitude-frequency relations for auto-sampled sites. Return period, *T*, in years.

3.5 Sediment yield vs. catchment characteristics

Relationships between specific sediment yield and catchment characteristics were examined in three ways: graphically (Figure 3-1), from a correlation matrix, and by a multiple-regression analysis. In each case, the comparison was made in terms of the average of the available specific sediment yield estimates (as in the last column of Table 3-3).

Figure 3-1 compares specific sediment yield with erosion "driving" factors (catchment mean slope, mean annual runoff, and mean annual rainfall) and factors that control sediment availability (catchment land-cover and lithology). In terms of the erosion driving factors, there appear to be general trends for sediment yield to increase as rainfall, runoff, and slope increase (as expected). Most deviations from these trends can be explained by land-cover and/or lithology. For example, while Wharekawa and Tapu have amongst the highest rainfalls and slopes, they show low sediment yields, apparently because both are almost totally forested and have significant proportions of their catchments underlain by erosion-resistant lava or ignimbrite. In contrast, Matahuru at Myjers has a high sediment yield despite a relatively low rainfall and slope by virtue of being mainly pasture-covered and being formed into erodible Tertiary sediments (“Papa” mudstone). The Waitomo has the highest yield by virtue of its higher rainfall and runoff, moderate slopes, and dominantly pasture cover on tephra. The lowest yields occur at the pasture covered Piako, Waitoa, and Mangaonua because of their low slopes, much of which is on relatively young alluvial deposits.

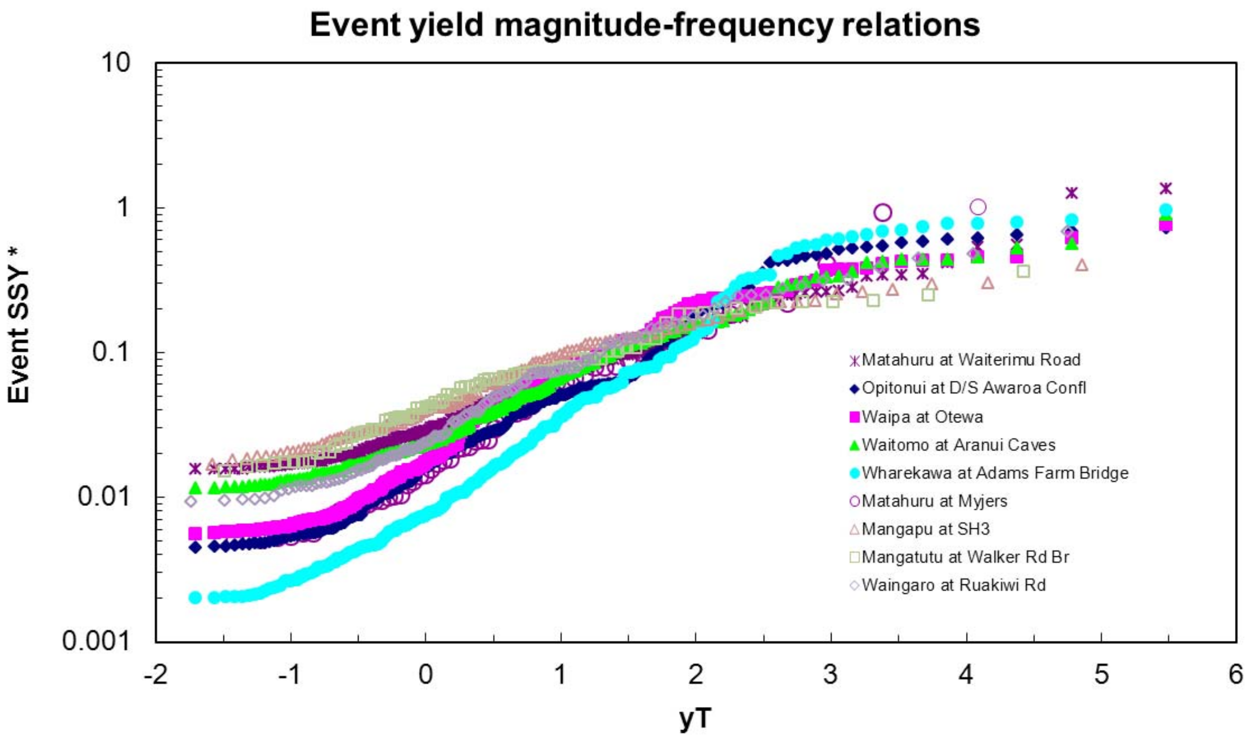

Figure 3-4: Normalised event-yield magnitude-frequency relations for auto-sampled sites. Event specific sediment yield (*SSY*) has been normalised by the mean annual specific sediment yield. The return period is represented by the extreme value reduced variate, *yT*.

These qualitative relations between sediment yield and rainfall, runoff, slope, land-cover, and lithology are generally confirmed in the matrix of correlation coefficients (Table 3-4). In this, the parameters correlated with sediment yield also include the products of slope with runoff and rainfall (termed “stream-power” and “rain-power”, respectively). Land-cover has been simplified by lumping exotic and native forest with scrub into an “all-forest” class, lumping pasture with horticulture and harvested forest into an “all-pasture” class, and lumping urban and other areas into an “urban&other” class. The only lithological parameters shown are for a class lumping vocaniclastic material (tephra and ash, mainly) with erodible sedimentary rocks (mainly Tertiary mudstones and sheared argillites) labelled “Tephra&Tertiary” – this was the only lithology class where any significant correlation was observed.

Table 3-4: Matrix of correlation coefficients relating specific sediment yield to catchment characteristics. Values in red are significant at the 5% level.

	Means	Std. Dev.	SSY	Area	%All-pasture	%All-forest	%Urban &Other	%Tephra &Tertiary	Slope	Rainfall	Runoff	Stream-power	Rain-power	SSY / Stream-power
SSY	74.0	59.4	1.00											
Area	399.1	639.8	-0.12	1.00										
%All-pasture	60.2	31.1	-0.06	0.17	1.00									
%All-forest	38.6	31.9	0.07	-0.17	-1.00	1.00								
%Urban&Other	1.04	2.19	-0.25	-0.03	0.30	-0.36	1.00							
%Tephra&Tertiary	15.7	23.9	0.23	-0.19	0.35	-0.33	-0.15	1.00						
Slope	0.25	0.10	0.41	-0.23	-0.77	0.79	-0.52	0.12	1.00					
Rainfall	1597	313	0.45	-0.10	-0.76	0.77	-0.38	-0.29	0.79	1.00				
Runoff	942	374	0.53	0.01	-0.63	0.64	-0.35	-0.29	0.66	0.94	1.00			
Stream-power	259	171	0.50	-0.18	-0.79	0.80	-0.42	-0.16	0.87	0.95	0.91	1.00		
Rain-power	422	232	0.42	-0.23	-0.83	0.85	-0.46	-0.07	0.96	0.90	0.78	0.96	1.00	
SSY/Stream-power	0.35	0.27	0.49	-0.08	0.52	-0.53	0.27	0.48	-0.30	-0.43	-0.36	-0.38	-0.38	1.00

Specific sediment yield (*SSY*) correlated significantly (i.e., at a 5% significance level) with both rainfall and runoff and with stream-power (the correlation with slope was significant at the 0.065 level). Runoff, rainfall, and slope were all inter-correlated – reflecting the higher rainfall in steeper catchments. Rainfall and slope was also well correlated with % all-forest cover, while % all-pasture was inversely correlated with these – showing, again as expected, that grazing tends towards the flatter, relatively drier areas while forest cover is more likely in the steeper, wetter catchments. A normalised sediment yield (obtained by dividing specific yield by stream-power) correlated significantly with % all-pasture, inversely with % all-forest, and with % area with tephra and Tertiary lithologies (which are expected to be the most erodible).

Continuing on from the correlation analysis, a multiple regression analysis was undertaken focussing on parameters showing significant correlations. Given that rainfall and runoff were highly correlated, runoff was preferred because it produced slightly better regression results. Also, given that slope and runoff were also correlated, the stream-power parameter (*RS*) was preferred over using slope (*S*) and runoff (*R*, mm/y) separately. The best linear model found was:

$$SSY_{\ (t/km^2/y)} = 0.42\ RS + 1.70\ \%all\text{-}pasture\ - 137 \qquad \text{Equation 2}$$

The adjusted r^2 for this model is 0.50 (i.e., the model explains 50% of the variance in the sediment yields over the dataset), the standard error of the estimate is 42 t/km^2/y, and all coefficients are significant at the 5% level. Adding the *%Tephra&Tertiary* lithology parameter into the regression model did not improve the r^2 or standard error of the estimate, and the *%Tephra&Tertiary* coefficient was not significantly different from zero, thus Equation 2 was preferred.

The equivalent regression analysis using rainfall (P, mm/y) instead of runoff produced a similar model:

$$SSY = 0.31\ PS + 1.81\ \%all\text{-}pasture\ - 165 \qquad \text{Equation 3}$$

All the coefficients are significant at the 5% level, but the adjusted r^2 (0.39) and the standard error of the estimate (46 t/km^2/y) were poorer than provided by Equation 2.

An alternative regression model related the ratio of SSY/stream-power to the land-cover and *%Tephra&Tertiary* parameters. Only the %all-pasture parameter made a significant contribution to the regression, thus the derived model was:

$$SSY/(RS) = 0.0044\ \%all\text{-}pasture + 0.082 \qquad \text{Equation 4}$$

In this model, the adjusted r^2 is 0.23, the standard error of the estimate is 0.233, and the intercept coefficient (0.082) is not significantly different from zero (and so could be deleted). The dataset was too ill-conditioned to derive a model that provided weighting coefficients to each land-cover – probably because of the confusion induced by the range in lithologies.

In summary, what this regression analysis indicates is that the variation in specific sediment yield in the dataset is due mainly to catchment rainfall, mean slope, and land-cover; and, while there was a hint of a lithological effect, this did not make a significant contribution to any regression model. Equation 2 provides the best predictive model from this reconnaissance-level analysis, with a standard error of ± 42 t/km^2/y on predictions of specific sediment yield.

3.6 Comparison of results with other studies from Waikato-Auckland region

Several previous studies have calculated suspended sediment yields within the Waikato region.

Hicks et al. (2001) calculated suspended sediment yields from 18 Waikato catchments using suspended sediment gaugings data with the sediment rating approach, and generally using LOWESS to fit the ratings. Five of those sites were also analysed in this study by much the same approach. For these, the differences in the yield estimates (compared to the results in Table 3-3) are 1.5% at Waikato at Rangiriri, 7.5% at Waikato at Hamilton Traffic Bridge, 21% at Matahuru at Waitarimu Road, 25% at Mangaonua at Dreadnought, and 1.3% at Waipa at Otewa). Hicks et al. (2001) also noted that the specific yields across the Waikato region tended to vary by Hydrological Region, as defined by Toebes and Palmer (1969), with average yields of 69 t/km^2/y for the Taupo Rhyolite region, 34 t/km^2/y for the Taupo Pumice Region, and 58 t/km^2/y for the Hamilton Region. They explained the lower average yields from the pumice catchments as being due to reduced runoff (and erosion) due to high infiltration rates.

McKerchar and Hicks (2003) calculated an average yield of 5470 t/y over the period 1995-2000 for the Waitomo Stream site; this equates to a specific yield of 267 t/km^2/yr[2], which is similar to the 286 t/km^2/y result obtained by the sediment rating approach in this study.

Wild and Hicks (2005) also used the sediment rating approach to calculate a specific yield of 115 t/km^2/y from the Opitonui River downstream of the Awaroa confluence. This compares well with the result from the present study (126 t/km^2/y).

All of the differences between the results of these previous studies and the present study are acceptable and stem mainly from the longer spans of flow record and increased number of suspended sediment samples available for the present study.

Hicks et al. (2009) carried out a study, similar to the one reported here, assessing the sediment yields in nine catchments in Auckland's Waitemata Formation terrain. The main points of comparison are:

- Specific suspended sediment yields from the Auckland catchments ranged from 13 to 241 t/km^2/y, with most sites in the 50-100 t/km^2/y range. This is very similar to the Waikato, where specific yields ranged from 8 to 230 t/km^2/y.
- Correlation and multiple-regression analysis of the Auckland dataset indicated that the variation in specific sediment yield was due mainly to catchment rainfall (or runoff), mean slope, and land-cover – which aligns with the results from the Waikato sites.
- The Auckland regression study was able to resolve weighting coefficients for land-cover such that for a given rainfall x slope product, the yields from forested

[2] This is based on a catchment area of 20.5 km^2. This was derived by GIS analysis but differs from the area 30.8 km^2 assigned to this site by Walter (2000) and noted in McKerchar and Hicks (2003).

areas were 2/3 those from pasture areas, while the yields from urbanised areas were ¼ of those from pasture areas. This land-cover discrimination was not resolved to the same level of detail in the present study of the Waikato sites, although (other factors being equal) the yields were clearly higher from pasture-dominated catchments compared with forested ones.

4 Recommended further work

Based on the positive results from the above reconnaissance-level analysis of the factors influencing variation in mean annual sediment yield, it is recommended that the sediment yield results from this study be combined with those from other Waikato catchments (e.g., the 13 additional catchments covered by Hicks et al., 2001) and from the Auckland region (e.g., Hicks et al., 2009) to calibrate an improved inter-regional empirical model for predicting sediment yield that is sensitive to catchment hydrology, slope, land-cover, and lithology parameters. This should be a spatially-distributed model, predicting yields on a pixel or sub-catchment basis, to incorporate within-catchment spatial variability in runoff (or rainfall) and slope (which was not done in the present analysis) as well as land-cover and lithology.

5 Conclusions

The main conclusions from this study of suspended sediment yields from 23 catchments over the Waikato region are as follows:

- Specific mean annual yields ranged from 8 to 230 t/km^2/y, with most catchments having yields in the range 40-100 t/km^2/y.
- Substantial hydrologically-driven inter-annual variability occurs in suspended sediment yields, with standard deviations in annual yield averaging 47% of the mean annual yield. This annual variability indicates that yield estimates among catchments with short and different record periods should be interpreted with caution.
- The regional variation in mean annual specific yield is due mainly to catchment runoff (or rainfall, which is highly correlated with runoff), mean slope, and land-cover. Other factors being equal, sediment yields are lower from forested catchments compared with catchments in pasture or horticulture. While there is a hint of a lithology influence, with higher yields from catchments formed in erodible Tertiary sedimentary rocks or tephra, this was not statistically significant.
- Event-yield magnitude-frequency relations developed for the auto-sampled sites showed generally that the catchments with higher (or lower) mean annual yields have higher (or lower) yields over all return periods. The mainly forested Wharekawa and Opitonui catchments on the Coromandel Peninsula were exceptions, showing relatively lower yields from common events (return period of about 1 year and less) and relatively higher yields from less common events. This behaviour likely reflects limited sediment sources during smaller, more frequent events in these catchments.
- Previous yield estimates for some of the study catchments agree acceptably well with those of the present study, allowing that the present analysis has the benefit of longer spans of flow record and increased numbers of suspended sediment samples.
- Sediment yields from nine catchments in Auckland’s Waitemata Formation terrain showed much the same range in specific sediment yields as those found across the Waikato region. Yield variation across the Auckland region was also found to relate to catchment rainfall (or runoff), mean slope, and land-cover.
- It is recommended that the sediment yield results from this study are combined with those from other Waikato catchments and from the Auckland region to calibrate an empirical model for predicting sediment yield that is sensitive to spatially-distributed characteristics of catchment hydrology, slope, land-cover, and lithology.

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Appendix A Sediment Concentration Rating Plots

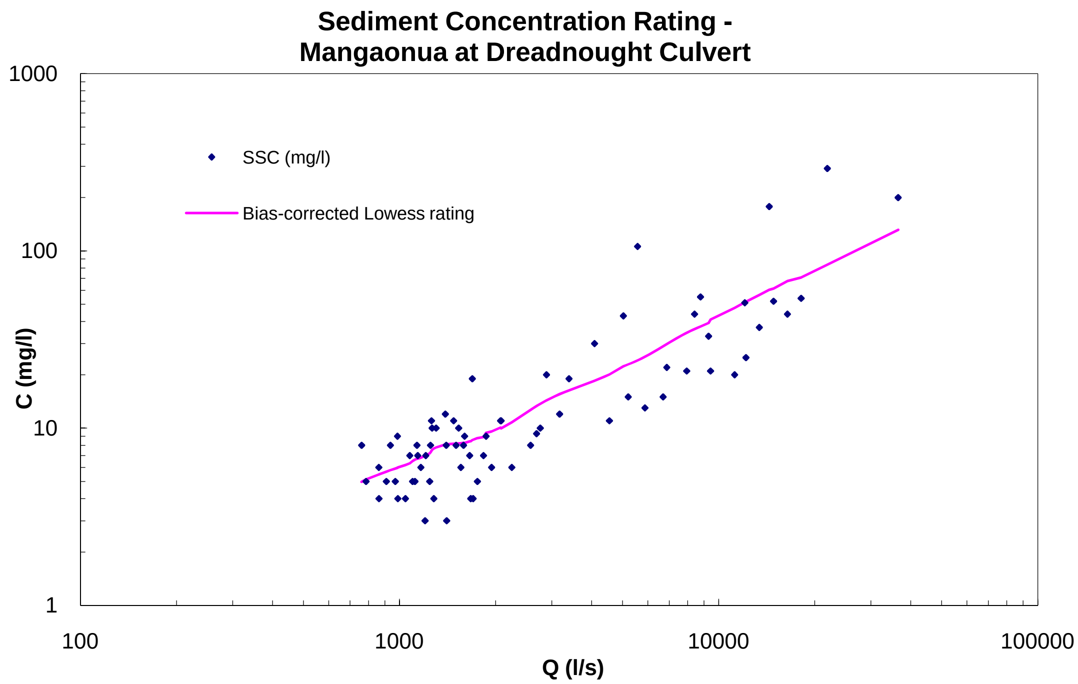

Figure A-1: Mangaonua at Dreadnought Culvert SH1 sediment concentration rating.

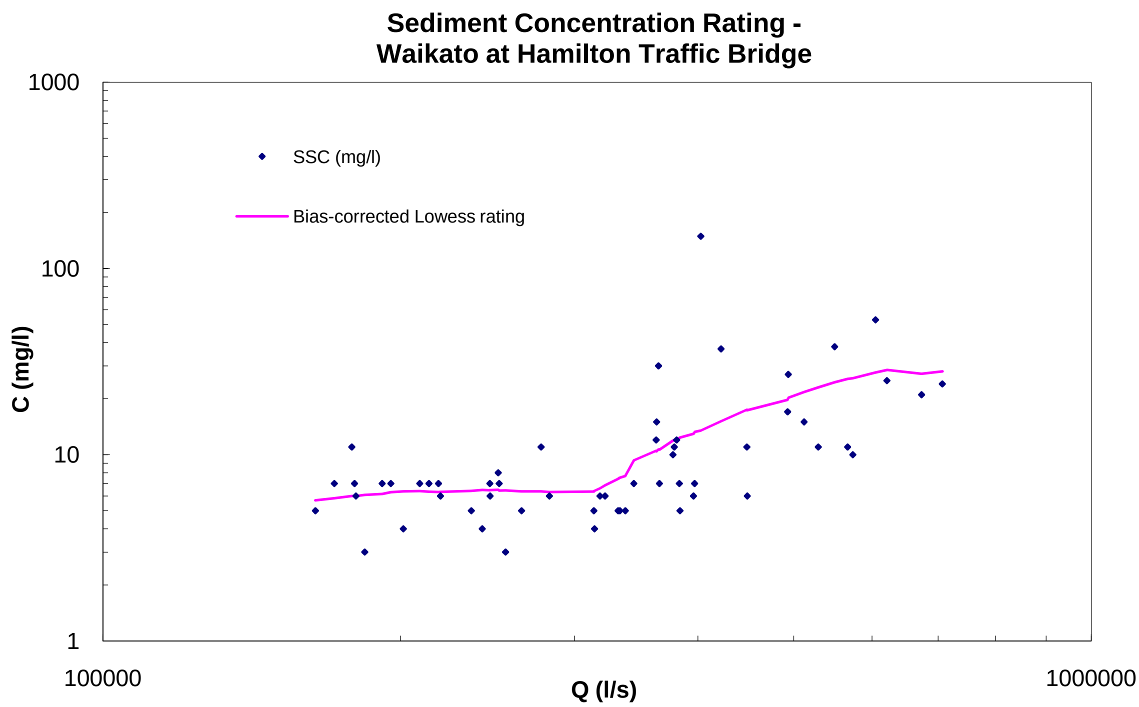

Figure A-2: Waikato at Hamilton Traffic Bridge sediment concentration rating.

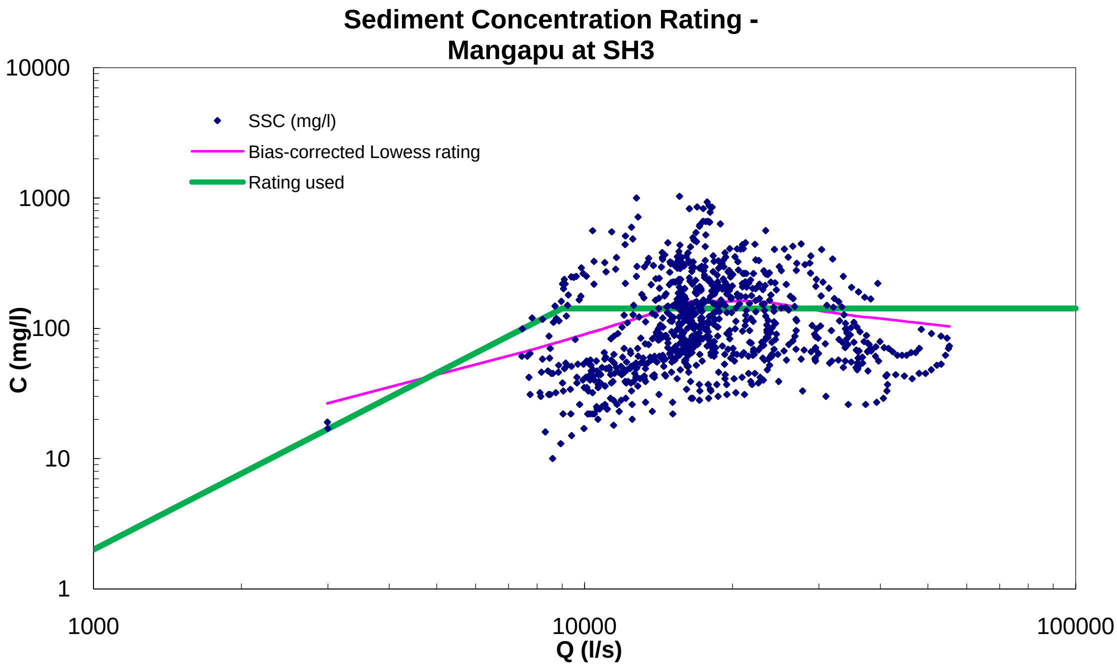

Figure A-3: Mangapu at SH3 sediment concentration rating. NB Due to the broad scatter of data at this site, the lowess rating was not considered appropriate. Instead, a simple rating was developed, using the mean SSC for Q > 9000 l/s and, for Q < 9000 l/s SSC tends to 0 mg/l as flow tends to 0 l/s.

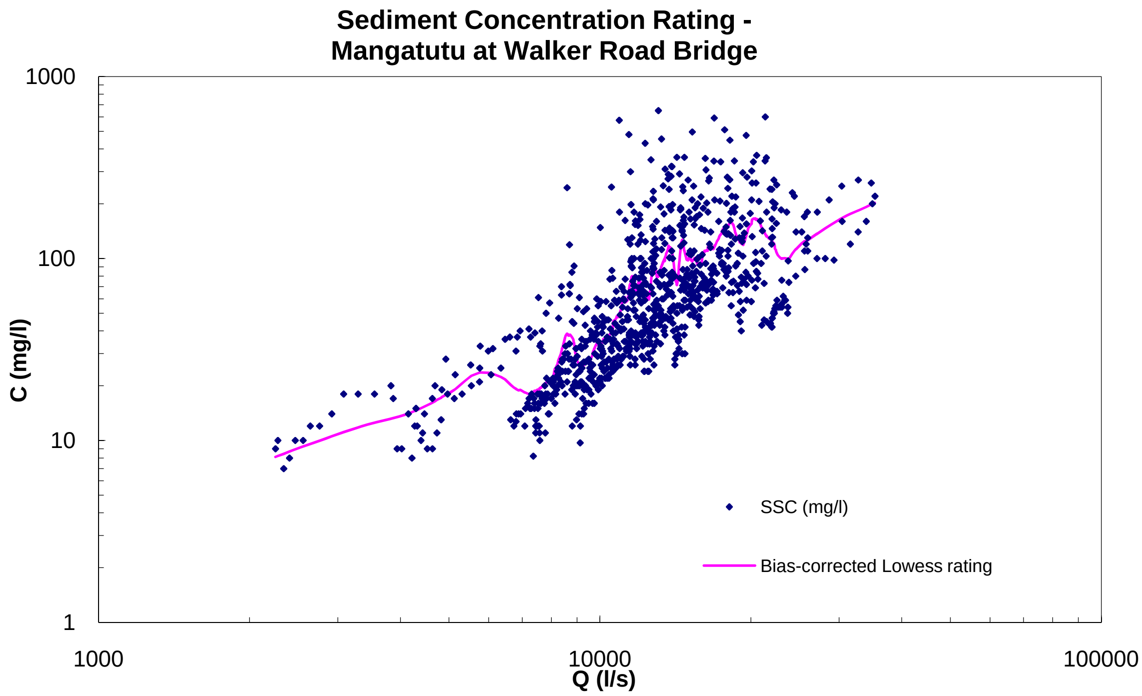

Figure A-4: Mangatutu at Walker Road Bridge sediment concentration rating.

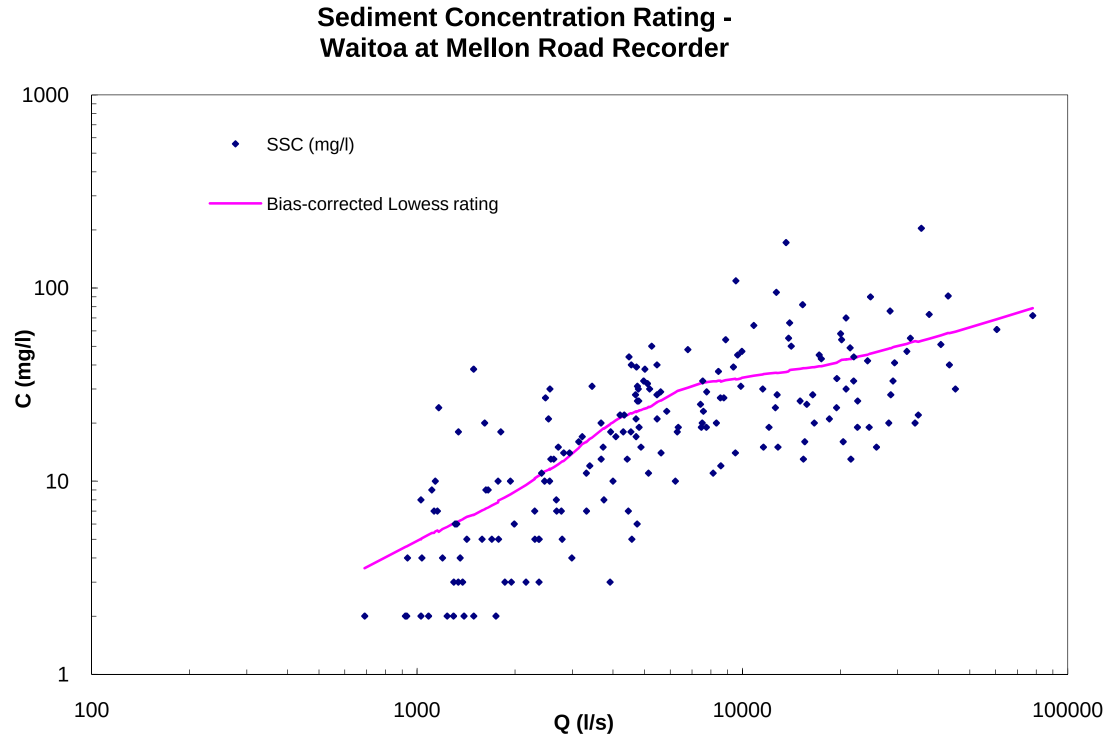

Figure A-5: Waitoa at Mellon Road sediment concentration rating.

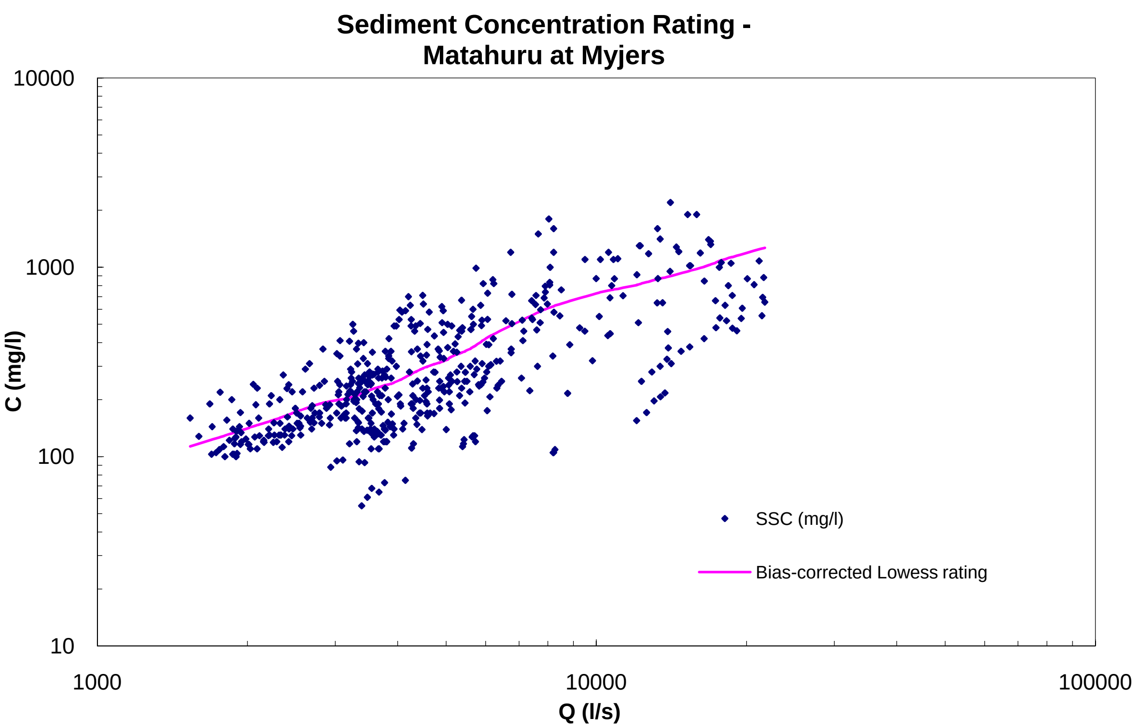

Figure A-6: Matahuru at Myjers sediment concentration rating.

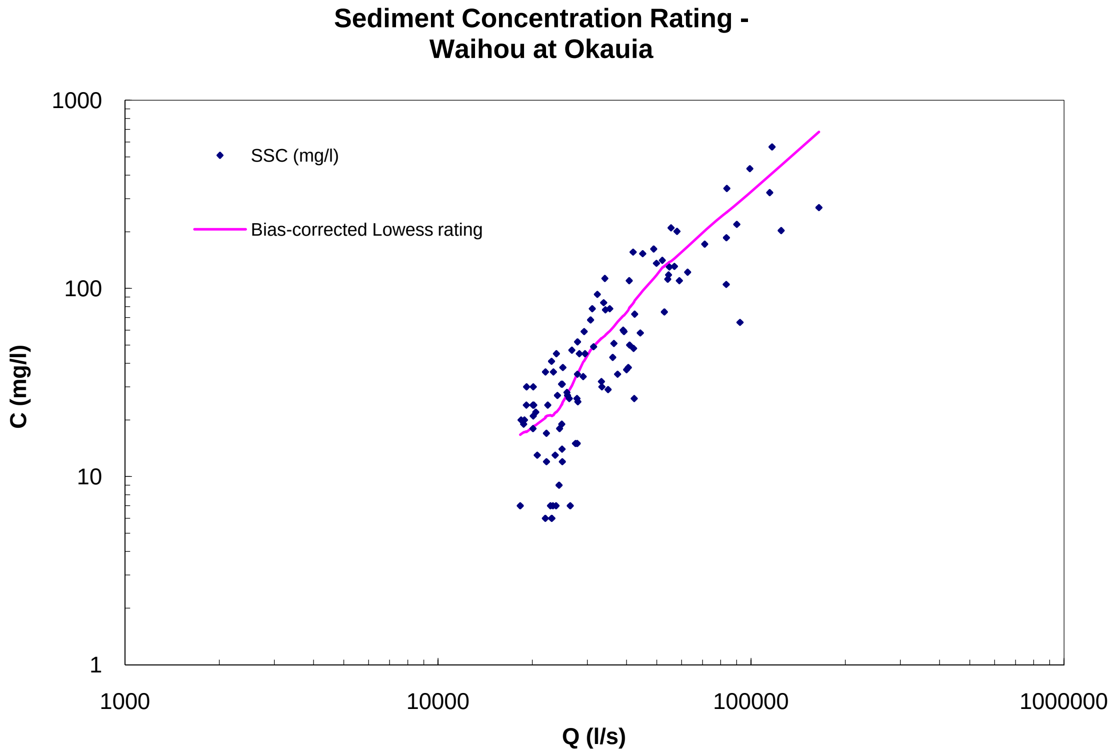

Figure A-7: Waihou at Okauia sediment concentration rating.

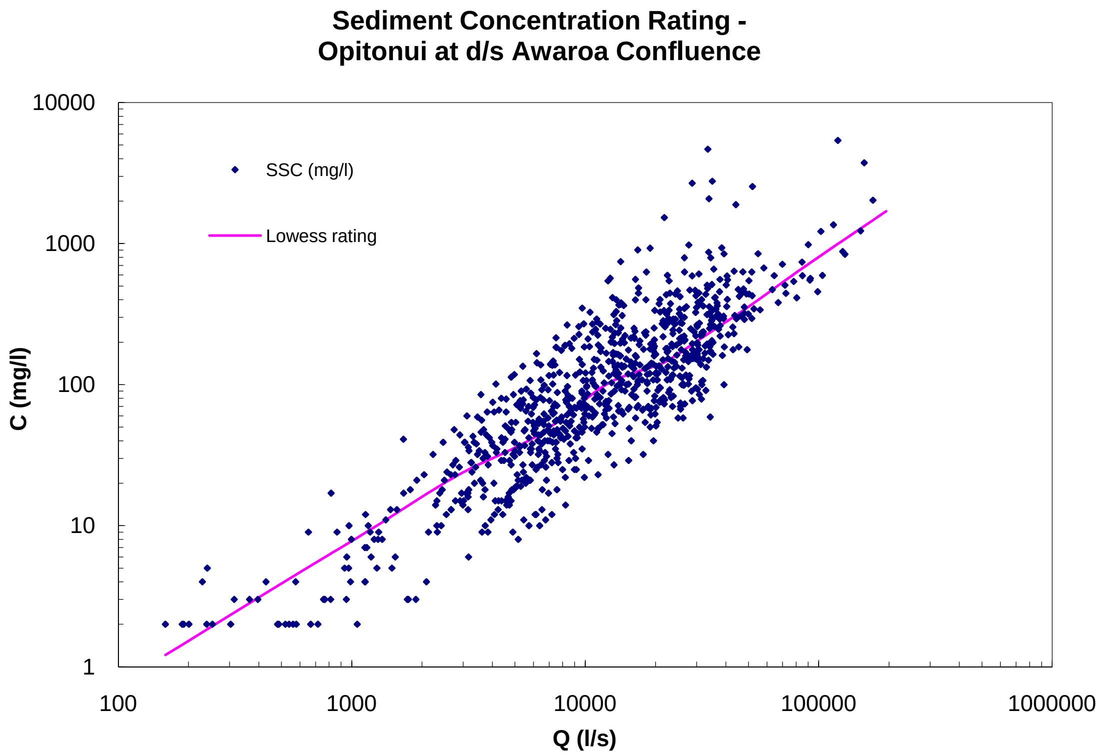

Figure A-8: Opitonui at d/s Awaroa confluence sediment concentration rating.

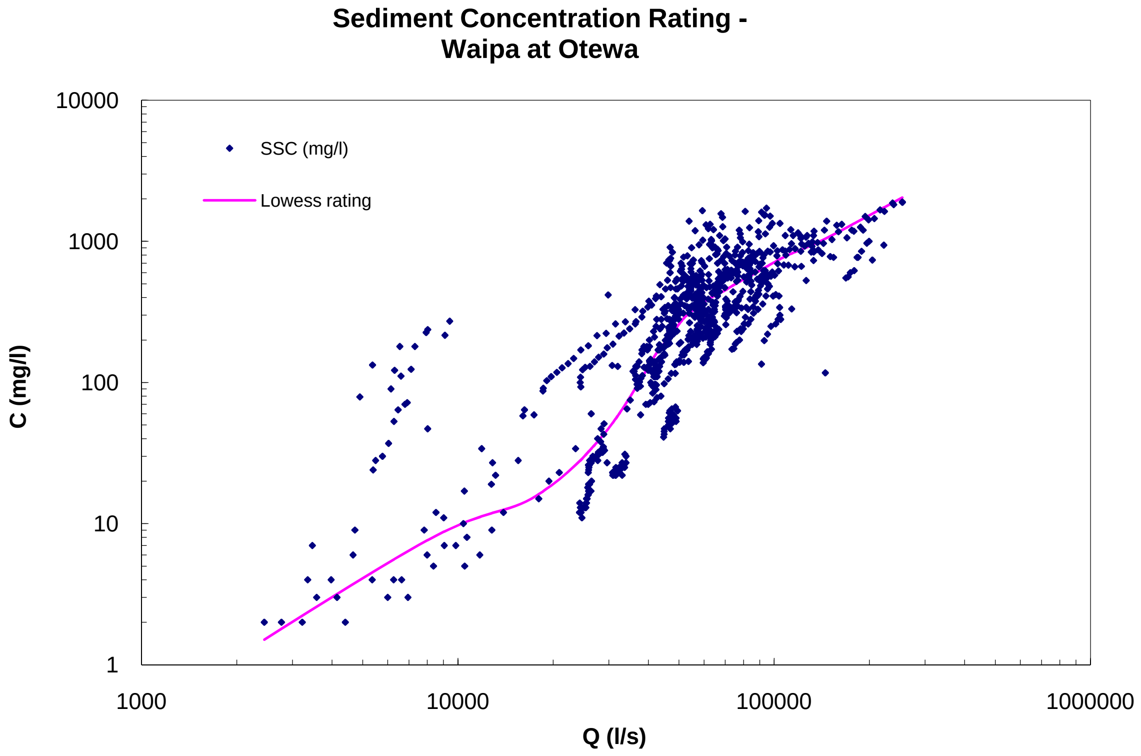

Figure A-9: Waipa at Otewa sediment concentration rating.

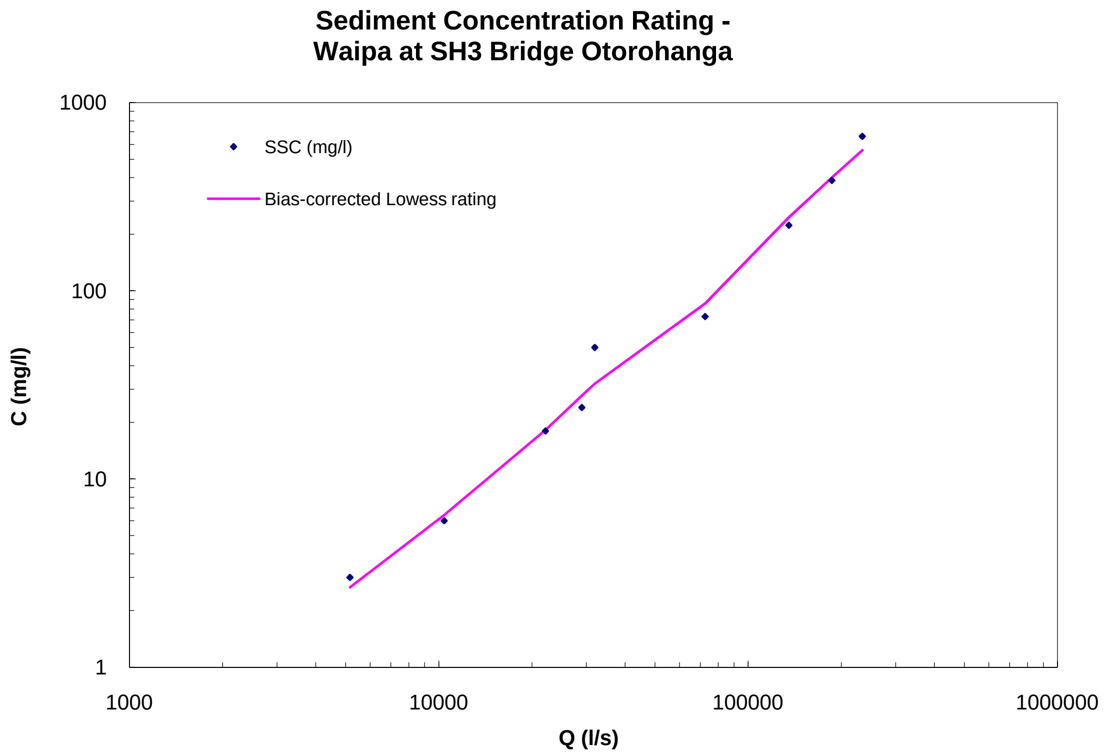

Figure A-10: Waipa at SH3 Bridge Otorohanga sediment concentration rating.

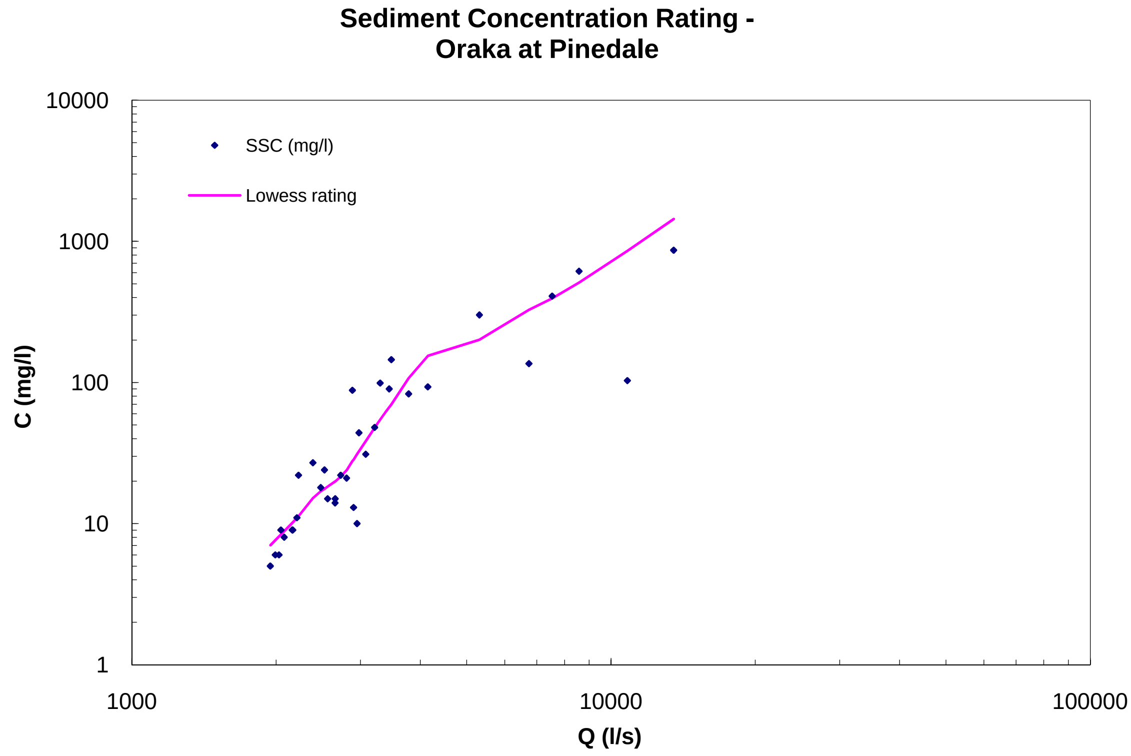

Figure A-11: Oraka at Pinedale sediment concentration rating.

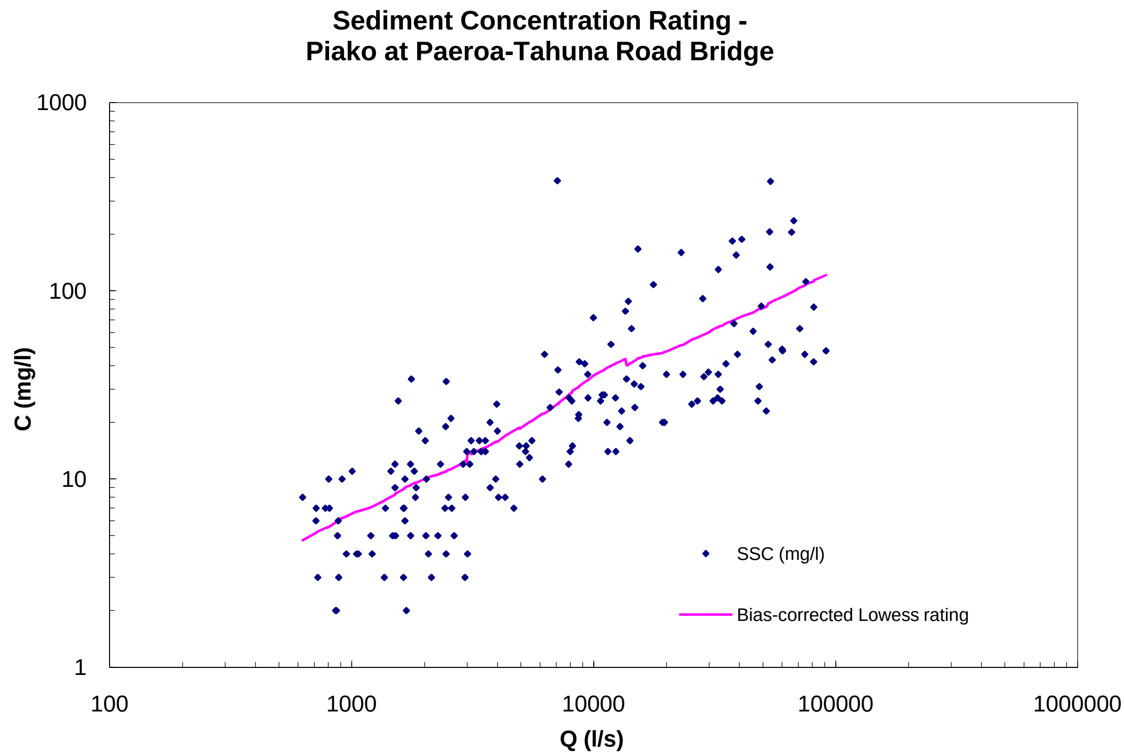

Figure A-12: Piako at Paeroa-Tahuna Road Bridge sediment concentration rating.

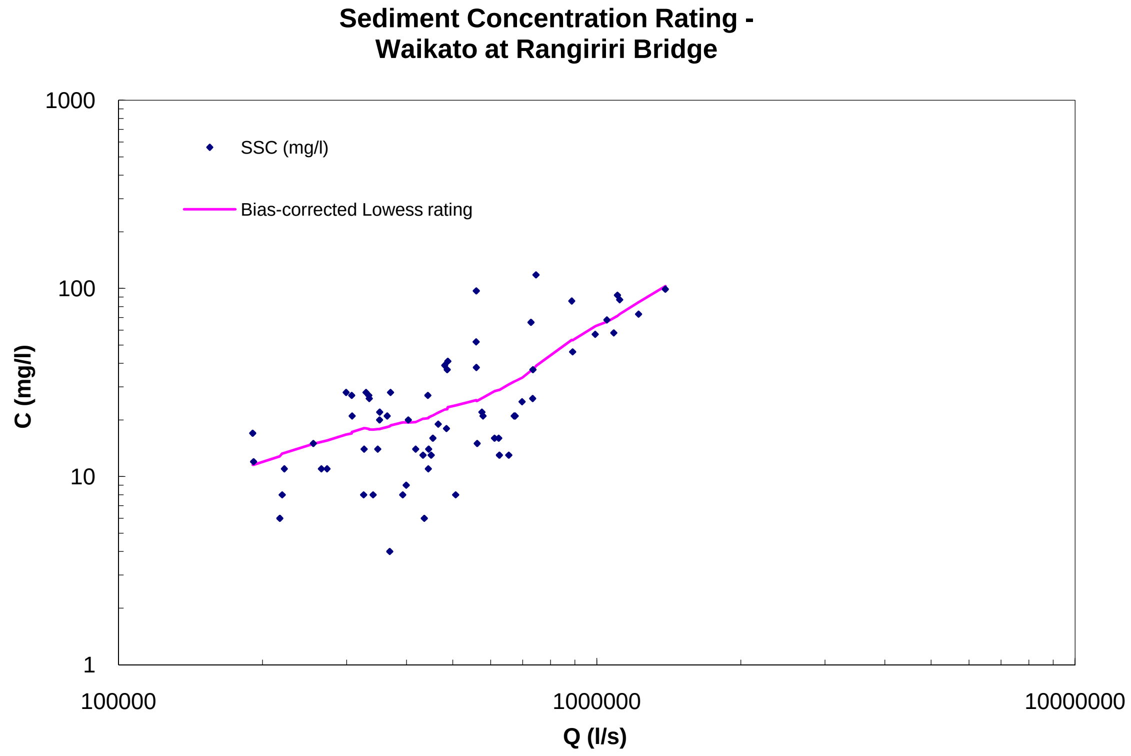

Figure A-13: Waikato at Rangiriri Bridge sediment concentration rating.

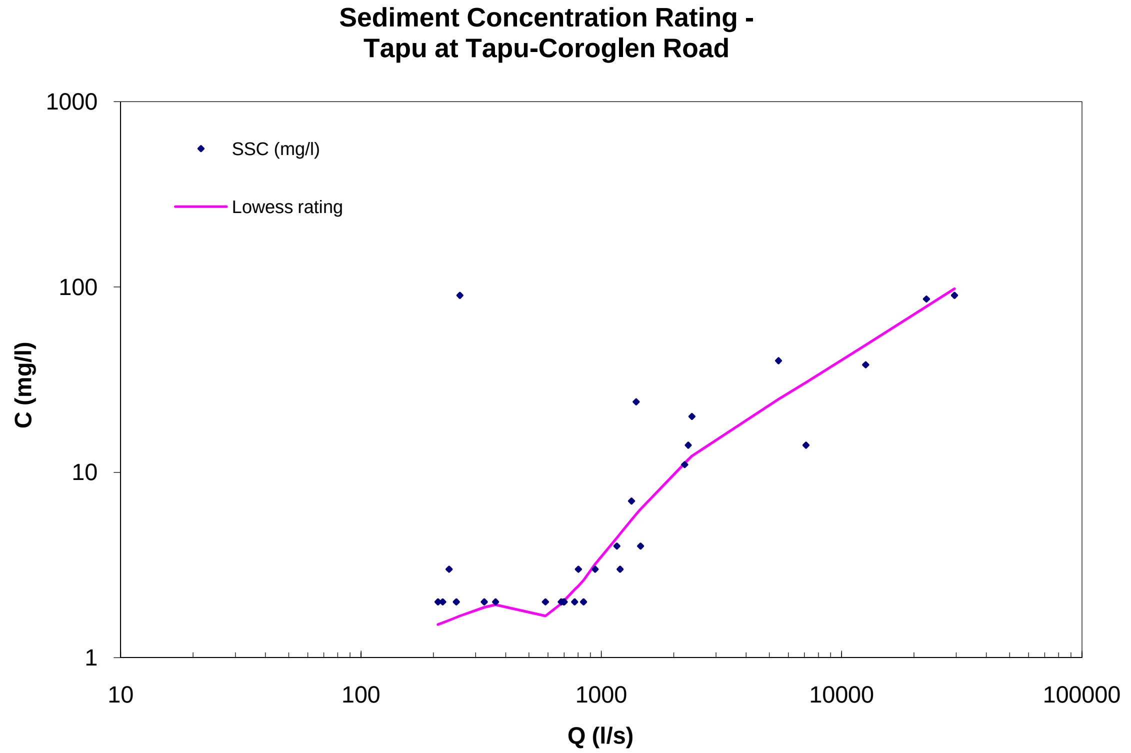

Figure A-14: Tapu at Tapu-Coroglen Road sediment concentration rating.

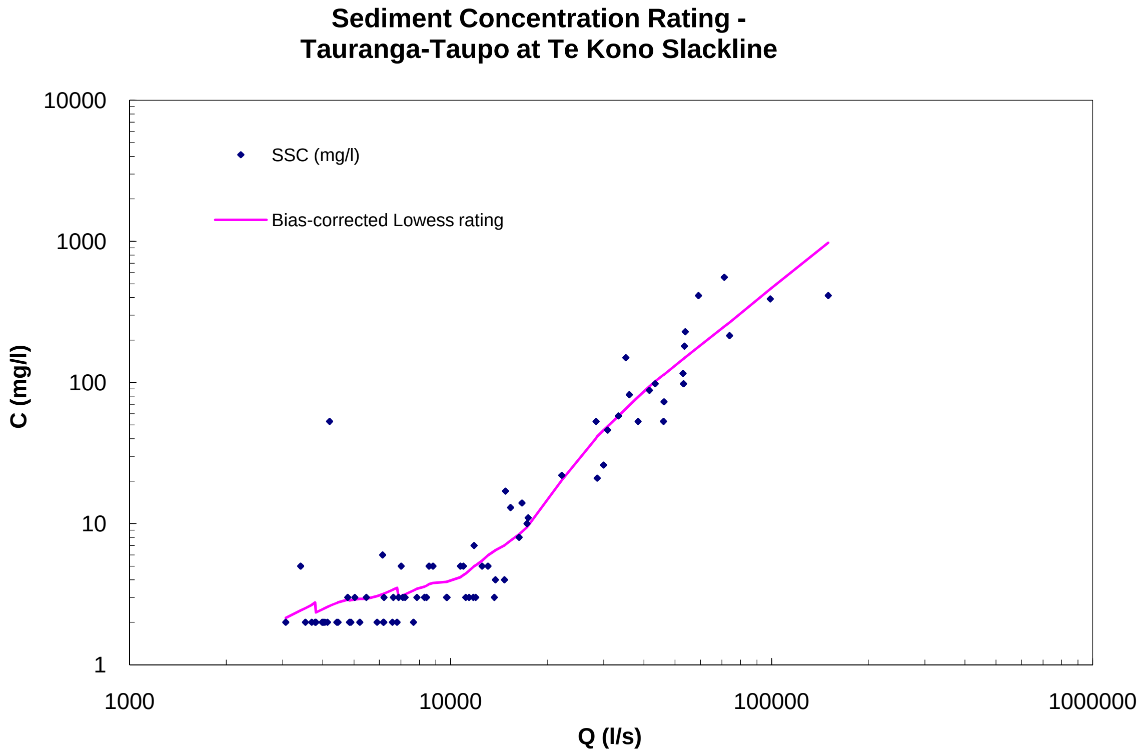

Figure A-15: Tauranga-Taupo at Te Kono Slackline sediment concentration rating.

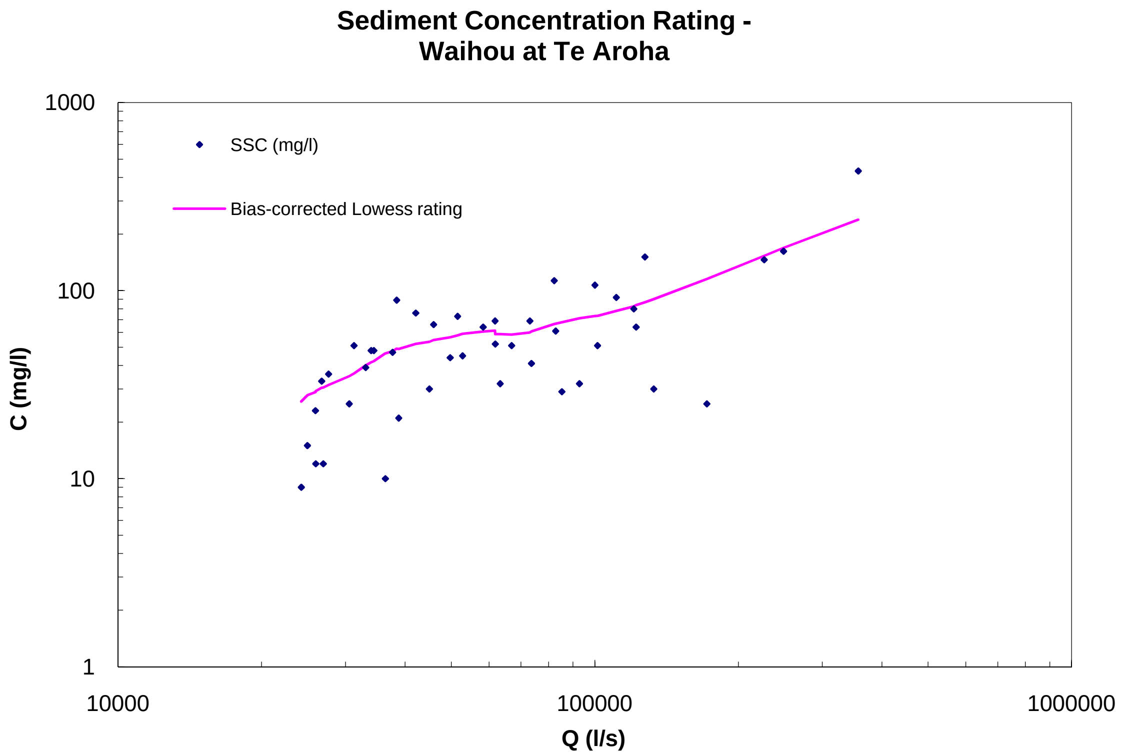

Figure A-16: Waihou at Te Aroha sediment concentration rating.

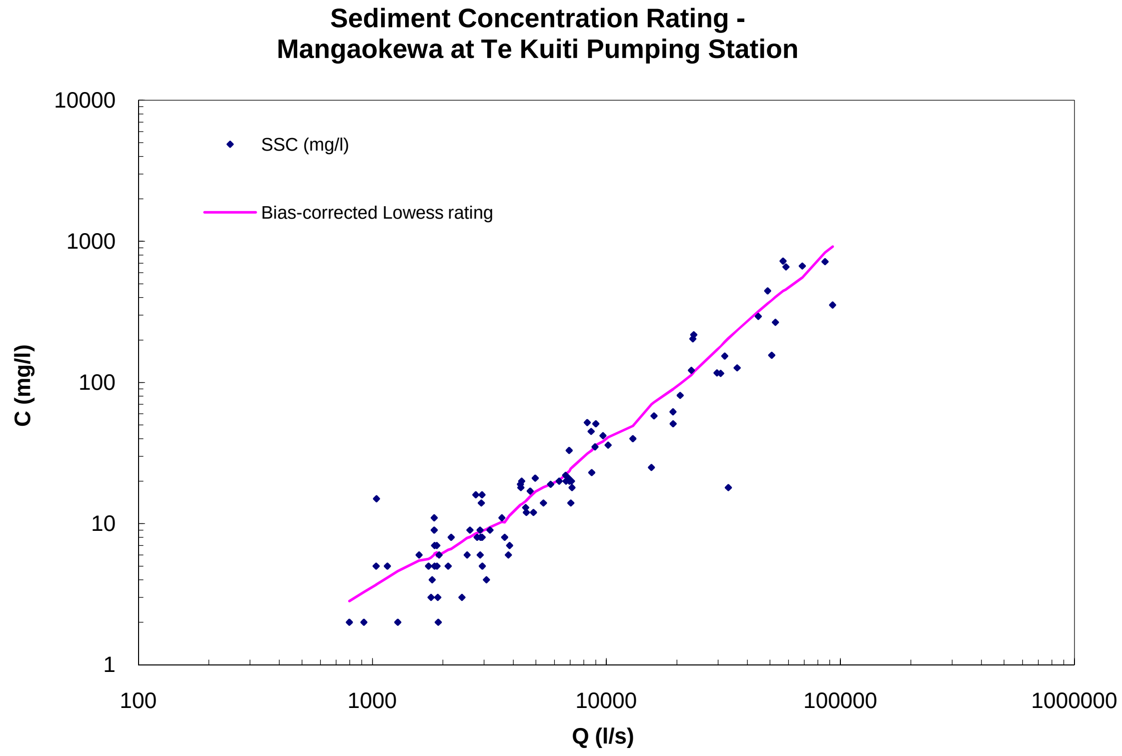

Figure A-17: Mangaokewa at Te Kuiti Pumping Station sediment concentration rating.

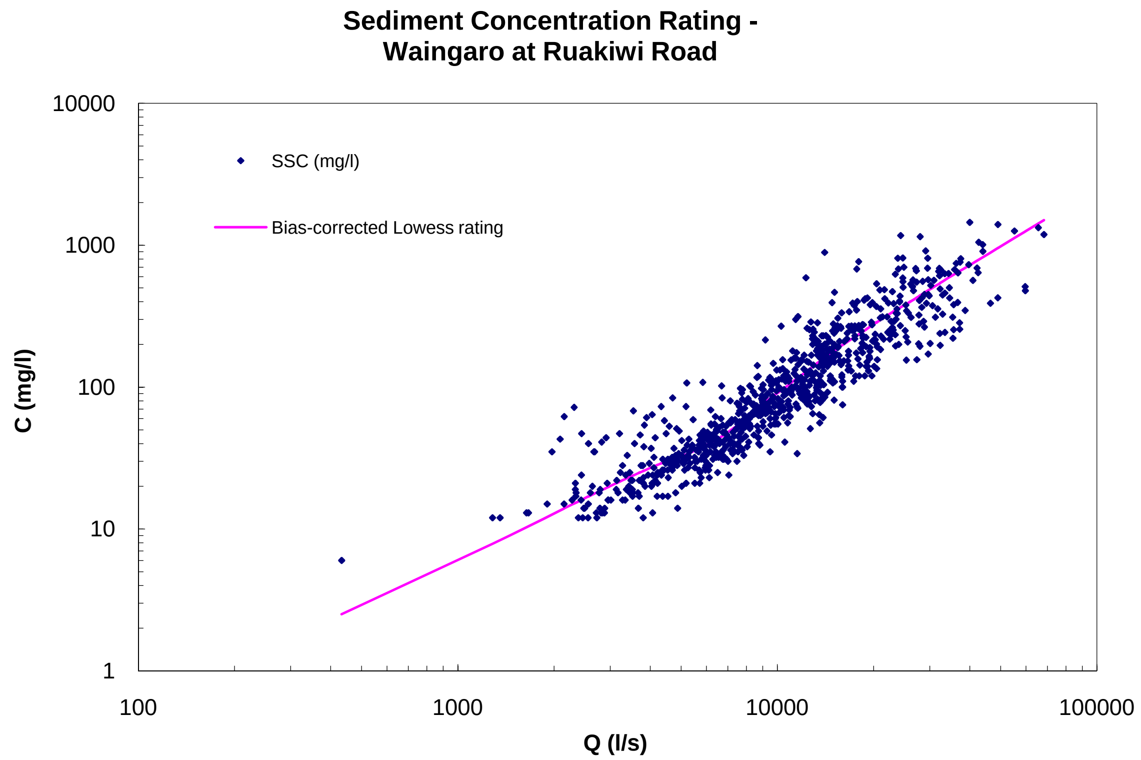

Figure A-18: Waingaro at Ruakiwi Road sediment concentration rating.

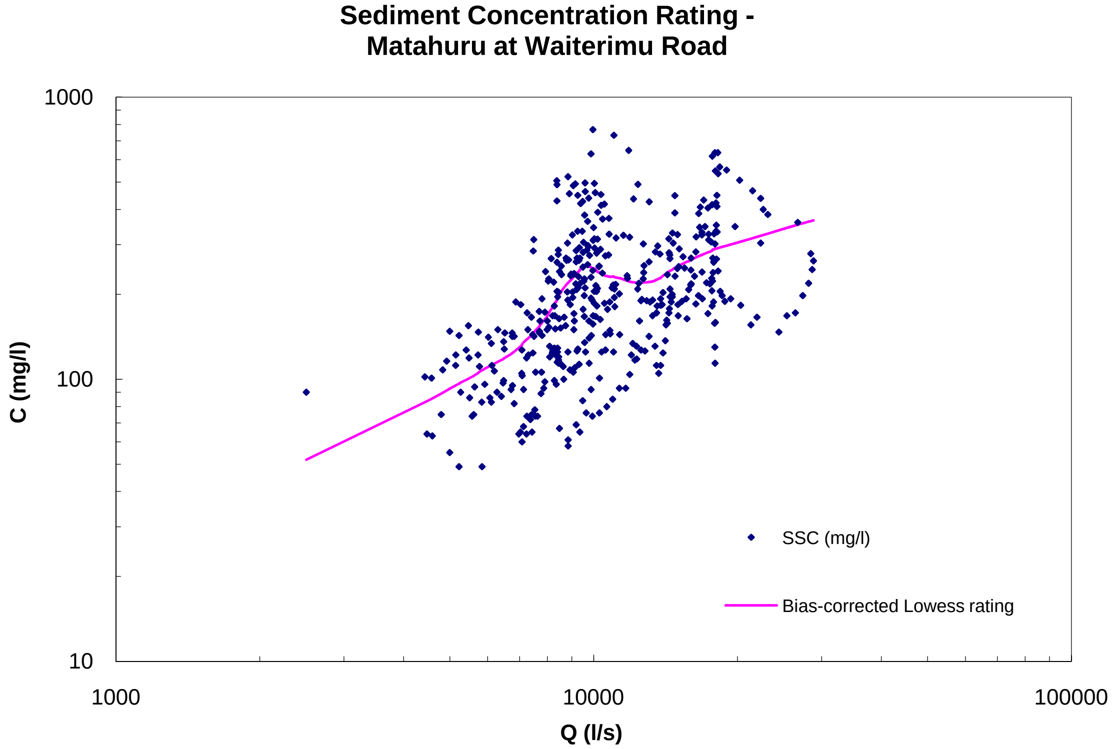

Figure A-19: Matahuru at Waiterimu Road sediment concentration rating.

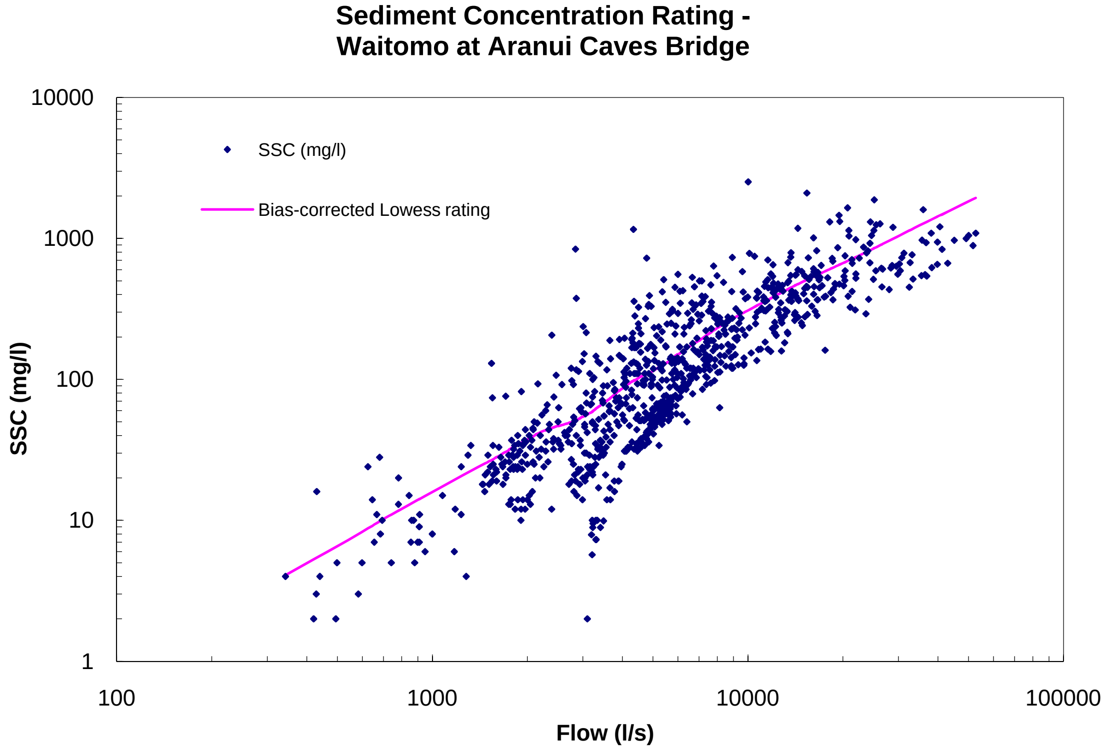

Figure A-20: Waitomo at Aranui Caves Bridge sediment concentration rating.

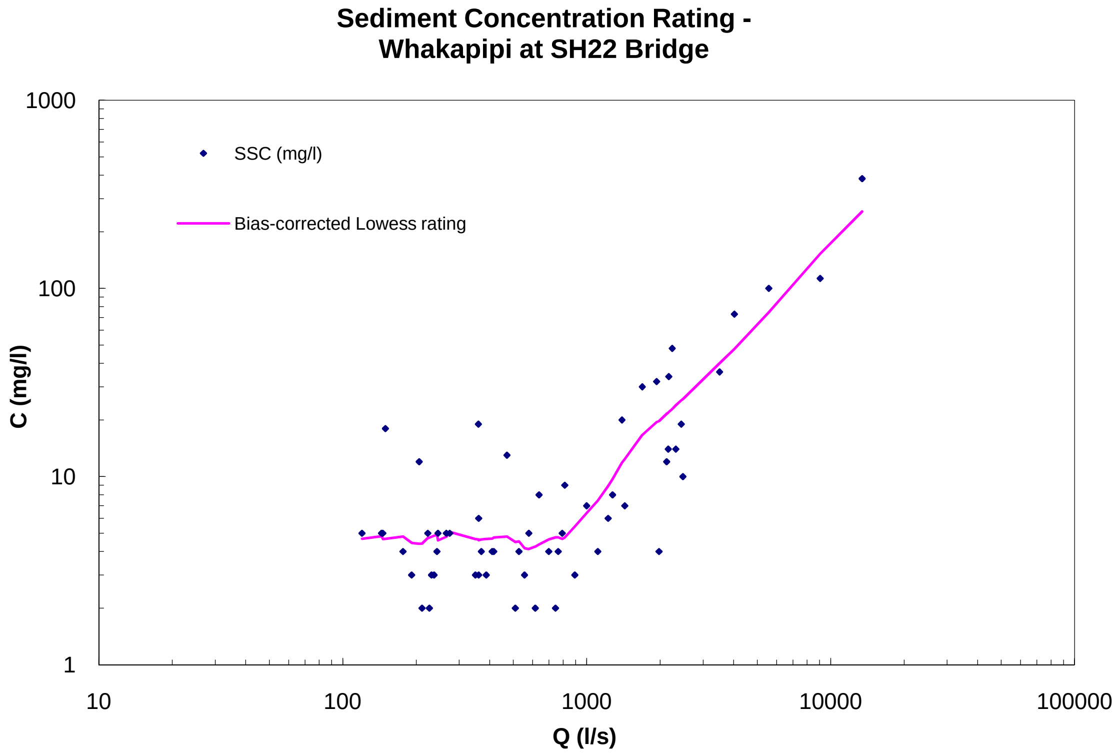

Figure A-21: Whakapipi at SH22 Bridge sediment concentration rating.

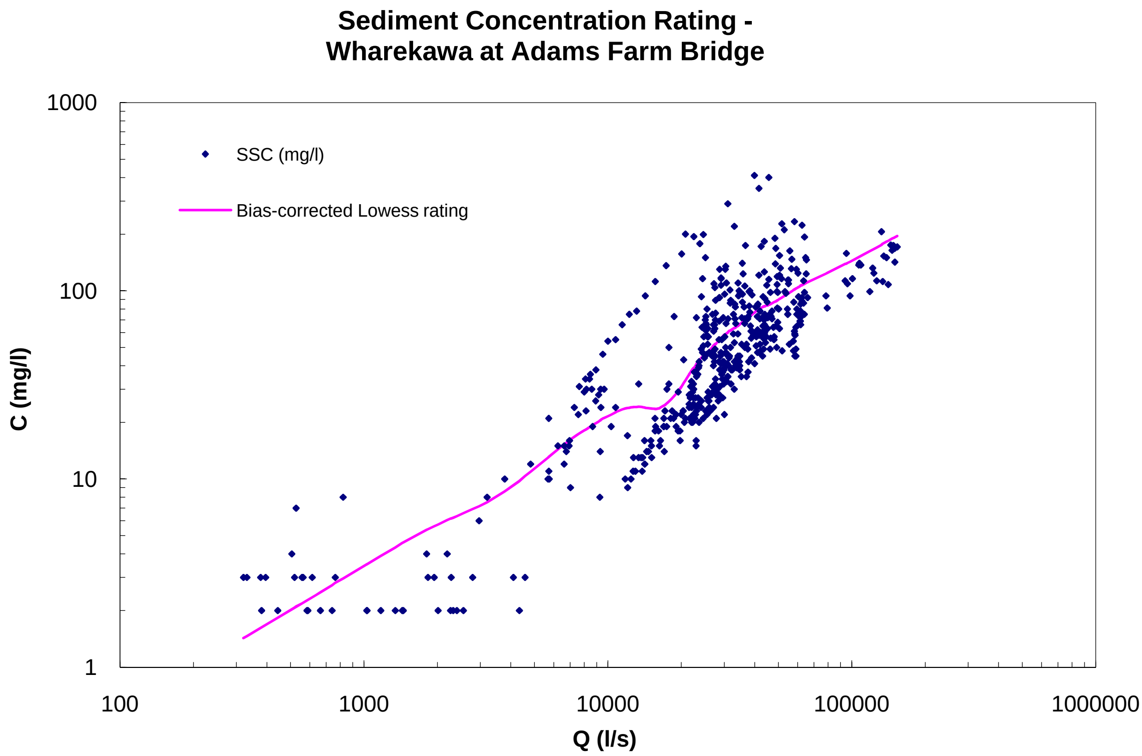

Figure A-22: Wharekawa at Adams Farm Bridge sediment concentration rating.

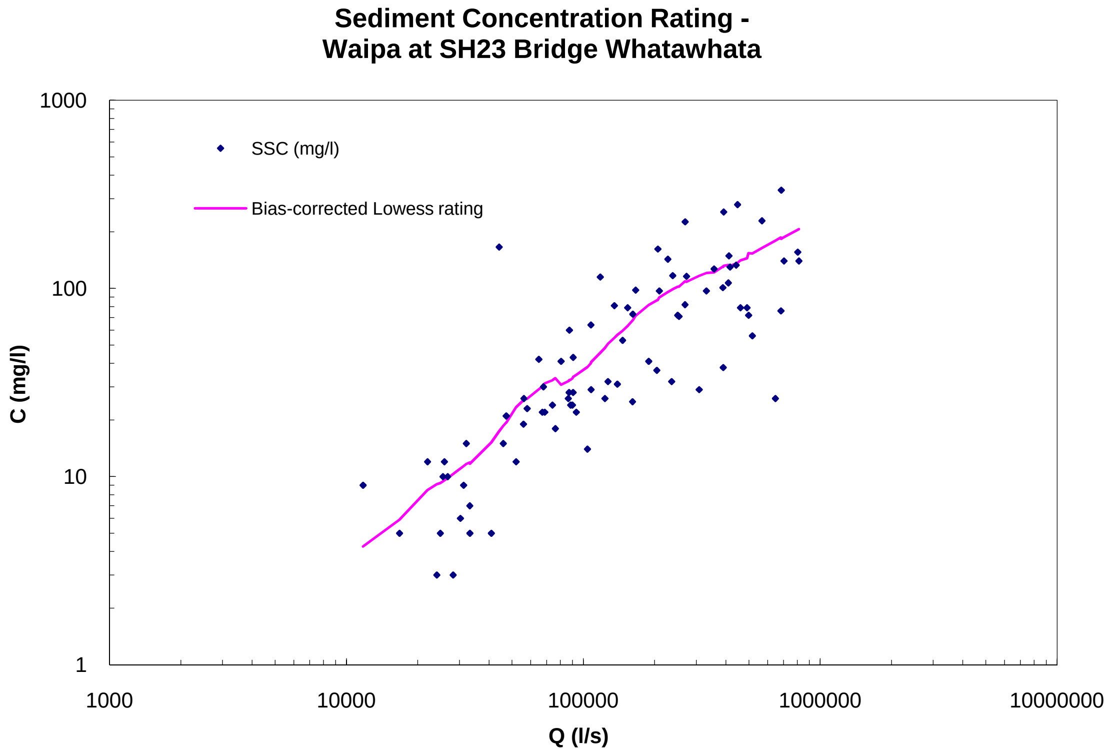

Figure A-23: Waipa at SH23 Bridge Whatawhata sediment concentration rating.

Appendix B Event Sediment Yield ratings

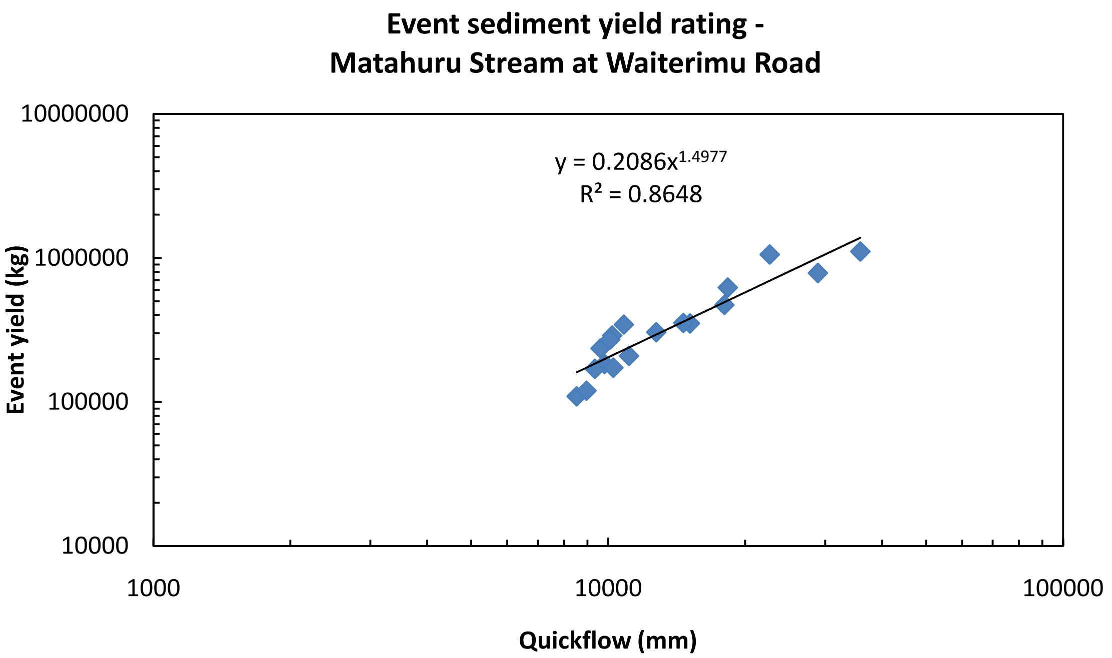

Figure B-1: Matahuru Stream at Waiterimu Road event yield rating. This rating has a power relationship.

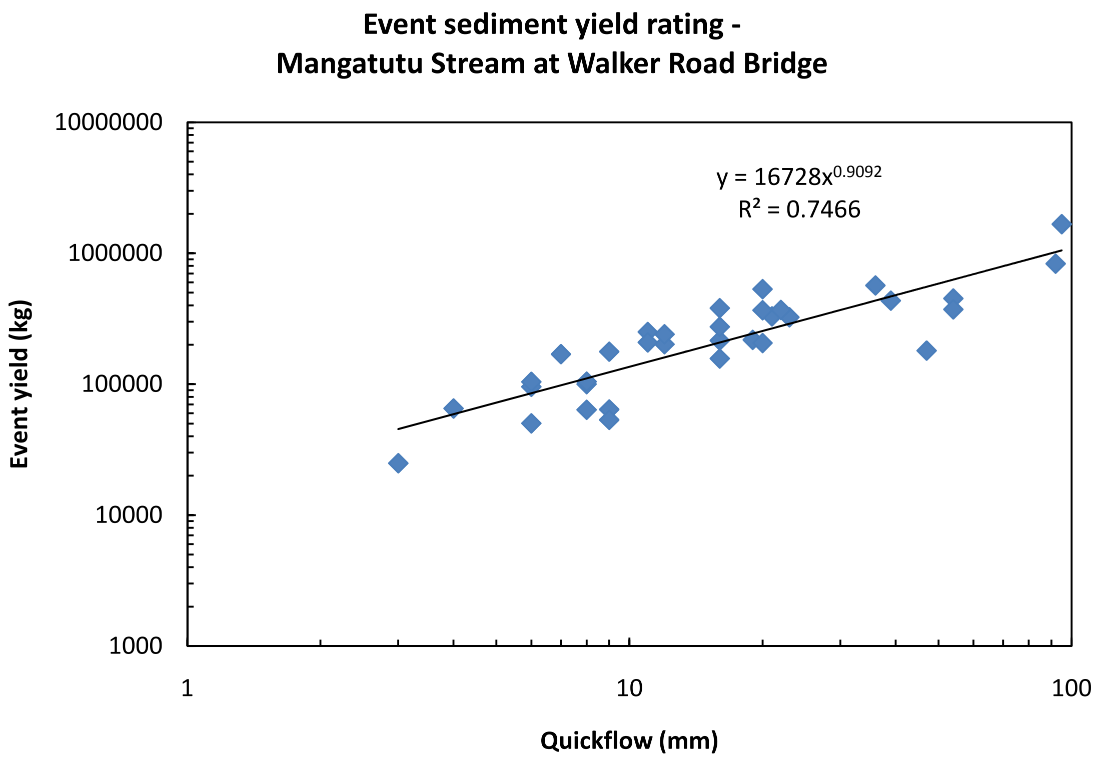

Figure B-2: Mangatutu at Walker Road Bridge event yield rating. This rating has a power relationship.

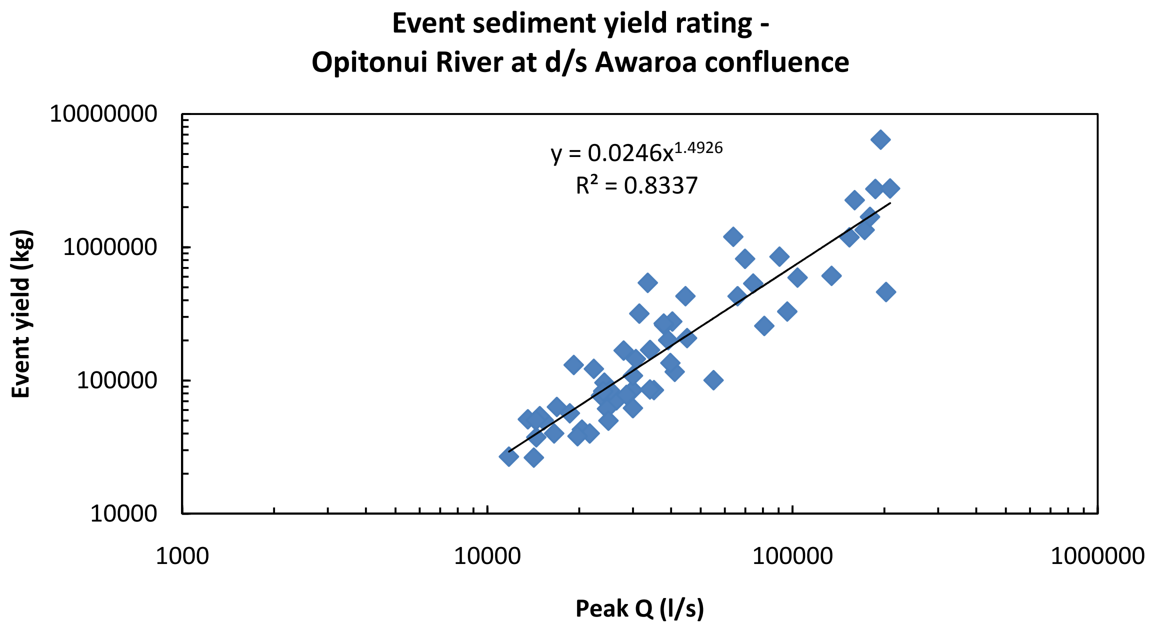

Figure B-3: Opitonui River at d/s Awaroa confluence event yield rating. This rating has a power relationship.

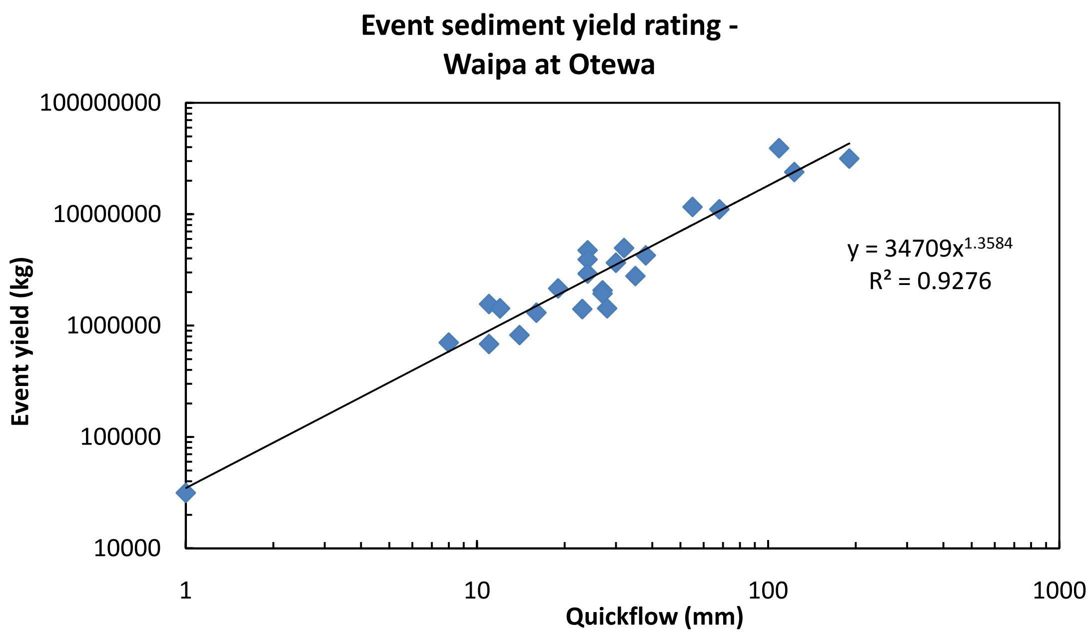

Figure B-4: Waipa at Otewa event yield rating. This rating has a power relationship.

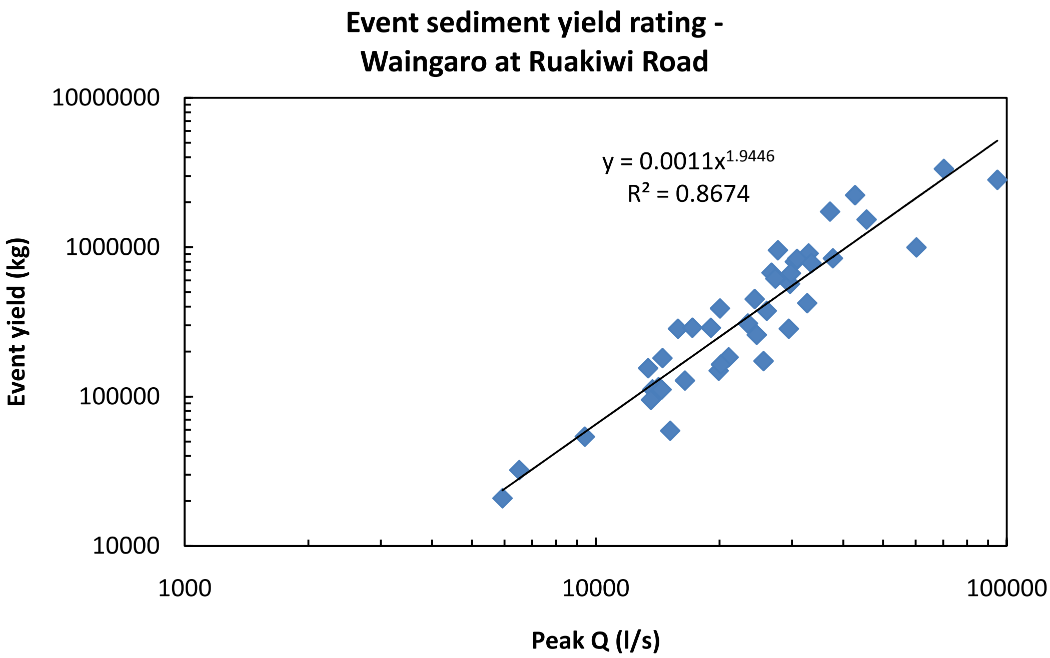

Figure B-5: Waingaro at Ruakiwi Road event yield rating. This rating has a power relationship.

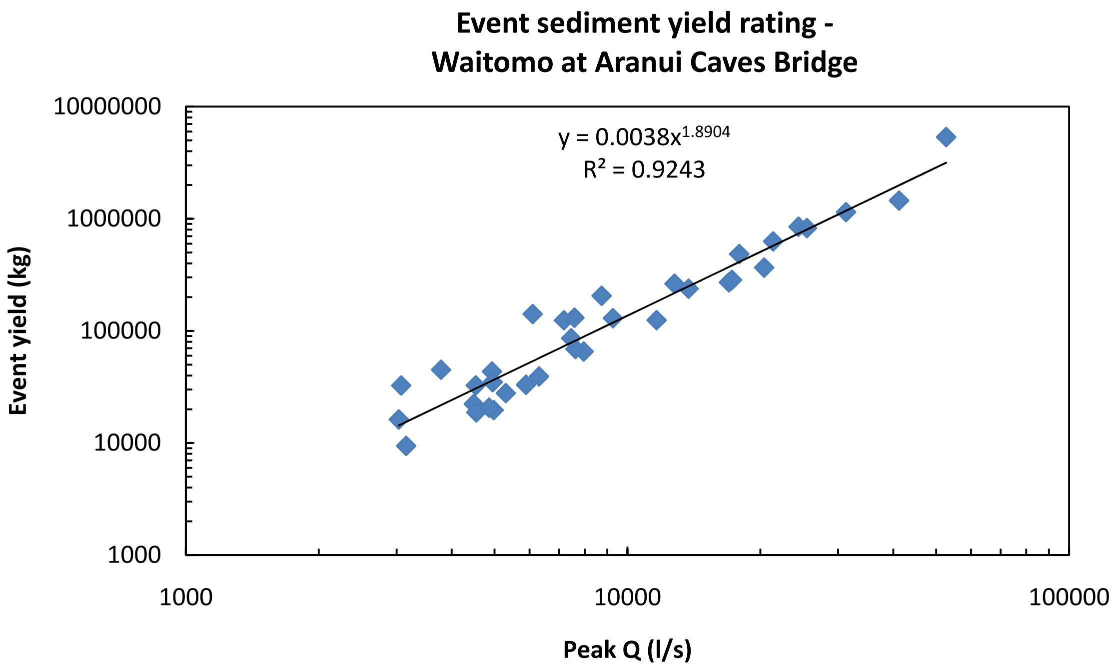

Figure B-6: Waitomo at Aranui Caves event yield rating. This rating has a power relationship.

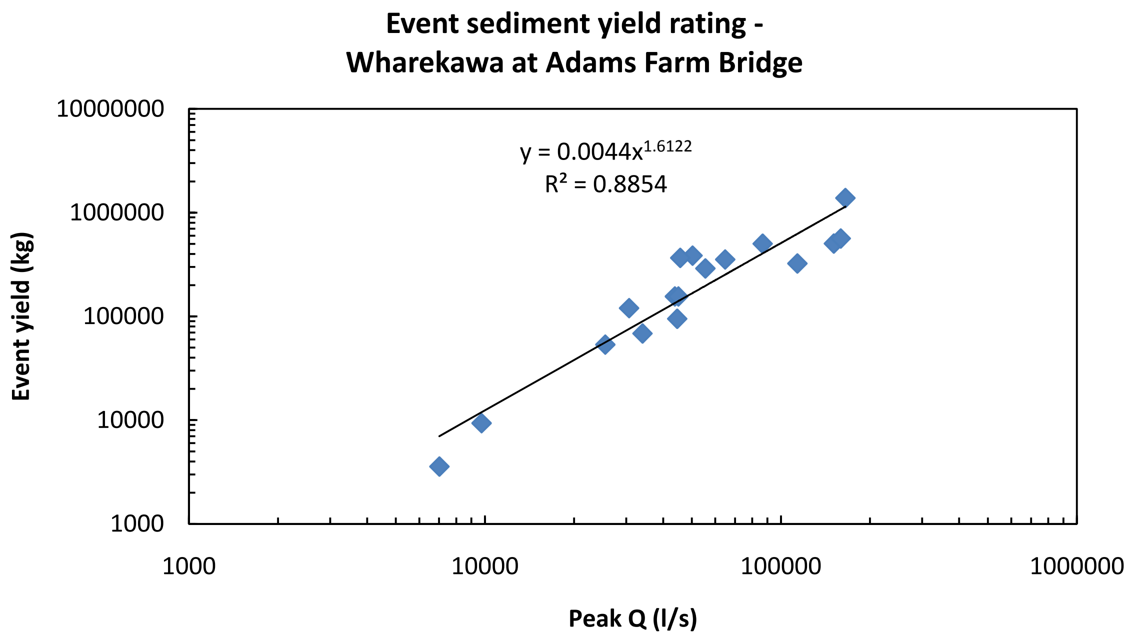

Figure B-7: Wharekawa at Adams Farm Bridge event yield rating. This rating has a power relationship.

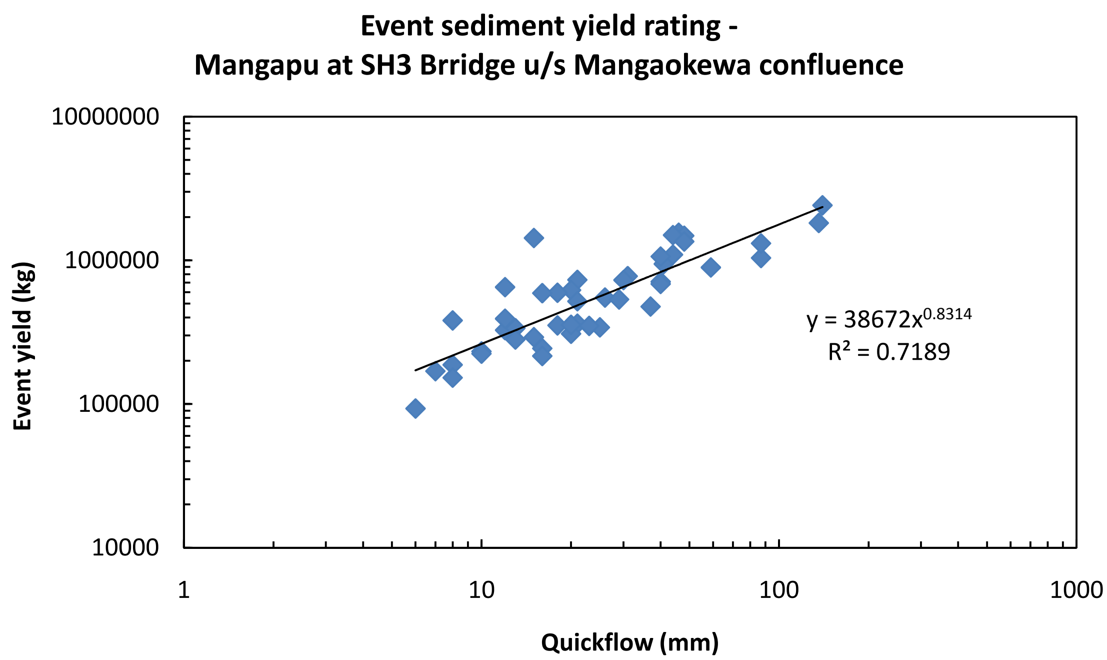

Figure B-8: Mangapu at SH3 Bridge u/s Mangaokewa confluence event yield rating. This rating has a power relationship.

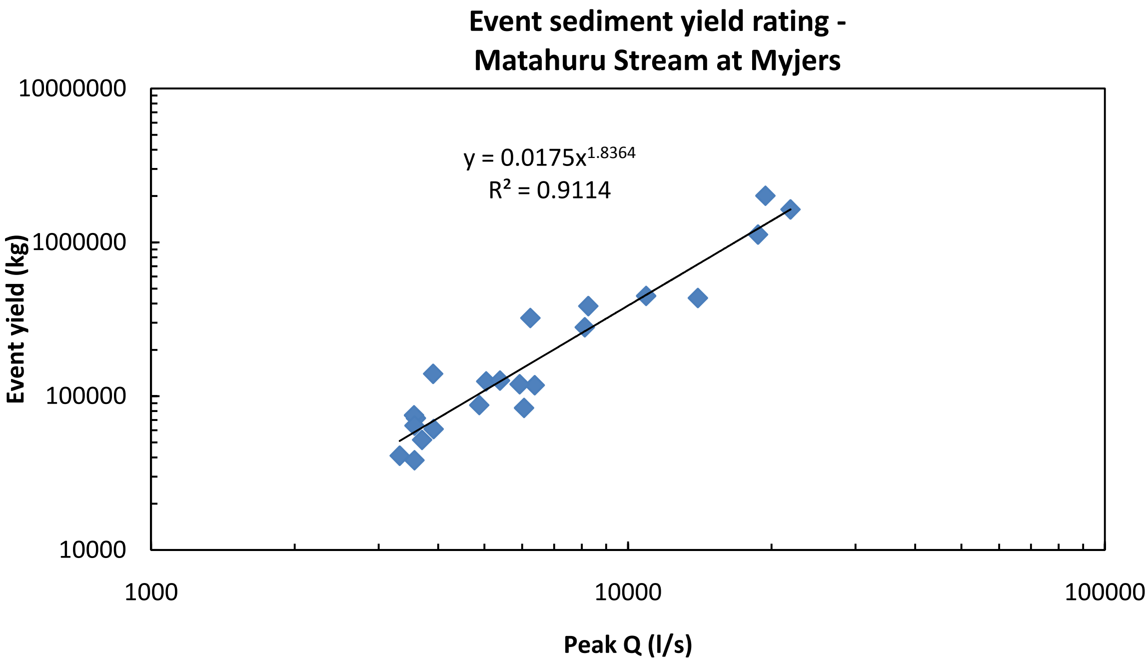

Figure B-9: Matahuru Stream at Myjers event yield rating. This rating has a power relationship.