Quantifying Catchment Sediment Yields in Auckland

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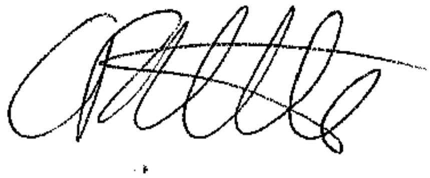

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Quantifying catchment sediment yields in Auckland

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Executive Summary

The Auckland region has many significant marine estuaries and harbours. These have great recreational, cultural, seafood harvesting and aesthetic values. They also support a wide variety of marine organisms and bird life. Loss of sediment from land to water increases turbidity which adversely affects the activity and diversity of many biota. An increase in sediment delivery to water bodies also has the potential to disrupt primary production. Sediment is also a vector for other pollutants such as phosphorus and heavy metals.

A key state of the environment (SoE) requirement is to report sediment yield, with sediment monitoring being conducted across the Auckland region. Sediment monitoring was officially adopted by Auckland Council in and around 2009. This study reports sediment yield (t) and specific sediment yields (SSY, t/km^2/yr) for ten sediment monitored catchments across Auckland.

The table below is a summary of specific sediment yields recorded at the ten catchments in Auckland for sampled events and using the sediment event yield (kg) vs Qpeak (l/s) rating for missing events. Specific sediment yield was sensitive to large infrequent storm events particularly for catchments with short spanning sediment records.

Site (dominant land cover)	**Specific sediment yield** (t/km^2/yr)	**Length of sediment record** (yrs)
Awanohi (indigenous forest)	48.3	4
Hoteo (pasture)	74.3	2.6
Kaipara (pasture)	32.3	1
Kaukapakapa (pasture)	75.8	2.6
Mangemangeroa (pasture)	167.0	1
Orewa (pasture)	80.0	3.5
Vaughan (pasture)	45.8	9.6
Wairoa (pasture)	47.4	2.6
Weiti (plantation forest)	32.1	4.7
West Hoe (indigenous forest)	26.3	1

Excluding the sites with only one year of record, the SSY range across catchments (32-80 t/km^2/yr) was relatively tight. The SSY reported for sites in the current study were similar in range, if not at the lower end, to recently reported Waikato yields which mostly fell within the 40-100 t/km^2/yr range.

It is recommended that future work explores an empirical model for predicting sediment yield within the Auckland region so that yields from unmonitored catchments can be estimated. Sediment yield analyses from previous studies in Auckland, Waikato and Northland can potentially be pooled together to locally calibrate the chosen model.

Several considerations and approaches to measure the Auckland Plan target, which is to reduce sediment yields from 2012 levels by 15% by 2040, have been discussed. It is recommended that future work concentrate on the approach used to measure change when sediment data becomes more refined and reliable for all sites over time. This will provide an improved measure of annual variability and so will inform on an appropriate averaging period.

Contents

1.0 Introduction

The Auckland region has many significant marine estuaries and harbours. These have great recreational, cultural, seafood harvesting and aesthetic values. They also support a wide variety of marine organisms and bird life. The Auckland public put great value on these marine environments and there is concern that the delivery of sediment to both marine and freshwater receiving water bodies degrades such systems. Loss of sediment from land to water increases turbidity, which adversely affect the activity and diversity of many biota (Bilotta and Brazier 2008; 2010). An increase in sediment delivery to water bodies also has the potential to disrupt primary production. Sediment is also a vector for other pollutants such as phosphorus (Haygarth *et al.* 2006), heavy metals and PAHs (Mills *et al.* 2012).

A key state of the environment (SoE) requirement is to report sediment yield, with sediment monitoring being conducted across the Auckland region. A scientifically robust and defensible sediment monitoring plan was designed for Auckland Council in 2009 that is spatially representative and stratified by geology, climate and land cover (Hicks *et al.* 2009a). A subsequent sediment monitoring methods report for Auckland Council was released in 2011 to ensure accurate sediment monitoring in Auckland (Hicks 2011).

Ten catchments have been selected for sediment monitoring purposes across Auckland (Figure 1) that meet these latter reports' objectives. These ten catchments include Okura at Awanohi (hereafter referred to as Awanohi), Hoteo at Gubbs (Hoteo), Kaipara at Waimauku (Kaipara), Kaukapakapa at Taylors (Kaukapakaka), Mangemangeroa at Craigs (Mangemangeroa), Orewa at Kowhai Ave (Orewa), Vaughan at Lower Weir (Vaughan), Wairoa at Tourist Road (Wairoa), Okura at Weiti forest (Weiti) and West Hoe at Hall Farm (West Hoe) (Figure 1 and Table 1).

The objectives of the study are to report results to date (up to 31 December 2012) for:

- determining and reporting each of the sites' dominant characteristics;
- the analyses of sediment yields for ten sediment monitoring catchment sites for the period since the site was first established;
- comparing specific sediment yields;
- sediment modelling considerations;
- considerations and approaches to measure the Auckland Plan target which is to reduce sediment yields from 2012 levels by 15% by 2040.

2.0 Background

A sampling programme for sediment monitoring has been designed that is regionally representative and stratified by geology, climate and land cover (Hicks *et al.* 2009a). Sites for sediment monitoring have been selected on the basis of the latter, and the duration that the site is monitored depends on the number of events sampled and the site type. Typically, this could take between 2-10 years depending on the site. Reference sites are established for long term monitoring to determine background yields, those uninfluenced by anthropogenic activity. There are four types of sites for various monitoring purposes:

- Calibration/baseline – requires relatively uniform catchment land use; small catchments; short term duration; monitoring event sediment yields. Kaukapakapa is the only calibration site. While the Kaukapakapa site is a relatively large site (62km $^{2)}$, it was suggested as a priority calibration site in the sediment monitoring plan (Hicks *et al.* 2009a) by virtue of its Northland Allochthon terrane to provide broader lithological variation for the region.

- Validation – requires large catchments; medium term duration; annual and mean annual data. These sites currently have sediment management schemes in place, and/or deliver sediment to sensitive coastal environments. Validation sites include Hoteo, Kaipara, Mangemangeroa, Orewa, Vaughan and Wairoa.

- Reference – requires catchments that are relatively pristine and are expected to remain so, with no significant development or land use change planned; uniform lithology and land cover; ongoing sediment yield monitoring. West Hoe is the only reference site which was recently established in 2012.

- Compliance – requires typically small catchments subject to development or activity requiring resource consent/ permitted activity, often with mitigation measures in place (such as sediment retention ponds). Awanohi and Weiti are categorised as compliance sites.

The basis for developing the regional picture would be a spatially-distributed sediment yield model that would be responsive to rainfall, land cover and erosion treatment measures. Monitoring is undertaken to service a sediment yield model and its predictions in time. It is proposed that monitoring is split between tactical (short term monitoring at small uniform catchments focusing on filling gaps in current land use-lithology knowledge) and strategic objectives (long-term monitoring at key receiving environments and measuring sediment yields from larger mixed use catchments). The calibration and validation sites are selected to provide calibration and validation data for the intended sediment regional yield model. The calibration sites will also provide baseline data for catchments and the latter validate the effectiveness of sediment management policies.

3.0 Materials and methods

3.1 Data collected for sediment yield analysis

3.1.1 Automatic sampling

Automatic water samplers (ISCO model 3700s) are set up at each site. These samplers operate in a flow-proportional manner, triggered during storm events to collect one sample per bottle or to composite eight sub-samples per bottle (24 bottles in an ISCO sampler). The latter is known as 'composite sampling' and allows greater resolution through storm events. Except for the Hoteo, Weiti and West Hoe catchments, all sites are set up to collect composite samples. The trigger is set to capture sediment yield during storm events, when the bulk of suspended sediment is generated (Basher *et al.* 2011). The trigger is site specific and is based on winter thresholds. For the purposes of this report, an event has been defined as a storm event whereby the flow reaches the trigger level and triggers the ISCO to automatically sample suspended sediment. Once triggered, an ISCO is set up to sample based on a certain volume of flow accumulation, with more regular samples occurring at the peak of the event when the flow is greater and flow accumulation is quicker. When the flow or water level drops below the trigger the ISCO stops sampling which marks the end of the event. This process is automated and run by the datalogger on site. The Research, Investigations and Monitoring Unit (RIMU) staff can remotely monitor this through RIMU's in-house telemetry system. The amount of flow between samples also varies depending on the site and is set so the whole event will be well sampled (Appendix A).

3.1.2 Suspended sediment laboratory methods

The sediment samples are sent to an ISO (International Organisation for Standardisation) accredited laboratory for analysis, allowing reliable quality control on data. Samples are analysed for Total Suspended Sediment (TSS) (APHA 2005 2540 D, E Method) and Suspended Sediment Concentration (SSC) (APHA 2005 2540 D Method).

The total suspended sediment (TSS) laboratory method was originally used to quantify sediment concentration from samples collected from catchments in Auckland. Briefly, this involved stirring and pipetting a shaken sub-sample from the original sample and passing it through a glass-fibre filter. While this sub-sample represents a surrogate for the larger sample and is a commonly practiced laboratory method, it can under estimate coarser particles that quickly settle out of suspension and do not get captured in the pipette. It therefore potentially under- (or over-) estimates the true suspended sediment concentrations (SSC) of the full sample depending on the sediment size grade (Guo 2006). Consequently, in 2012 all sites, except for the Hoteo, were converted to analyse for suspended sediment concentration (SSC) whereby the whole sample is shaken and used. A second auto sampler was installed at the Hoteo site in September 2012 to analyse SSC but for the purposes of this report TSS will only be reported for this site. Furthermore, while both SSC and TSS is being analysed at the West Hoe site, a TSS and turbidity relationship was used to develop the site's rating which will be discussed in more detail in the next section. A TSS and SSC relationship was developed for sites to covert previous TSS data to SSC data (Appendix B).

Manual sediment gaugings are undertaken at sites during storm events to determine how representative the bank-side concentration sampled by the ISCO auto samplers is of the cross-section mean sediment concentration, i.e. Cmean/Cpoint. If Cmean/Cpoint=1, it infers good mixing. The sediment gaugings are used to calculate the Cmean/Cpoint ratio which is subsequently used to correct the SSC value from the laboratory (Appendix C). More gaugings better refine the factorial standard error of the estimate of the relationship, and an acceptable value is generally a factor of 1.25 (Hicks 2011). For the purposes of this report, SSC data has not been corrected using the Cmean/Cpoint relation because of too few gaugings to date. Thus the assumption is that Cmean/Cpoint = 1.

3.1.3 Sediment rating

A sediment rating was developed for each site to correct for gaps in the auto-sampled record. These gaps appear for various reasons including when a sampler runs out of bottles or may malfunction. These gaps have been filled using event yield vs peak discharge ratings. This requires the yield from the un-sampled event to be estimated using a rating based on data from identified well-developed/sampled events. Individual storm events were assessed to determine whether they were well sampled by examining their hydrographs using the continuous water level data collected by RIMU, managed in accordance with ISO 9001, and stored in RIMU's HYDSTRA Time-series Database. When the bottles were sampled over the majority of the quickflow portion of the event, the event was then deemed to be well sampled. Quickflow is the fast moving discharge that flows through a catchment during a storm event. We also used the split between the baseflow and quickflow portion of the hydrograph to determine if an event had single or multiple peaks. Single peak events were primarily used for the rating while both single and multi-peak events were used to calculate total yield per event.

Ratings for each site appear in Appendix D. All sites have been calculated using this method except for:

- West Hoe: whereby a TSS and turbidity relationship was developed due to the poor number of samples. Although SSC is also being analysed for the site, the rating appeared more sensible using this relationship than the SSC- turbidity rating. The SSC data will be used in time once more events are captured and the site becomes better established.
- Weiti: whereby prior to 03/2012 a rating between event yield and event runoff was utilized (Hoyle 2012).

Errors in the rating-derived event yields were based on the standard error of the estimate of the ratings.

The error in the yield induced by this event-infilling is accumulated over the record period by the root-sum-square approach. This gives the error in tonnes for the total yield over all events (t). Dividing this by the total estimated yield (t) gives an overall % error. The % estimate error in rating-estimated yield is presented for each site in Appendix D.

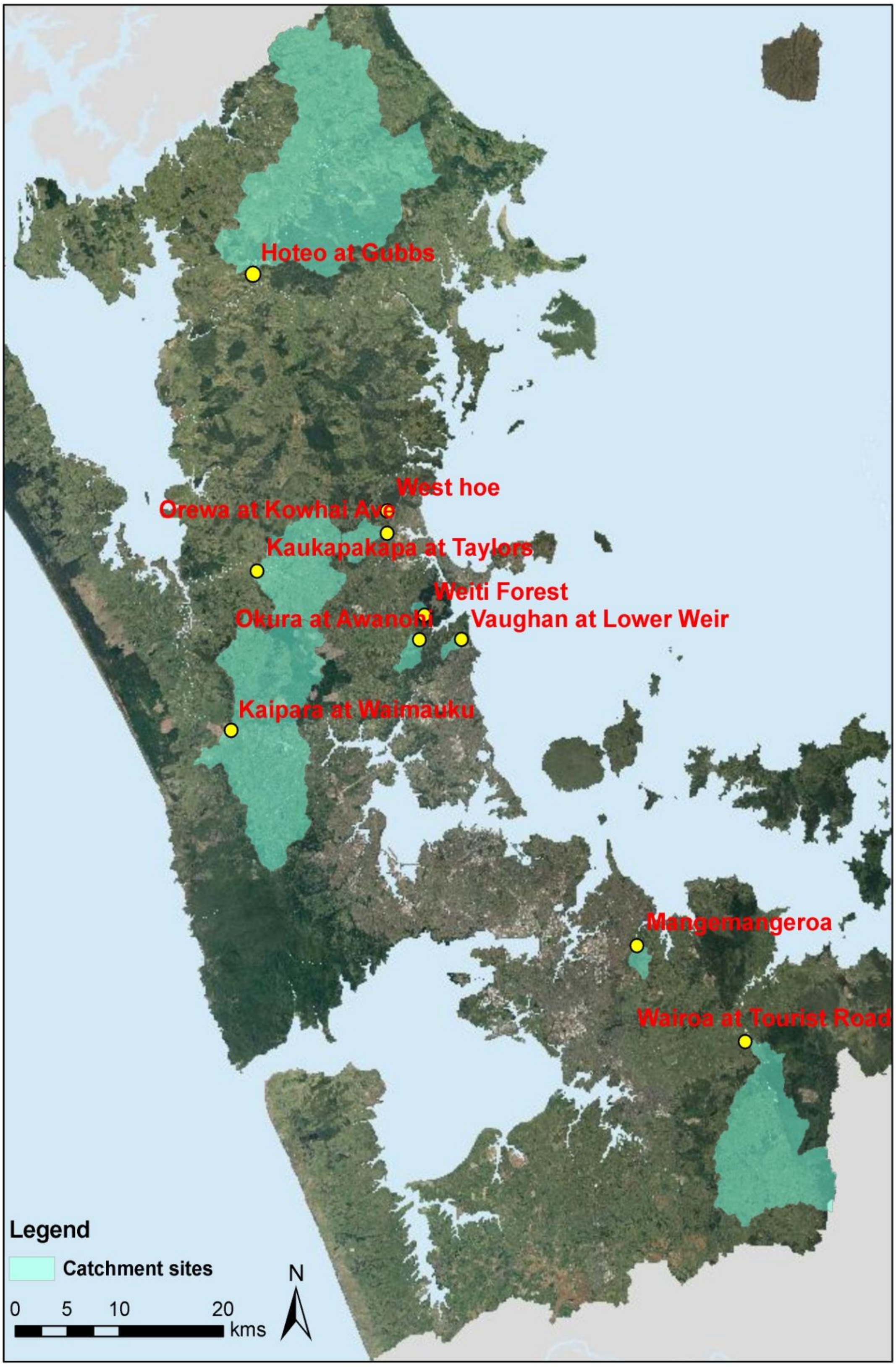

Figure 1. Distribution of the ten sediment monitoring catchment sites across Auckland. Yellow circles indicate the exact location of the sediment stations per site.

Table 1. Site name, number and coordinates.

Site name	Site number	NZTM Easting	NZTM Northing
Okura at Awanohi	7502	1751391	5938700
Hoteo at Gubbs	45703	1735424	5972357
Kaipara at Waimauku	45311	1733345	5930348
Kaukapakapa at Taylors	45415	1735809	5945031
Mangemangeroa at Craigs	8304	1772261	5910514
Orewa at Kowhai Ave	7202	1748295	5948502
Vaughan at Lower Weir	7506	1755422	5938731
Wairoa at Tourist Road	8516	1782663	5901676
Okura at Weiti Forest	7505	1751872	5940969
West Hoe at Hall Farm	7206	1748302	5950580

3.2 Catchment characteristics

ArcGIS software was used to calculate catchment area and boundary, and was also used to determine the catchments' dominant characteristics including land cover, slope (Table 2), geology and Soil Order. Briefly, a union was created for catchment boundary against land cover, slope, geology and soil layers which was then dissolved and geometry calculated for the given catchment (Table 3). Mean annual rainfall (Figure 2 and Table 3) and runoff data (Table 3) were extracted from telemetered hydrological monitoring stations set up across the region and information determined for corresponding sites. As per Hicks (2009b), mean annual runoff was calculated based on mean annual discharge over the period of the flow record, divided by the catchment area and multiplied by the number of seconds in a year. This is then multiplied by 1000 to give runoff in mm/yr. A summary of the dominant site specific characteristics is presented in Table 3.

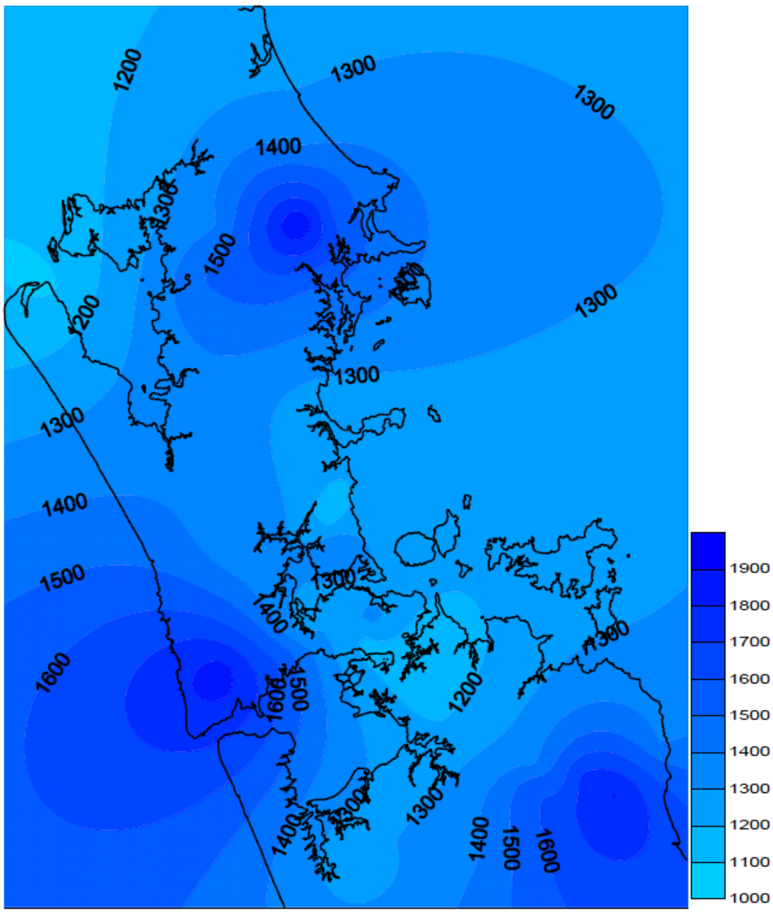

Figure 2. Mean annual rainfall (mm) patterns across the Auckland region (data generated from over 60 rainfall sites using RIMU automatic rain gauge network, Metservice and Watercare Laboratory Services datasets).

Soil Order, slope and land cover information were determined from the appropriate layers in the Land Resource Inventory (LRI) (NZLRI 2010a; b; c). Soil Order is the most generalised level of soil classification, and there are a total of 15 Soil Orders in New Zealand (Hewitt 1998). Soil Orders can be broken down further into 73 groups and 272 sub groups demonstrating the diversity of soils that can stem from Soil Order. According to the Fundamental Soil Layer (FSL), Ultic soils are the most dominant Soil Order in Auckland representing about 38-40% total area following by Granular soil representing 17% of total area. Geology data was sourced from GNS.

The land cover database version 3 (LCDBv3), which is based on 2008 aerial photography, was used to derive surrounding land cover information and data for each site.

Slope is broken into seven groups and is summarised in Table 2. More site specific soil, slope and land cover detail is described for individual sites in the results section and in Figures 13 and 14.

Table 2. Slope description adapted from Lynn et al (2009).

Slope group	Slope	Description
A	0-3degree	Flat to gently undulating
B	4-7 degree	Undulating
C	8-15degree	Rolling
D	16-20degree	Strongly rolling
E	21-25degree	Moderately steep
F	26-35degree	Steep
G	>35 degree	Very Steep

Table 3. Summary of catchment characteristics.

Characteristic	Site name									
	Awanohi	Hoteo	Kaipara	Kaukapakapa	Mangemangeroa	Orewa	Vaughan	Wairoa	Weiti	West Hoe
Catchment size (km^2)	5.5	268	163	62	4.5	9.7	2.3	114	1.7	0.5
Geology	Waitemata (75%) Mudstone (22%) Limestone (2%) Alluvium (1%)	Waitemata (77%) Mudstone (8%) Alluvium (8%) Limestone (6%) Greywacke (<1%)	Waitemata (45%) Alluvium (34%) Sand/sand dune 10% Conglomerate (9%) Mudstone (2%)	Mudstone (33%) Waitemata (25%) Alluvium (23%) Conglomerate (16%) Limestone (3%)	Waitemata (100%)	Mudstone (50%) Waitemata (26%) Alluvium (23%) Limestone (1%)	Waitemata (97%) Limestone (3%)	Greywacke (58%) Waitemata (33%) Alluvium (6%) Mudstone (2%)	Mudstone (51%) Limestone (42%) Waitemata (4%) Greywacke (3%)	Waitemata (100%)
Land cover										
Indigenous vegetation	60%	21%	10%	13%	37%	14%	27%	23%	2%	97%
Pasture	33%	56%	60%	80%	56%	83%	61%	63%	13%	3%
Exotic vegetation	7%	23%	23%	6%	6%	3%	6%	14%	84%	
Other[1]		<0.5%	7%	1%	<2%	<1%	6%			
Soil Order[2] (most dominant)	Ultic (97%) Gley (3%)	Ultic (75%) Recent (16%)	Ultic (43%) Allophanic (25%)	Ultic (74%) Allophanic (13%)	Ultic (100%)	Ultic (89%) Gley (11%)	Ultic (90%) Organic (8%)	Granular (36%) Ultic (28%)	Ultic (100%)	Ultic (100%)
Slope[3] (most dominant)	Moderately steep (61%)	Moderately steep (44%)	Rolling (35%)	Rolling (39%)	Strongly rolling (51%)	Rolling 52%	Strongly rolling (53%)	Moderately steep (29%)	Rolling (51%)	Moderately steep (74%)
Mean annual rainfall (mm/yr)	1330	1387	1278	1283	1210	1232	1067	1413	1330	1232
Mean annual runoff (mm/yr)	436	659	567	651	344	547	508	731	316	536

[1] Other includes cropland, orchard, built up area, urban parkland, surface mine and lake/pond.
[2] Full breakdown of Soil Orders described for individual sites in the results section.
[3] Full breakdown of slopes for individual sites is illustrated in Figure 13.

4.0 Results for individual catchments

4.1 Awanohi

Awanohi catchment is 5.5km^2 and is predominately covered in indigenous vegetation followed by pasture and exotic land (Table 3). Soils mapped in the catchment include Soil Orders Ultic (97%) and Gley (3%). The majority (61%) of the catchment is on slopes of 21-25 degrees and is defined as moderately steep. Nineteen percent of the area has been mapped as rolling land, 18% strongly rolling and 3% flat to undulating. Awanohi is a compliance sediment monitoring site.

A sediment yield summary for the Awanohi catchment is presented in Table 5 (which will appear in each section for all of the sites except West Hoe). Below is an example of how this information is presented and how it should be interpreted:

Example sediment summary and interpretation:

Description	Value (unit)
1. Total sediment across all events	t
2. Total sediment across sampled events	t
3. Total predicted sediment using rating	t
4. Error of predicted sediment yield	t
5. % total error of predicted sediment yield	%
6. % total sediment yield sampled	%
7. Length of record	yr
8. Catchment area	km^2
9. Specific sediment yield	t/km^2/yr
10. Yield trend	t/day
11. Specific yield trend	t/km^2/yr

1. Interpreted as total sediment yield for the site.
2. Sediment yield sampled by the automatic ISCO sediment sampler.
3. Sediment yield predicted for unsampled events via the rating.
4. The error indicates how reliable the rating predicted yield is. Briefly, the error on each rating predicting event yield is the factorial standard error of the rating function (expressed as a %) multiplied by the event's yield predicted from the rating. The total error for the site from all predicted events is accumulated using the RMS method.
5. Proportional error (%) on the total yield (sampled + predicted).
6. Proportion (%) of total sediment yield sampled (the residual % is that needing to be predicted using the rating). This indicates the performance of the auto-sampling.
7. Length of sediment record.
8. Catchment area.
9. Specific sediment yield (SSY) - this value should be the used when comparing across sites.
10. The trend-based yield result (t/day) taken from the cumulative yield plot for each site is an alternative yield estimate that is less sensitive to the events at the start and end of the record i.e. it provides a result less sensitive to the dominant/bounding events. Cumulative yield plots have

been presented to illustrate inter-annual variability in yield, i.e. the influence one (or multiple) dominant event(s) can have on annual yield and SSY.

11. Specific yield trend (t/km^2/yr) is an estimate of the SSY using the yield trend.

It should also be noted that for several sites, when calculating yield, the time span taken covered the full period of observation, which is often longer than the time span between the first and last events.

At Awanohi, the observation period spans from 01/01/2009 to 31/12/2012 (i.e. four years), but the time span between the first and last events was shorter. Event sediment yields were calculated for the 128 events occurring throughout the 4 year duration of sediment monitoring in the Awanohi catchment. The total sediment yield from storm events over the monitoring period was 1062 t (Tables 4 and 5), equating to a specific sediment yield of 48.3 t/km^2/year.

Table 4. Event sediment yields for the Awanohi catchment between 01/01/2009-31/12/2012.

Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)
1*	20/02/2009	1.3	44	4/08/2010	3.3	87*	10/10/2011	1.3
2*	28/02/2009	6.1	45	7/08/2010	2.4	88*	13/10/2011	16.3
3*	6/03/2009	5.5	46	14/08/2010	5.2	89*	17/10/2011	7.2
4*	9/05/2009	0.9	47	20/08/2010	7.5	90*	1/11/2011	6.3
5*	10/05/2009	2.5	48	25/08/2010	6.3	91*	15/12/2011	11.5
6*	11/05/2009	1.0	49*	7/09/2010	4.0	92*	29/12/2011	7.2
7*	25/05/2009	1.2	50*	11/09/2010	3.9	93*	7/01/2012	2.3
8*	9/06/2009	7.5	51*	16/09/2010	5.2	94*	15/02/2012	3.2
9*	12/06/2009	2.2	52*	17/09/2010	3.2	95*	11/03/2012	3.6
10*	14/06/2009	3.9	53*	22/09/2010	1.4	96*	19/03/2012	27.0
11*	28/06/2009	5.3	54*	19/12/2010	5.1	97*	25/03/2012	1.2
12*	29/06/2009	5.1	55	23/01/2011	23.5	98*	8/05/2012	4.1
13	30/06/2009	5.2	56*	28/01/2011	75.7	99*	14/05/2012	1.2
14	11/07/2009	14.9	57	21/03/2011	33.0	100*	15/05/2012	1.4
15	17/07/2009	9.3	58*	26/03/2011	2.9	101*	16/05/2012	2.3
16*	24/07/2009	1.4	59*	16/04/2011	1.9	102*	16/05/2012	1.0
17*	1/08/2009	1.2	60	25/04/2011	63.9	103*	16/05/2012	1.0
18*	14/08/2009	2.8	61*	2/05/2011	0.9	104*	7/06/2012	1.5
19*	15/08/2009	0.9	62*	2/05/2011	2.6	105*	26/06/2012	1.5
20*	15/08/2009	0.9	63	3/05/2011	54.1	106*	28/06/2012	1.0
21*	16/08/2009	1.0	64	7/05/2011	4.7	107*	3/07/2012	1.1
22*	26/08/2009	2.4	65*	11/05/2011	4.5	108*	3/07/2012	34.7
23*	30/08/2009	1.3	66*	26/05/2011	10.1	109*	4/07/2012	0.9
24*	30/08/2009	2.4	67*	4/06/2011	1.9	110*	16/07/2012	2.5
25*	24/09/2009	1.1	68*	10/06/2011	10.5	111*	17/07/2012	1.1
26*	26/09/2009	5.2	69*	17/06/2011	11.9	112*	22/07/2012	24.1
27*	29/09/2009	28.2	70*	19/06/2011	1.2	113*	24/07/2012	1.1
28	3/10/2009	1.1	71*	20/06/2011	3.4	114*	25/07/2012	1.1
29	15/10/2009	16.9	72*	24/06/2011	1.7	115*	29/07/2012	52.6
30	4/12/2009	87.5	73*	25/06/2011	2.8	116	8/08/2012	19.8
31	21/05/2010	13.7	74*	25/06/2011	5.0	117*	17/08/2012	1.4
32*	24/05/2010	6.9	75*	28/06/2011	2.1	118*	18/08/2012	2.0
33*	26/05/2010	1.3	76*	8/07/2011	5.0	119*	19/08/2012	1.1
34	28/05/2010	3.3	77*	9/07/2011	1.0	120*	19/08/2012	6.1
35	1/06/2010	11.1	78*	12/07/2011	2.1	121*	21/08/2012	1.6
36*	7/06/2010	2.0	79*	14/07/2011	3.4	122*	23/08/2012	2.0
37*	13/06/2010	1.9	80*	21/07/2011	7.4	123*	24/08/2012	0.9
38	25/06/2010	6.3	81*	22/07/2011	27.9	124*	25/08/2012	0.9
39*	30/06/2010	1.2	82*	11/08/2011	11.9	125*	3/09/2012	26.3
40*	4/07/2010	11.5	83*	12/08/2011	0.9	126*	12/09/2012	1.4
41*	16/07/2010	1.6	84*	15/08/2011	1.6	127*	15/09/2012	3.7
42	21/07/2010	51.3	85*	11/09/2011	1.7	128*	6/12/2012	2.5
43*	2/08/2010	2.4	86*	13/09/2011	1.6			

* denotes missing events which are predicted based on the event peak flow rating.

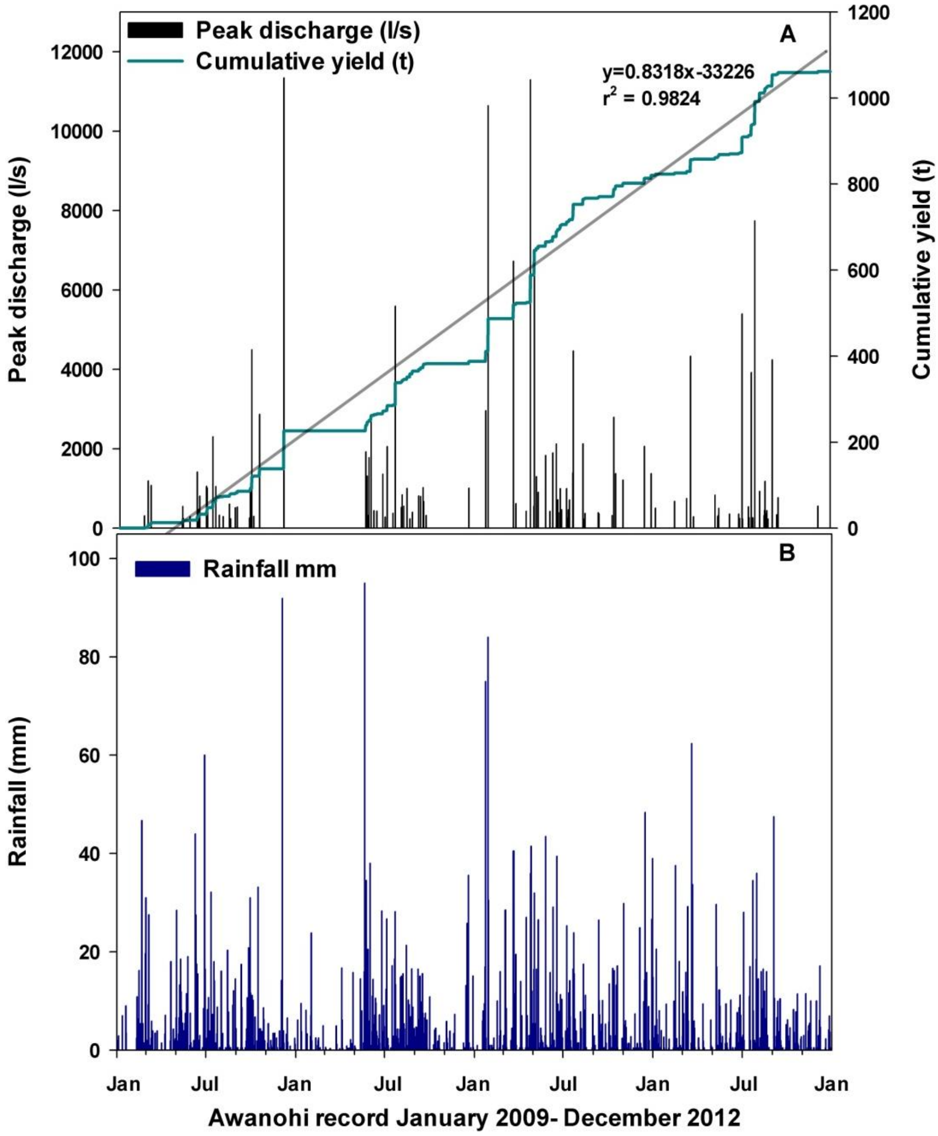

Figure 3. Cumulative sediment yields and peak discharge (A) and rainfall (B) for the Awanohi sediment monitoring record from January 2009-December 2012. The slope of the cumulative curve (units t/day) provides the Yield trend value in Table 5.

Table 5. Sediment yield summary for the Awanohi catchment.

Description	Value (unit)
Total sediment across all events	1062 t
Total sediment across sampled events	445 t
Total predicted sediment using rating	617 t
Error of predicted sediment yield	57 t
% total error of predicted sediment yield	5 %
% total sediment yield sampled	42 %
Length of record	4 yr
Catchment area	5.5 km^2
Specific sediment yield	48.3 $t/km^2/yr$
Yield trend	0.8 t/day
Specific yield trend	55.2 $t/km^2/yr$

4.2 Hoteo

The Hoteo catchment (268 km^2) is predominantly pastoral land overlaying Waitemata rock (Table 3). Dominant soil types include Ultic (75%) and Recent (16%) Soil Orders with pockets of Granular (4%), Allophanic (3%), Gley (1%) and Brown soils (1%). The Hoteo is predominantly moderately steep (44%) with the full slope breakdown illustrated in Figure 13. The Hoteo site has been selected as a validation site.

The sediment record at Hoteo spans from May 2010 to December 2012, hence a record of 2.6 years. Event sediment yields were calculated for 48 events occurring over this 2.6 year period (Table 6 and Figure 4). The total sediment yield from storm events over the monitoring period was 51748 t, equating to a specific sediment yield of 74.27 t/km^2/year (Tables 6 and 7).

It should also be noted that the sediment record of 2.6 years at the Hoteo catchment captures sediment yield for three winters and two summers. Considering that the majority of the sediment load occurs during the winter and early spring period (Basher *et al.* 2011; Hicks *et al.* 2011; McDowell and Srinivasan 2009; Srinivasan and McDowell 2009), the predominance of winter captured at this site could potentially over-estimate the sediment yield. To avoid skewing the data the SSY was also calculated for the two complete physical years (2011-12) which yielded a SSY of 78.8 t/km^2/yr. This figure is more than that calculated for the complete sediment record for the site and suggests that the summer storm event in January 2011 (event 17 Table 6) had a dominating influence on sediment yields.

Only 16% of the sediment yield was auto-sampled at the Hoteo catchment (Table 7), and therefore the site had one of the poorest performing auto-samplers, the other being the Vaughan site. The majority of the yield was therefore derived from the rating. Furthermore, the largest event occurring across the entire record between 23-31/01/2011, when the peak discharge (Qpeak) was recorded as 306 m^3/s (Figure 4), was unsampled. The ISCO failed to sample because the event was so large it uplifted the ISCO which was top heavy and therefore tipped and spilled the bottles. Such an event has a 1:25 year return period based on flow (Appendix E1). The Qpeak recorded for this event is much larger than the largest Qpeak used to compile the rating (112 m^3/s) so for the higher flows the rating accuracy is unknown. This can potentially over- or under-estimate the site's annual yield and SSY.

Table 6. Event sediment yields for the Hoteo catchment between 21/05/2010-31/12/2012.

Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)
1*	21/05/2010	1284.57	17*	28/01/2011	22395.09	33*	15/12/2011	508.47
2*	24/05/2010	844.67	18*	22/03/2011	387.23	34*	30/12/2011	919.65
3*	28/05/2010	430.03	19*	26/03/2011	638.60	35	19/03/2012	2490.21
4*	1/06/2010	1065.64	20*	26/04/2011	155.65	36*	9/05/2012	205.13
5*	13/06/2010	141.44	21	2/05/2011	464.50	37*	3/07/2012	982.64
6	26/06/2010	92.99	22	12/05/2011	91.20	38*	22/07/2012	1655.49
7	5/07/2010	1784.56	23	26/05/2011	1215.06	39*	26/07/2012	320.04
8*	22/07/2010	1316.13	24	5/06/2011	21.03	40*	30/07/2012	1055.47
9*	4/08/2010	389.55	25*	18/06/2011	149.35	41*	2/08/2012	835.60
10*	8/08/2010	184.70	26	26/06/2011	668.93	42*	4/08/2012	128.66
11*	14/08/2010	527.62	27	29/06/2011	272.06	43*	5/08/2012	122.14
12*	26/08/2010	348.51	28*	14/07/2011	348.51	44*	5/08/2012	156.05
13*	7/09/2010	195.00	29	22/07/2011	806.81	45*	9/08/2012	279.66
14*	16/09/2010	252.11	30*	11/10/2011	159.85	46*	12/08/2012	935.02
15*	19/12/2010	667.74	31*	12/10/2011	394.54	47*	3/09/2012	1858.81
16*	23/01/2011	1109.18	32	20/10/2011	295.02	48*	16/09/2012	197.46

* denotes missing events which are predicted based on the event peak flow rating.

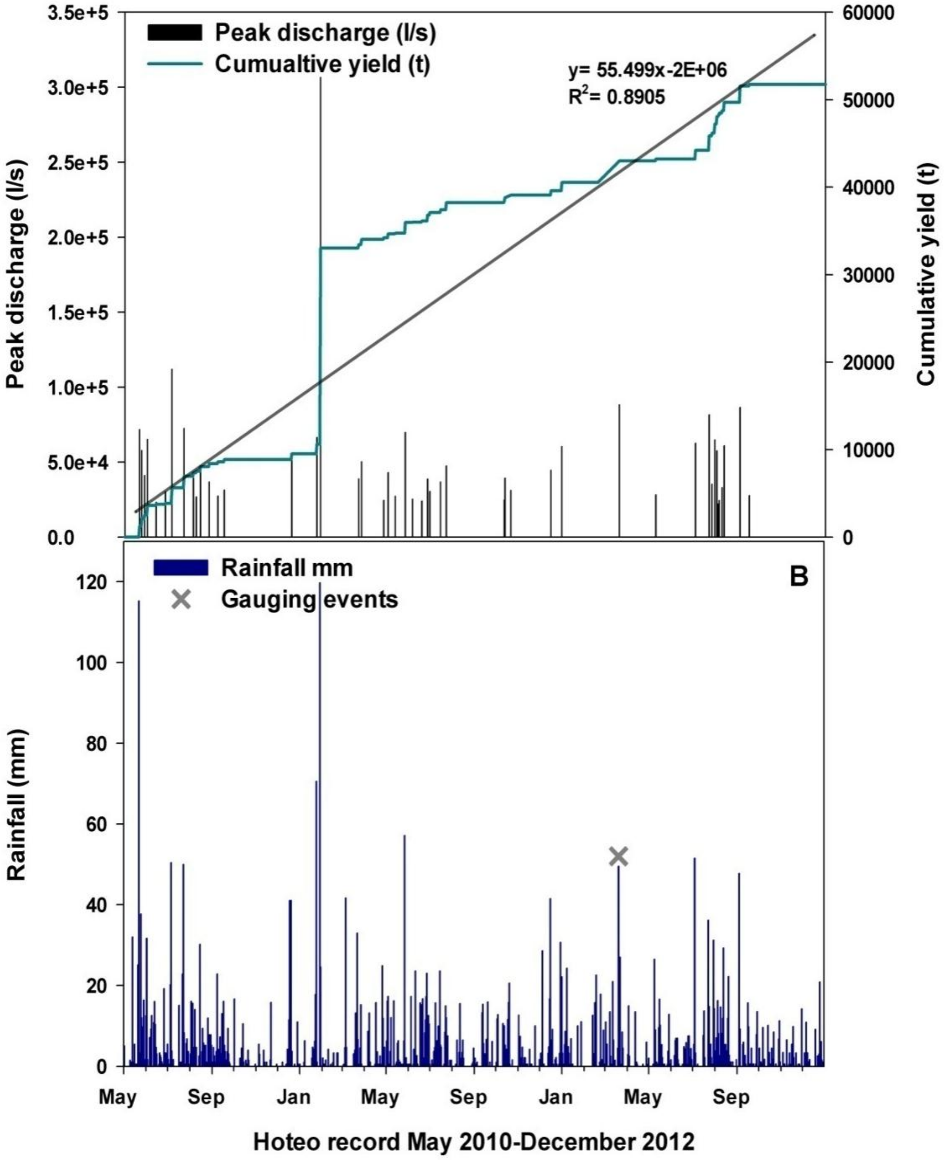

Figure 4. Cumulative sediment yields and peak discharge (A) and rainfall (B) for the Hoteo sediment monitoring record from May 2010-December 2012. Note **X** indicate sediment gauging events.

Table 7. Sediment yield summary for the Hoteo catchment

Description	**Value (unit)**
Total sediment across all events	51748 t
Total sediment across sampled events	8202 t
Total predicted sediment using rating	43546 t
Error of predicted sediment yield	13497 t
% total error of predicted sediment yield	26 %
% total sediment yield sampled	16 %
Length of record	2.6 yr
Catchment area	268 km^2
Specific sediment yield	74.3 $t/km^2/yr$
Yield trend	55.5 t/day
Specific yield trend	75.6 $t/km^2/yr$

4.3 Kaipara

Dominant geology and land cover in the Kaipara catchment include Waitemata Formation and pastoral land, respectively (Table 3). Dominant soils at the site include Ultic and Allophanic representing 43% and 25% total area, respectively, followed by Granular (23%), Gley (5%) and Recent (3%) soils. The Kaipara is predominantly rolling (35%) with the full slope breakdown illustrated in Figure 13. The Kaipara site has been selected as a validation site.

The sediment record at the Kaipara site spans for 1 physical year (01/01/2012-31/12/2012) although no events above the trigger level occurred for the first two and last three months of the year.

Event sediment yields were calculated for the 19 events occurring throughout the 1-year duration of sediment monitoring in the Kaipara catchment (Table 8 and Figure 5). The total sediment yield from storm events over the monitoring period was 5259 t, equating to a specific sediment yield of 32.3 t/km^2/year (Tables 8 and 9).

Table 8. Event sediment yields for the Kaipara catchment between 31/01/2012-31/12/2012.

Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)
1*	12/03/2012	95.79	11	22/07/2012	476.89
2	19/03/2012	593.34	12	30/07/2012	1246.66
3*	25/03/2012	36.68	13	8/08/2012	121.25
4	9/05/2012	65.38	14	12/08/2012	610.44
5*	17/05/2012	33.04	15	15/08/2012	108.16
6*	7/06/2012	43.58	16*	18/08/2012	47.25
7*	25/06/2012	39.74	17	19/08/2012	155.77
8*	28/06/2012	42.32	18*	3/09/2012	266.95
9	3/07/2012	1063.04	19*	16/09/2012	108.17
10*	16/07/2012	104.56			

* denotes missing events which are predicted based on the event peak flow rating.

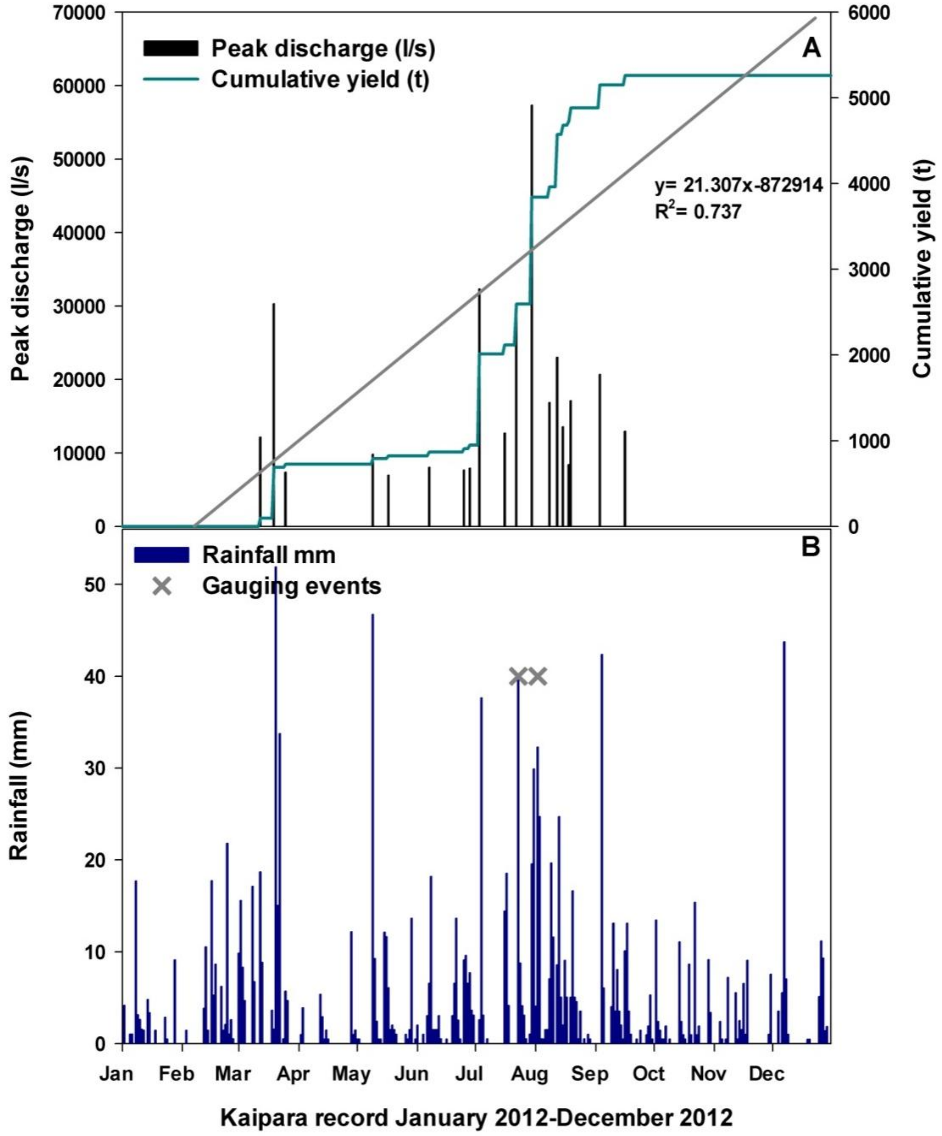

Figure 5. Cumulative sediment yields and peak discharge (A) and rainfall (B) for the Kaipara sediment monitoring record from January 2012-December 2012. Note **X's** indicate sediment gauging events.

Table 9. Sediment yield summary for the Kaipara catchment

Description	Value (unit)
Total sediment across all events	5259 t
Total sediment across sampled events	4440 t
Total predicted sediment using rating	818 t
Error of predicted sediment yield	159 t
% total error of predicted sediment yield	3 %
% total sediment yield sampled	84 %
Length of record	1 yr
Catchment area	163 km^2
Specific sediment yield	32.3 $t/km^2/yr$
Yield trend	21 t/day
Specific yield trend	48 $t/km^2/yr$

4.4 Kaukapakapa

Mudstone and pastoral land are the dominant geology and land cover, respectively, in the Kauakapakapa catchment (Table 3). Dominant soil types at the site include Ultic and Allophanic soils (Table 3) followed by smaller pockets of Recent (10%), Melanic (2%) and Gley (1%) soils. The Kaukapakapa site is predominantly rolling (39%) with the full slope breakdown illustrated in Figure 13. The Kaukapakapa site has been selected as a calibration site.

The sediment record at Kaukapakapa spans from May 2010 to December 2012, hence a record of 2.6 years. However, the last events do not align with the full physical record because there were no events after 16/09/2012. Event sediment yields were calculated for 66 events occurring throughout the 2.6 year duration (21/05/2010- 31/12/2012) of sediment monitoring in the Kaukapakapa catchment (Table 10 and Figure 6). The total sediment yield from storm events over the monitoring period was 12194 t, equating to a specific sediment yield of 76 $t/km^2/year$ (Tables 10 and 11).

Similarly, to the Hoteo catchment the SSY for the two physical years at the Kaukapakapa catchment was calculated in order to avoid skewing the SSY for three winters and two summers captured at this site. The SSY for 2011-12 at this catchment was 69.0 $t/km^2/year$ (Table 10). Therefore, the figure above using a record spanning for 2.6 years is potentially biased towards the contribution of winter sediment yields. This also suggests that the very large storm event in January 2011 did not have such an over-riding influence at the Kaukapakapa catchment as it did at the Hoteo catchment.

Table 10. Event sediment yields for the Kaukapakapa catchment between 21/05/2010-31/12/2012.

Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)
1*	21/05/2010	515.06	23*	22/03/2011	197.94	45	8/03/2012	31.46
2*	24/05/2010	124.58	24*	26/03/2011	29.18	46	12/03/2012	87.11
3*	1/06/2010	226.03	25*	16/04/2011	35.11	47	19/03/2012	295.48
4*	6/06/2010	63.13	26	26/04/2011	46.66	48	21/03/2012	314.30
5*	11/06/2010	78.72	27	2/05/2011	57.09	49	9/05/2012	41.47
6*	25/06/2010	742.56	28	7/05/2011	86.07	50	14/05/2012	78.37
7*	4/07/2010	623.84	29*	26/05/2011	164.13	51*	21/06/2012	20.34
8	16/07/2010	23.76	30*	4/06/2011	47.76	52*	24/06/2012	20.65
9	21/07/2010	527.20	31*	10/06/2011	146.04	53*	26/06/2012	38.67
10	2/08/2010	39.48	32	18/06/2011	288.72	54*	28/06/2012	24.83
11	4/08/2010	97.33	33	10/07/2011	106.07	55	3/07/2012	834.83
12	7/08/2010	70.65	34	21/07/2011	812.66	56	16/07/2012	70.17
13	14/08/2010	100.64	35	11/08/2011	131.94	57	22/07/2012	574.91
14	25/08/2010	176.69	36	13/09/2011	311.85	58*	26/07/2012	25.18
15*	15/09/2010	30.60	37	18/10/2011	221.27	59	30/07/2012	414.48
16*	16/09/2010	60.81	38	15/12/2011	155.72	60	2/08/2012	838.00
17*	21/09/2010	20.14	39	30/12/2011	80.79	61	8/08/2012	70.52
18*	22/09/2010	29.77	40	8/01/2012	38.12	62	11/08/2012	352.28
19*	19/12/2010	35.70	41*	15/02/2012	198.28	63	15/08/2012	77.95
20*	23/01/2011	64.29	42*	16/02/2012	24.83	64*	23/08/2012	21.36
21	28/01/2011	512.71	43*	17/02/2012	140.87	65*	3/09/2012	385.57
22*	6/03/2011	20.95	44*	23/02/2012	37.49	66*	16/09/2012	32.77

* denotes missing events which are predicted based on the event peak flow rating.

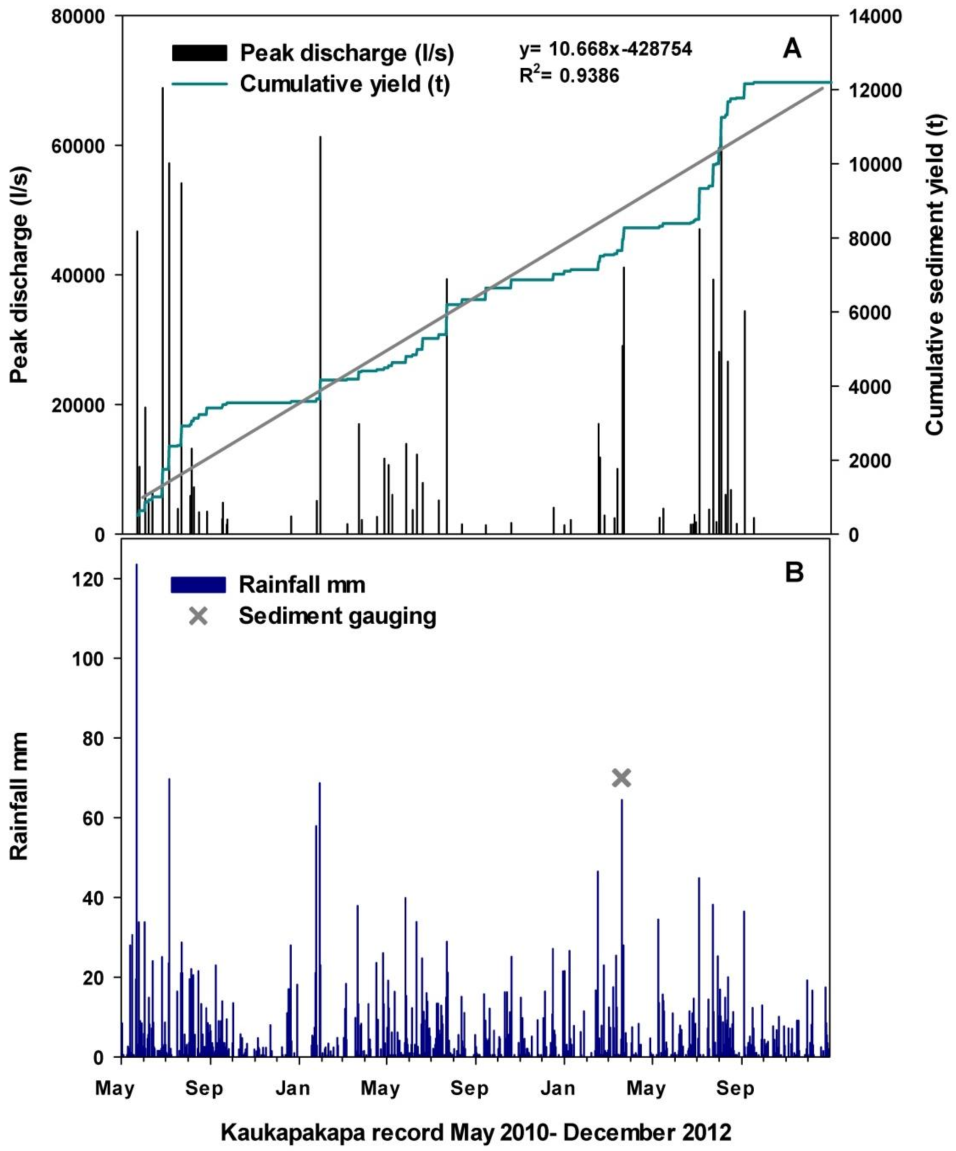

Figure 6. Cumulative sediment yields and peak discharge (A) and rainfall (B) for the Kaukapakapa sediment monitoring record from May 20010-December 2012. Note **X** indicate sediment gauging events.

Table 11. Sediment yield summary for the Kaukapakapa catchment

Description	Value (unit)
Total sediment across all events	12194 t
Total sediment across sampled events	7967 t
Total predicted sediment using rating	4227 t
Error of predicted sediment yield	686 t
% total error of predicted sediment yield	6 %
% total sediment yield sampled	65 %
Length of record	2.6 yr
Catchment area	61.9 km^2
Specific sediment yield	76 $t/km^2/yr$
Yield trend	11 t/day
Specific yield trend	63 $t/km^2/yr$

4.5 Mangemangeroa

Mangemangeroa catchment geology and soils include Waitemata and Ultic, respectively. Dominant land cover includes pasture land followed by indigenous vegetation (Table 3). The majority (51%) of the catchment slopes at 16-20 degrees and is defined as strongly rolling. Forty percent of the area has been mapped as moderately steep and 9% as undulating (Figure 13). The Mangemangeroa site has been selected as a validation site.

The sediment record at Mangemangaroa spans from 01/01/2012 to 31/12/12, and event sediment yields were calculated for 27 events occurring throughout the 1 year duration of sediment monitoring (Table 12 and Figure 7). The total sediment yield from storm events over the monitoring period was 752.4 t, equating to a specific sediment yield of 167.2 t/km^2/year (Tables 12 and 13). The event occurring in 24-26/7/12 (event number 13 Table 12) contributed over one third of the annual yield recorded at this site and such an event has a return period, in terms of flow (m^3/s), of about 1:10 year (Appendix E2). This will be discussed in more detail in the discussion.

Table 12. Event sediment yields for the Mangemangeroa catchment between 01/01/2012 and 31/12/2012.

Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)
1*	15/02/2012	1.93	15	30/07/2012	7.03
2*	15/02/2012	1.42	16	31/07/2012	6.41
3*	28/02/2012	24.98	17	9/08/2012	12.61
4*	19/03/2012	2.88	18	12/08/2012	4.24
5*	21/03/2012	76.35	19	13/08/2012	10.17
6*	8/05/2012	4.16	20	18/08/2012	75.61
7*	9/05/2012	4.67	21	19/08/2012	18.49
8*	7/06/2012	1.84	22	20/08/2012	4.81
9	3/07/2012	24.73	23*	3/09/2012	106.01
10*	15/07/2012	1.54	24*	4/09/2012	3.60
11	16/07/2012	11.54	25*	15/09/2012	7.74
12	22/07/2012	25.14	26*	16/09/2012	24.98
13	24/07/2012	253.30	27*	13/11/2012	2.45
14	29/07/2012	33.75			

* denotes missing events which are predicted based on the event peak flow rating.

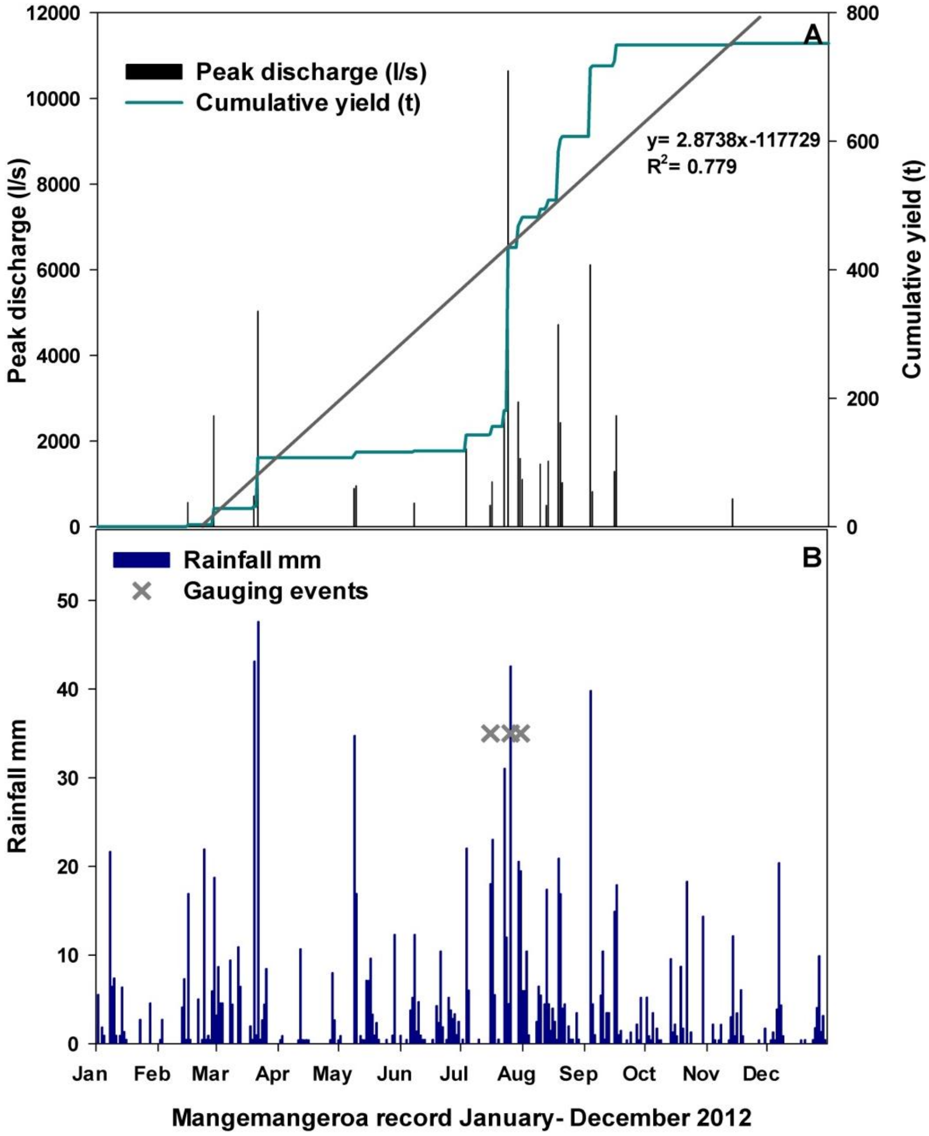

Figure 7. Cumulative sediment yields and peak discharge (A) and rainfall (B) for the Mangemangeroa sediment monitoring record from January-December 2012. Note **X's** indicate sediment gauging events.

Table 13. Sediment yield summary for the Mangemangeroa catchment.

Description	**Value (unit)**
Total sediment across all events	752 t
Total sediment across sampled events	488 t
Total predicted sediment using rating	265 t
Error of predicted sediment yield	41 t
% total error of predicted sediment yield	5 %
% total sediment yield sampled	65 %
Length of record	1 yr
Catchment area	4.5 km^2
Specific sediment yield	167 $t/km^2/yr$
Yield trend	2.9 t/day
Specific yield trend	233 $t/km^2/yr$

4.6 Orewa

Waitemata and pasture are the dominant geology and land cover, respectively, in the Orewa catchment (9.7 km^2), and the dominant soils are Ultic and Gley (Table 3). The majority of the catchment is rolling (52%) followed by strongly rolling (17%), undulating (15%) and flat to undulating (15%) land (Figure 13). The Orewa site has been selected as a validation site.

The sediment record at Orewa spans from 29 June 2009 to 31 December 2012. Event sediment yields were calculated for 90 events occurring throughout the 3.5 year duration of sediment monitoring (Table 14 and Figure 8). The total sediment yield from storm events over the monitoring period was 2721.3 t, equating to a specific sediment yield of 80.2 t/km^2/year (Tables 14 and 15).

The SSY for the Orewa catchment for the three physical years, 2010-12, is 68.0 t/km^2/year (Table 14). Therefore, the figure above using a record spanning for 3.5 years that captures four winters and three summers is potentially biased towards the contribution of winter sediment yields.

Orewa was one of the best sampled sites (the other being Wairoa), sampling 87% of the recorded sediment yield and rendering it an appropriate validation site for the purposes of a spatially-distributed sediment yield model for the region.

Table 14. Event sediment yields for the Orewa catchment between 29/06/2009-31/12/2012,

Event no.	**Event start date**	**Event yield (t)**	**Event no.**	**Event start date**	**Event yield (t)**	**Event no.**	**Event start date**	**Event yield (t)**
1*	29/06/2009	181.16	31	4/07/2010	64.65	61	25/03/2011	2.51
2	5/07/2009	4.07	32*	16/07/2010	4.31	62*	16/04/2011	2.41
3	11/07/2009	38.47	33	21/07/2010	138.57	63	25/04/2011	15.12
4*	15/07/2009	2.68	34*	27/07/2010	0.61	64	2/05/2011	13.46
5*	16/07/2009	0.75	35*	28/07/2010	0.64	65	6/05/2011	5.91
6	17/07/2009	53.15	36	2/08/2010	22.68	66	11/05/2011	6.98
7*	22/07/2009	2.48	37	7/08/2010	11.88	67	16/05/2011	13.37
8*	24/07/2009	0.86	38*	14/08/2010	5.10	68	4/06/2011	2.37
9*	24/07/2009	0.63	39*	18/08/2010	0.66	69	10/06/2011	1.20
10*	1/08/2009	2.15	40*	19/08/2010	0.87	70	18/06/2011	28.51
11*	14/08/2009	10.91	41*	20/08/2010	1.09	71	28/06/2011	35.99
12*	17/08/2009	0.63	42*	21/08/2010	0.77	72*	21/07/2011	1.46
13*	27/08/2009	3.32	43*	22/08/2010	0.65	73	22/07/2011	344.19
14*	31/08/2009	4.77	44*	23/08/2010	0.71	74	19/09/2011	52.07
15*	26/09/2009	3.90	45*	25/08/2010	4.39	75	19/10/2011	2.56
16	29/09/2009	115.74	46*	27/08/2010	3.29	76*	1/11/2011	1.05
17*	3/10/2009	0.95	47*	30/08/2010	2.67	77	15/12/2011	4.26
18*	4/10/2009	1.15	48	7/09/2010	9.96	78	30/12/2011	4.44
19*	5/10/2009	1.29	49*	9/09/2010	0.76	79	15/02/2012	23.83
20*	15/10/2009	21.77	50*	11/09/2010	2.54	80	12/03/2012	1.85
21	4/12/2009	292.56	51*	15/09/2010	1.05	81	19/03/2012	33.78
22	21/05/2010	35.17	52*	16/09/2010	6.00	82	8/05/2012	5.63
23	24/05/2010	2.26	53*	17/09/2010	1.00	83	26/06/2012	198.65
24*	25/05/2010	0.66	54*	22/09/2010	0.88	84*	16/07/2012	1.09
25	26/05/2010	1.70	55*	19/12/2010	3.02	85	22/07/2012	70.24
26	28/05/2010	5.42	56	23/01/2011	7.94	86*	29/07/2012	61.02
27	1/06/2010	16.90	57	28/01/2011	126.64	87	1/08/2012	60.17
28	6/06/2010	3.49	58*	6/03/2011	0.70	88	8/08/2012	35.11
29	25/06/2010	306.72	59*	16/03/2011	1.15	89	19/08/2012	103.39
30*	30/06/2010	2.42	60	21/03/2011	44.54	90	16/09/2012	0.83

* denotes missing events which are predicted based on the event peak flow rating.

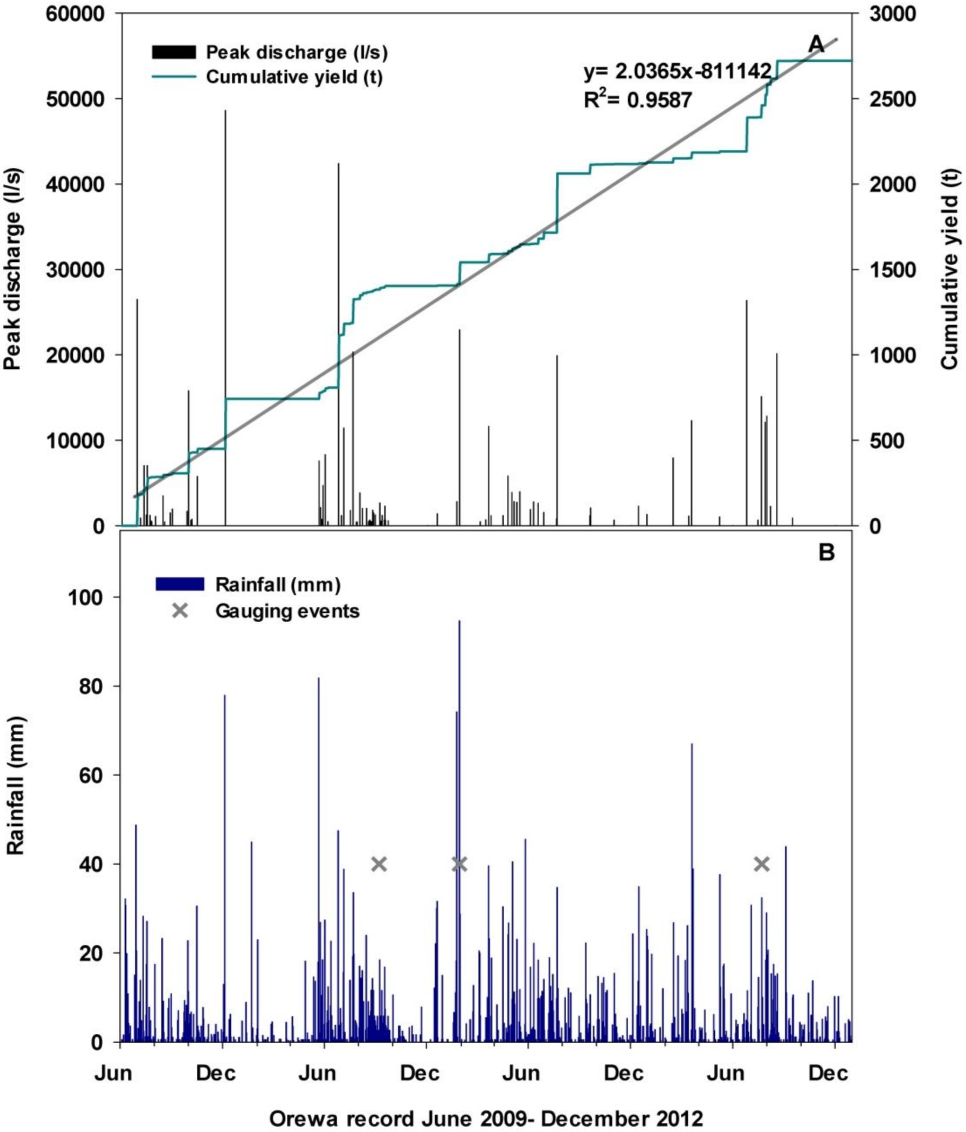

Figure 8. Cumulative sediment yields and peak discharge (A) and rainfall (B) for the Orewa sediment monitoring record from June 2009-December 2012. Note **X's** indicate sediment gauging events.

Table 15. Sediment yield summary for the Orewa catchment.

Description	Value (unit)
Total sediment across all events	2721 t
Total sediment across sampled events	2369 t
Total predicted sediment using rating	352 t
Error of predicted sediment yield	104 t
% total error of predicted sediment yield	4 %
% total sediment yield sampled	87 %
Length of record	3.5 yr
Catchment area	9.7 km^2
Specific sediment yield	80 $t/km^2/yr$
Yield trend	2.0 t/day
Specific yield trend	76 $t/km^2/yr$

4.7 Vaughan

The Vaughan catchment (2.3 km^2) is predominantly Waitemata geology and pastoral land cover (Table 3). A small town makes up 2% of the catchment area. Dominant soils include Ultic and Organic. The Vaughan catchment is predominantly strongly rolling (53%) with the full slope classification illustrated in Figure 13. The Vaughan site has been selected as a validation site.

The sediment record at the Vaughan site spans from June 2003 to December 2012, and it is the longest established site. Event sediment yields were calculated for the 485 events occurring throughout the 9.6 year duration (1/06/2003 - 31/12/2012) of sediment monitoring (Table 16 and Figure 9). The total sediment yield from storm events over the monitoring period was 1077 t, equating to a specific sediment yield of 48.8 t/km^2/year (Tables 16 and 17).

Only 12% of the yield was sampled, with the majority being derived from the rating, indicating a poor performing auto-sampler. However, this is largely due to the auto-sampler only sampling storm-based sediment between 2004-2005 and not again until 2012 onwards (Table 16)

However, the highest Qpeak (17.4 m^3/s recorded on 01/07/2010) used in the rating was not too much larger than the highest sampled Qpeak (9.99 m^3/s recorded on 27/07/2012). Therefore, the rating was not largely extrapolated particularly in contrast to the Hoteo case, whereby the largest Qpeak was substantially larger than the largest sampled Qpeak and substantial rating extrapolation was required.

The specific yield trend is very similar to the specific sediment yield at the Vaughan catchment by virtue of the long record (Table 17). This was also the case for the Hoteo, Orewa, Wairoa and Weiti sites. The cumulative yield plot rises relatively steadily, indicating a stable sediment discharge at the Vaughan (Figure 9). This catchment is currently undergoing extensive housing development, and the future sediment record is expected to show land use change effects on SSY over time.

Table 16. Event sediment yields for the Vaughan catchment between 01/06/2003 and 31/12/2012.

Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)
1	15/06/2003	0.20	163	25/01/2006	1.36	325	14/06/2009	0.24
2	15/06/2003	0.17	164	2/04/2006	0.29	326	28/06/2009	27.27
3	15/06/2003	0.17	165	2/04/2006	0.24	327	4/07/2009	0.22
4	15/06/2003	0.18	166	10/04/2006	0.18	328	6/07/2009	0.28
5	16/06/2003	0.25	167	25/04/2006	6.89	329	6/07/2009	0.42
6	17/06/2003	0.21	168	27/04/2006	22.70	330	11/07/2009	6.88
7	17/06/2003	0.68	169	29/04/2006	0.17	331	15/07/2009	0.20
8	18/06/2003	0.35	170	29/04/2006	4.69	332	17/07/2009	5.98
9	29/06/2003	0.85	171	2/05/2006	0.22	333	19/07/2009	0.17
10	1/07/2003	0.17	172	2/05/2006	0.51	334	24/07/2009	0.21
11	3/07/2003	1.57	173	5/05/2006	0.48	335	1/08/2009	0.40
12	7/07/2003	5.61	174	9/05/2006	0.30	336	14/08/2009	0.29
13	8/07/2003	0.17	175	10/05/2006	0.19	337	15/08/2009	0.17
14	17/07/2003	0.38	176	11/05/2006	0.18	338	16/08/2009	0.17
15	28/07/2003	0.95	177	12/05/2006	0.17	339	26/08/2009	0.84

16	28/07/2003	0.19	178	12/05/2006	0.50	340	31/08/2009	0.34
17	29/07/2003	8.96	179	13/05/2006	0.64	341	26/09/2009	0.18
18	31/07/2003	38.24	180	14/05/2006	0.65	342	26/09/2009	2.74
19	1/08/2003	0.17	181	23/05/2006	0.22	343	29/09/2009	8.30
20	11/08/2003	0.57	182	23/05/2006	5.67	344	1/10/2009	0.20
21	20/08/2003	6.50	183	25/05/2006	0.17	345	3/10/2009	0.31
22	23/08/2003	0.41	184	26/05/2006	7.15	346	4/10/2009	0.17
23	27/08/2003	0.52	185	28/05/2006	0.17	347	4/10/2009	0.17
24	2/09/2003	0.75	186	4/06/2006	1.12	348	5/10/2009	0.28
25	4/09/2003	2.55	187	5/06/2006	0.45	349	15/10/2009	6.49
26	21/09/2003	0.39	188	12/06/2006	0.40	350	4/12/2009	0.20
27	21/09/2003	1.04	189	13/06/2006	0.26	351	4/12/2009	22.85
28	28/09/2003	12.03	190	16/06/2006	0.18	352	1/02/2010	0.32
29	30/09/2003	1.29	191	16/06/2006	1.99	353	27/04/2010	0.18
30	3/10/2003	28.47	192	19/07/2006	1.62	354	21/05/2010	2.73
31	9/10/2003	4.02	193	5/08/2006	8.37	355	24/05/2010	1.20
32	11/10/2003	22.42	194	8/08/2006	0.17	356	28/05/2010	3.62
33	28/10/2003	0.17	195	8/08/2006	0.17	357	1/06/2010	7.58
34	28/10/2003	0.23	196	8/08/2006	0.17	358	6/06/2010	0.22
35	28/10/2003	0.18	197	8/08/2006	0.17	359	7/06/2010	0.22
36	24/11/2003	0.22	198	26/08/2006	0.66	360	7/06/2010	0.30
37	26/11/2003	0.19	199	9/09/2006	4.92	361	13/06/2010	0.61
38	26/11/2003	0.18	200	10/09/2006	0.17	362	14/06/2010	0.18
39	26/11/2003	0.18	201	10/09/2006	0.19	363	25/06/2010	0.49
40	26/11/2003	0.93	202	11/09/2006	6.93	364	30/06/2010	0.21
41	27/11/2003	0.45	203	1/10/2006	13.06	365	5/07/2010	2.08
42	9/12/2003	0.41	204	4/10/2006	0.17	366	16/07/2010	0.29
43	10/12/2003	0.40	205	4/10/2006	0.17	367	21/07/2010	7.78
44	21/01/2004	0.24	206	4/10/2006	0.22	368	23/07/2010	1.91
45	31/01/2004	0.20	207	16/10/2006	0.17	369	2/08/2010	0.76
46	31/01/2004	0.20	208	23/10/2006	1.14	370	4/08/2010	2.33
47	1/02/2004	37.07	209	13/11/2006	0.26	371	7/08/2010	0.83
48	4/02/2004	1.86	210	13/11/2006	0.17	372	9/08/2010	0.23
49	20/02/2004	0.88	211	17/12/2006	0.28	373	13/08/2010	0.19
50	28/02/2004	32.89	212	19/12/2006	0.23	374	13/08/2010	0.18
51	29/04/2004	0.99	213	20/12/2006	0.60	375	13/08/2010	0.19
52	1/05/2004	1.43	214	10/01/2007	0.42	376	14/08/2010	2.50
53	12/05/2004	0.18	215	28/01/2007	0.25	377	19/08/2010	0.19
54	12/05/2004	0.22	216	29/01/2007	0.20	378	20/08/2010	0.66
55*	14/05/2004	17.59	217	12/03/2007	0.23	379	21/08/2010	0.18
56	25/05/2004	0.18	218	29/03/2007	13.63	380	22/08/2010	0.17
57	28/05/2004	0.35	219	10/04/2007	0.19	381	25/08/2010	1.09
58	29/05/2004	0.17	220	28/04/2007	0.22	382	27/08/2010	0.28
59	29/05/2004	0.18	221	30/04/2007	0.22	383	31/08/2010	0.27
60	29/05/2004	0.20	222	1/05/2007	0.17	384	7/09/2010	1.77
61	29/05/2004	0.17	223	1/05/2007	0.17	385	9/09/2010	0.44
62	30/05/2004	0.51	224	20/06/2007	0.21	386	11/09/2010	3.75
63	5/06/2004	0.28	225	22/06/2007	0.30	387	15/09/2010	0.60
64	5/06/2004	0.22	226	29/06/2007	1.03	388	16/09/2010	5.27
65*	18/06/2004	18.00	227	30/06/2007	0.31	389	17/09/2010	0.41
66	21/06/2004	0.17	228	1/07/2007	0.18	390	21/09/2010	0.19
67	21/06/2004	0.17	229	1/07/2007	0.61	391	22/09/2010	0.27
68	21/06/2004	0.53	230	2/07/2007	0.20	392	16/12/2010	0.30
69	27/06/2004	0.64	231	4/07/2007	2.53	393	17/12/2010	0.24
70	2/07/2004	0.63	232	5/07/2007	0.17	394	18/12/2010	0.19
71	3/07/2004	0.17	233	5/07/2007	0.17	395	19/12/2010	1.95
72	3/07/2004	0.17	234	5/07/2007	0.17	396	23/01/2011	8.12
73	6/07/2004	0.24	235	6/07/2007	6.40	397	28/01/2011	29.73
74	6/07/2004	1.29	236	10/07/2007	1.57	398	4/03/2011	0.46
75	8/07/2004	0.17	237	16/07/2007	6.53	399	5/03/2011	0.30
76	15/07/2004	0.17	238	21/07/2007	0.73	400	6/03/2011	0.50
77*	20/07/2004	3.81	239	22/07/2007	0.17	401	21/03/2011	0.17

78	22/07/2004	0.19	240	29/07/2007	10.33	402	21/03/2011	0.19
79	23/07/2004	0.17	241	30/07/2007	0.71	403	21/03/2011	0.18
80	27/07/2004	0.20	242	4/08/2007	0.82	404	21/03/2011	10.74
81	28/07/2004	0.34	243	6/08/2007	0.48	405	22/03/2011	0.17
82	4/08/2004	1.08	244	8/08/2007	0.17	406	26/03/2011	0.31
83	6/08/2004	0.17	245	8/08/2007	0.17	407	16/04/2011	0.92
84	7/08/2004	0.97	246	8/08/2007	0.17	408	25/04/2011	21.79
85	10/08/2004	0.30	247	10/08/2007	0.22	409	27/04/2011	0.17
86	11/08/2004	0.22	248	12/08/2007	0.23	410	27/04/2011	0.17
87	15/08/2004	0.20	249	16/08/2007	31.64	411	27/04/2011	0.17
88	16/08/2004	0.31	250	27/08/2007	1.75	412	27/04/2011	0.18
89	22/08/2004	0.37	251	28/08/2007	0.24	413	27/04/2011	0.17
90	2/09/2004	0.40	252	10/09/2007	0.17	414	27/04/2011	0.17
91	13/09/2004	0.17	253	16/09/2007	3.53	415	27/04/2011	0.17
92	25/09/2004	2.41	254	23/09/2007	0.24	416	27/04/2011	0.17
93	1/10/2004	0.22	255	23/09/2007	0.19	417	28/04/2011	0.21
94	5/10/2004	0.31	256	24/09/2007	0.40	418	2/05/2011	0.33
95*	7/10/2004	9.41	257	25/09/2007	5.13	419	2/05/2011	0.40
96	8/10/2004	0.37	258	1/10/2007	49.89	420	3/05/2011	6.36
97	9/10/2004	0.17	259	5/10/2007	0.31	421	7/05/2011	5.31
98	29/10/2004	1.04	260	13/10/2007	0.67	422	11/05/2011	1.83
99	14/11/2004	0.19	261	15/10/2007	0.24	423	26/05/2011	6.13
100	14/11/2004	0.17	262	17/10/2007	0.32	424	4/06/2011	0.46
101	14/11/2004	0.44	263	6/11/2007	0.18	425	18/06/2011	12.49
102	15/11/2004	0.20	264	6/12/2007	0.29	426	20/06/2011	0.53
103	4/12/2004	0.43	265	6/12/2007	0.17	427	23/06/2011	0.27
104	6/12/2004	0.17	266	6/12/2007	0.18	428	24/06/2011	2.16
105	6/12/2004	0.17	267	23/02/2008	0.45	429	27/06/2011	0.17
106	15/12/2004	0.30	268	15/04/2008	1.18	430	27/06/2011	0.17
107	16/12/2004	0.18	269	29/04/2008	5.03	431	28/06/2011	0.18
108	16/12/2004	0.22	270	1/05/2008	0.75	432	28/06/2011	0.55
109	18/12/2004	0.19	271	4/05/2008	11.54	433	29/06/2011	0.17
110	18/12/2004	0.17	272	9/05/2008	0.19	434	8/07/2011	3.69
111	18/12/2004	0.17	273	26/05/2008	0.47	435	12/07/2011	0.58
112	18/12/2004	0.17	274	26/05/2008	0.17	436	14/07/2011	0.62
113	18/12/2004	0.17	275	8/06/2008	0.22	437	21/07/2011	8.32
114	18/12/2004	0.24	276	16/06/2008	0.47	438	22/07/2011	7.17
115	30/12/2004	0.40	277	22/06/2008	3.88	439	25/07/2011	0.18
116	7/01/2005	0.36	278	23/06/2008	0.18	440	11/08/2011	0.76
117	8/01/2005	0.17	279	24/06/2008	0.28	441	11/08/2011	0.24
118	5/02/2005	0.29	280	25/06/2008	1.25	442	12/08/2011	0.28
119	12/02/2005	0.18	281	27/06/2008	4.50	443	15/08/2011	0.50
120	12/02/2005	0.17	282	4/07/2008	0.17	444	11/09/2011	0.87
121	23/02/2005	0.21	283	4/07/2008	0.23	445	12/09/2011	0.22
122	24/03/2005	0.19	284	5/07/2008	0.82	446	13/09/2011	0.71
123	25/03/2005	0.75	285	7/07/2008	0.17	447	19/09/2011	0.75
124	30/03/2005	0.17	286	7/07/2008	0.17	448	3/10/2011	6.75
125	15/05/2005	0.23	287	17/07/2008	0.33	449	10/10/2011	0.31
126	17/05/2005	0.18	288	19/07/2008	3.05	450	12/10/2011	1.08
127	17/05/2005	0.23	289	20/07/2008	0.26	451	13/10/2011	7.89
128	22/05/2005	0.26	290	20/07/2008	0.17	452	17/10/2011	1.55
129	30/05/2005	0.19	291	20/07/2008	0.17	453	19/10/2011	2.72
130	30/05/2005	0.24	292	20/07/2008	0.30	454	1/11/2011	0.95
131	18/06/2005	0.19	293	22/07/2008	1.28	455	4/12/2011	0.18
132	18/06/2005	0.20	294	25/07/2008	0.17	456	15/12/2011	1.82
133	21/06/2005	0.29	295	26/07/2008	8.23	457	29/12/2011	0.18
134	22/06/2005	0.41	296	28/07/2008	0.17	458	30/12/2011	3.73
135	24/06/2005	2.18	297	28/07/2008	0.17	459	7/01/2012	0.37
136	25/06/2005	0.17	298	28/07/2008	0.17	460	14/02/2012	0.19
137	6/07/2005	6.70	299	29/07/2008	13.83	461	15/02/2012	0.46
138	9/07/2005	0.24	300	4/08/2008	0.17	462	23/02/2012	0.54
139	11/07/2005	0.67	301	9/08/2008	0.47	463	7/03/2012	0.22

140	16/07/2005	4.12	302	12/08/2008	1.62	464	8/03/2012	0.17
141	18/07/2005	0.89	303	13/08/2008	0.79	465	8/03/2012	0.24
142	18/07/2005	0.17	304	14/08/2008	0.51	466	11/03/2012	3.93
143	18/07/2005	0.18	305	15/08/2008	6.84	467	19/03/2012	5.27
144	19/07/2005	0.17	306	17/08/2008	0.19	468	21/03/2012	0.17
145	19/07/2005	0.17	307	17/08/2008	1.00	469	21/03/2012	12.74
146	21/07/2005	0.18	308	19/08/2008	0.23	470	25/03/2012	0.22
147	1/08/2005	0.34	309	19/08/2008	0.17	471	8/05/2012	0.26
148	24/08/2005	0.61	310	19/08/2008	0.17	472	8/05/2012	1.82
149*	18/09/2005	2.17	311	24/08/2008	5.76	473	14/05/2012	0.36
150	23/09/2005	0.17	312	7/10/2008	0.67	474	15/05/2012	0.19
151*	2/10/2005	5.13	313	23/10/2008	0.34	475	16/05/2012	0.33
152*	6/10/2005	2.46	314	24/10/2008	1.98	476	16/05/2012	0.18
153	8/10/2005	0.64	315	25/11/2008	0.17	477	5/06/2012	0.18
154	8/10/2005	0.17	316	23/12/2008	0.50	478	5/06/2012	0.19
155	10/10/2005	0.83	317	20/02/2009	0.76	479	7/06/2012	0.18
156	13/10/2005	0.21	318	28/02/2009	1.07	480	26/06/2012	0.24
157	14/10/2005	1.95	319	6/03/2009	0.42	481	28/06/2012	0.26
158	20/10/2005	6.02	320	2/05/2009	0.17	482*	3/07/2012	28.56
159	22/10/2005	0.17	321	10/05/2009	0.77	483*	27/07/2012	45.44
160	22/10/2005	0.17	322	25/05/2009	0.17	484	2/11/2012	0.40
161	26/11/2005	0.20	323	9/06/2009	5.78	485	7/11/2012	0.44
162	24/01/2006	0.82	324	12/06/2009	0.77			

* denotes those events ISCO sampled

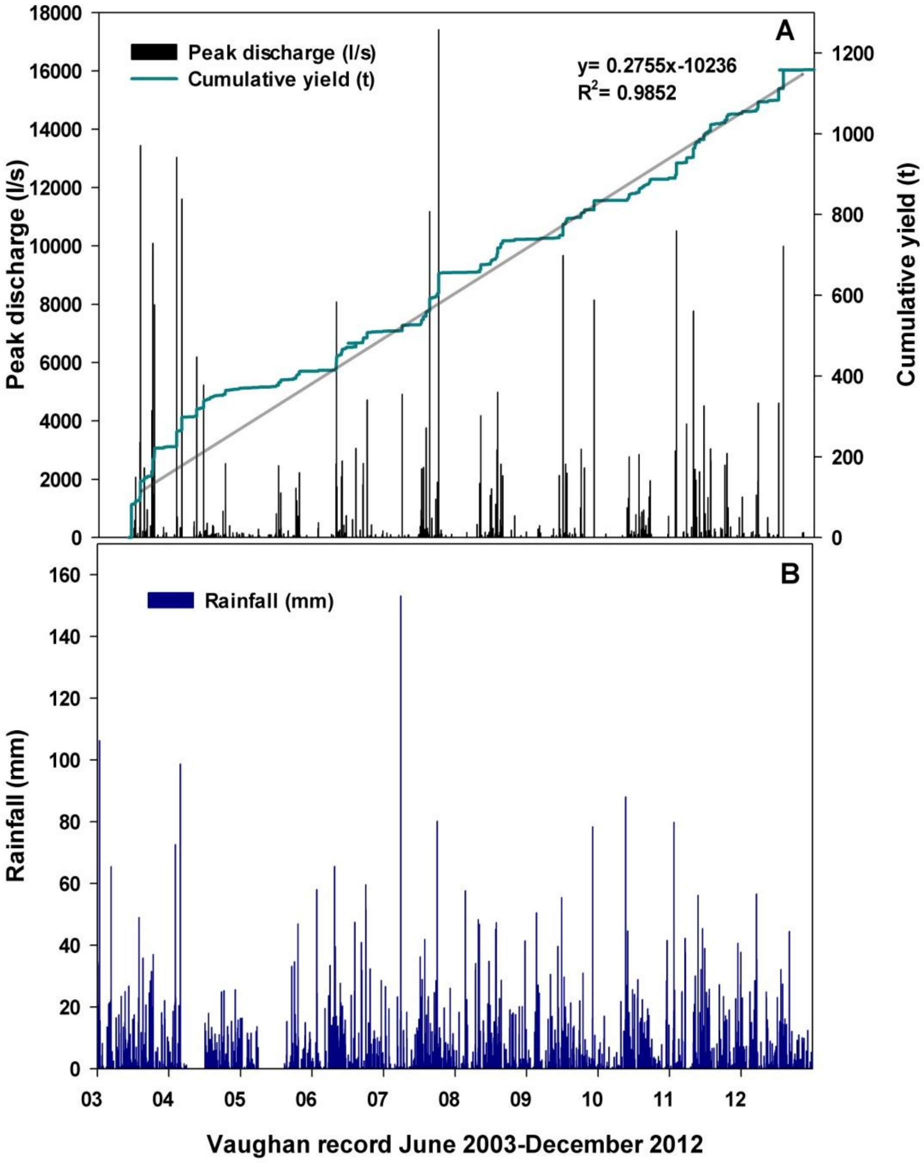

Figure 9. Cumulative sediment yields and peak discharge (A) and rainfall (B) for the Vaughan sediment monitoring record from January 2003-December 2012.

Table 17. Sediment yield summary for the Vaughan catchment

Description	Value (unit)
Total sediment across all events	1077 t
Total sediment across sampled events	133 t
Total predicted sediment using rating	944 t
Error of predicted sediment yield	33 t
% total error of predicted sediment yield	3 %
% total sediment yield sampled	12 %
Length of record	9.6 yr
Catchment area	2.3 km^2
Specific sediment yield	48.8 $t/km^2/yr$
Yield trend	0.3 t/day
Specific yield trend	44 $t/km^2/ yr$

4.8 Wairoa

Greywacke and pasture are the dominant geology and land cover, respectively, in the 114 km^2 Wairoa catchment (Table 3). Dominant soil types include Granular and Ultic (Table 3) followed by pockets of Recent (26%), Brown (6%), Allophanic (3%), Gley (1%) and Organic (1%) soils. The Wairoa catchment is predominantly steep and the full slope breakdown is illustrated in Figure 13. The Wairoa site has been selected as a validation site. In historic reports, it has been reported that the Wairoa catchment size was 150 km^2. In the current study, the dams in the bottom of the catchment have been excluded and the catchment area has been recalculated as 114 km^2whereby.

The sediment record at the Wairoa site spans from May 2010 to December 2012. Event sediment yields were calculated for 72 events occurring throughout the 2.6 year duration (Table 18 and Figure 10). The total sediment yield from storm events over the monitoring period was 14047 t, equating to a specific sediment yield of 47 t/km^2/year (Tables 18 and 19).

Wairoa was one of the best sampled sites, sampling 87% of the recorded sediment yield. Event number 26 (Table 18) between 28/1/2011 and 31/1/2011 contributed about 37% of the overall yield (Figure 10) and had a 1:25 year return period in terms of flow (m^3/s) (Appendix E3). It should be noted that this event wasn't sampled all the way through its recession, but the sampled yield as far as it went was used in preference to the rated yield because the sampled yield (as far as it went) was greater than the rated yield. Once another event of this magnitude is well sampled it will improve the upper end of the rating.

The SSY for the Wairoa catchment for the two physical years, 2011-12, was 51.8 t/km^2/year versus 47 t/km^2/year for the entire 2.6 year record. This suggests that the site was relatively uninfluenced by winter yields in 2010. Similarly to the Hoteo catchment, the Wairoa site yield was strongly influenced by the major summer storm event occurring in January 2011.

Table 18. Event sediment yields for the Wairoa catchment between 01/05/2010 and 31/12/2012.

Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)
1	21/05/2010	5.76	25*	25/01/2011	13.39	49	11/10/2011	40.14
2	24/05/2010	3.80	26	28/01/2011	5236.00	50	18/10/2011	242.77
3*	25/05/2010	25.41	27*	5/03/2011	156.80	51	18/12/2011	103.78
4	1/06/2010	390.14	28*	18/03/2011	37.44	52	31/12/2011	41.64
5*	6/06/2010	23.84	29	22/03/2011	24.40	53	8/01/2012	51.57
6*	11/06/2010	17.35	30*	17/04/2011	11.93	54*	23/02/2012	14.99
7*	20/06/2010	3.54	31	26/04/2011	157.73	55	20/03/2012	331.30
8*	25/06/2010	773.40	32	7/05/2011	49.05	56*	9/05/2012	49.65
9	4/07/2010	131.15	33	11/05/2011	8.43	57*	15/05/2012	22.25
10	22/07/2010	93.11	34	26/05/2011	1191.01	58*	7/06/2012	27.93
11	2/08/2010	265.80	35	10/06/2011	68.31	59	21/06/2012	135.33
12	14/08/2010	121.21	36	18/06/2011	91.63	60	25/06/2012	23.64
13	17/08/2010	22.71	37*	27/06/2011	13.13	61	3/07/2012	40.18
14	20/08/2010	20.44	38*	28/06/2011	14.97	62	15/07/2012	698.09
15	26/08/2010	64.99	39*	8/07/2011	31.09	63	22/07/2012	254.02
16*	30/08/2010	26.40	40*	12/07/2011	42.25	64	30/07/2012	641.21
17	7/09/2010	61.57	41*	21/07/2011	36.90	65*	9/08/2012	41.16
18	9/09/2010	42.96	42*	11/08/2011	74.31	66	12/08/2012	115.16
19*	16/09/2010	45.23	43*	15/08/2011	15.24	67*	18/08/2012	16.60
20*	21/09/2010	46.20	44*	16/08/2011	21.85	68*	19/08/2012	54.93
21*	25/09/2010	12.38	45	11/09/2011	98.33	69	3/09/2012	422.28
22*	1/10/2010	16.72	46*	14/09/2011	14.94	70	16/09/2012	18.33
23*	20/12/2010	11.80	47	18/09/2011	5.96	71	21/10/2012	69.49
24	23/01/2011	895.85	48*	3/10/2011	30.62	72*	6/12/2012	22.66

* denotes missing events which are predicted based on the event peak flow rating.

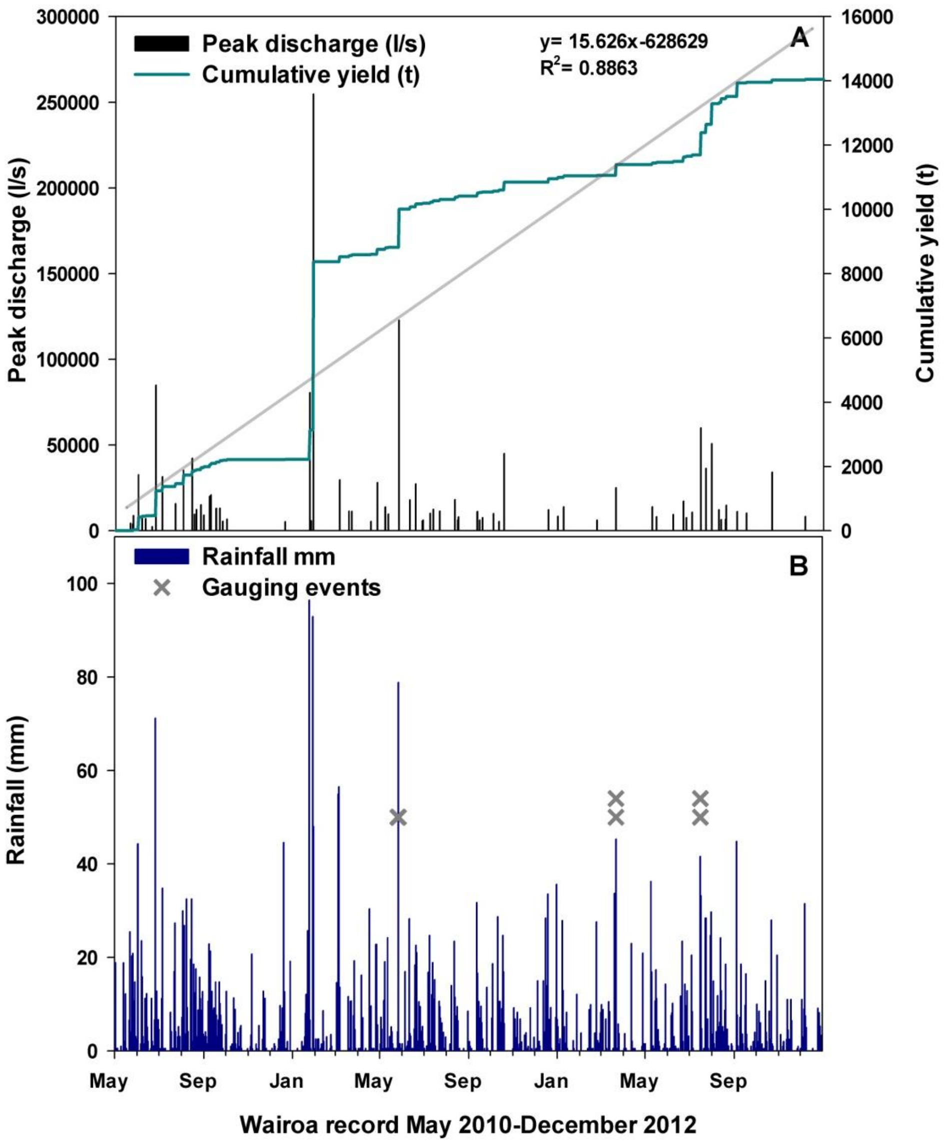

Figure 10. Cumulative sediment yields and peak discharge (A) and rainfall (B) for the Wairoa sediment monitoring record from May 2010-December 2012. Note **X's** indicate sediment gauging events.

Table 19. Sediment yield summary for the Wairoa catchment.

Description	Value (unit)
Total sediment across all events	14047 t
Total sediment across sampled events	12279 t
Total predicted sediment using rating	1767 t
Error of predicted sediment yield	771 t
% total error of predicted sediment yield	5 %
% total sediment yield sampled	87 %
Length of record	2.6 yr
Catchment area	114 km^2
Specific sediment yield	47 $t/km^2/yr$
Yield trend	16 t/day
Specific yield trend	50 $t/km^2/yr$

4.9 Weiti

Mudstone and exotic forestry are the dominant geology and land cover, respectively, in the 1.7km^2 Weiti catchment. The majority of the land is rolling (51%), forming into strongly rolling (45%) and moderately steep (4%) terrain (Figure 13). The Weiti site has been selected as a compliance site.

Event sediment yields were calculated for 99 events occurring throughout the 4.7 year duration of sediment monitoring (Table 20 and Figure 11). The total sediment yield from storm events over the monitoring period was 257 t, equating to a specific sediment yield of 32 t/km^2/year (Tables 20 and 21).

The SSY for the Weiti catchment for the four physical years, 2009-12, is 30 t/km^2/year. The SSY figure above using a record spanning for 4.7 years that captures five winters and four summers therefore suggests that winter in 2008 had a relatively negligible influence on the SSY for the entire record. This is despite the largest event recorded at this site (event number 10 Table 20; 23 t) on 29/07/2008 occurring during this period (Appendix E4). This supports the concept that longer spanning records are less sensitive to the influence of major storm events and partially sampled years.

Table 20. Event sediment yields for the Weiti catchment between 15/04/2008 and 31/12/2012.

Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)	Event no.	Event start date	Event yield (t)
1	15/04/2008	0.30	34*	5/07/2010	4.20	67*	1/11/2011	0.94
2	29/04/2008	0.16	35	21/07/2010	2.49	68	14/12/2011	2.59
3*	1/05/2008	0.65	36*	23/07/2010	1.17	69	29/12/2011	4.02
4	4/05/2008	0.92	37	7/08/2010	0.31	70*	15/02/2012	1.89
5	8/06/2008	7.82	38	13/08/2010	0.34	71*	11/03/2012	2.21
6*	16/06/2008	1.13	39*	7/09/2010	0.57	72*	19/03/2012	10.66
7*	22/06/2008	3.69	40*	16/09/2010	0.92	73*	21/03/2012	6.20
8*	28/06/2008	0.79	41*	19/12/2010	1.07	74*	24/03/2012	0.16
9*	26/07/2008	7.53	42	23/01/2011	2.32	75*	25/03/2012	0.10
10	29/07/2008	22.70	43	28/01/2011	16.06	76	8/05/2012	0.42
11*	12/08/2008	0.53	44*	21/03/2011	6.34	77*	14/05/2012	0.17
12*	13/08/2008	1.00	45*	26/03/2011	1.11	78*	15/05/2012	0.14
13*	15/08/2008	0.98	46*	16/04/2011	0.56	79*	16/05/2012	0.16
14*	16/08/2008	0.86	47	25/04/2011	8.90	80	3/07/2012	12.59
15*	24/08/2008	4.55	48	2/05/2011	7.45	81*	16/07/2012	0.11
16*	28/02/2009	0.79	49*	7/05/2011	1.07	82*	16/07/2012	0.10
17	10/05/2009	0.25	50*	11/05/2011	1.78	83*	16/07/2012	0.15
18	9/06/2009	6.10	51*	26/05/2011	3.23	84*	16/07/2012	0.34
19	12/06/2009	0.18	52*	10/06/2011	1.58	85	22/07/2012	4.60
20	28/06/2009	7.79	53*	17/06/2011	3.15	86*	24/07/2012	0.10
21	4/07/2009	0.17	54*	18/06/2011	1.08	87*	26/07/2012	0.11
22	11/07/2009	1.71	55*	25/06/2011	0.61	88	29/07/2012	11.60
23	14/07/2009	0.07	56*	28/06/2011	0.52	89*	1/08/2012	0.12
24	17/07/2009	1.43	57	8/07/2011	4.64	90*	1/08/2012	1.08
25	29/09/2009	2.76	58	10/07/2011	0.66	91*	7/08/2012	0.12
26	3/10/2009	0.44	59	11/07/2011	1.02	92*	8/08/2012	0.33
27	15/10/2009	1.19	60	14/07/2011	1.28	93*	11/08/2012	2.88
28	4/12/2009	6.59	61*	21/07/2011	0.71	94*	15/08/2012	0.46
29*	21/05/2010	1.65	62*	22/07/2011	6.34	95*	18/08/2012	0.13
30*	24/05/2010	1.39	63	10/10/2011	1.75	96	19/08/2012	1.24
31*	28/05/2010	1.63	64*	13/10/2011	0.93	97	3/09/2012	12.55
32*	1/06/2010	3.04	65	17/10/2011	0.56	98*	15/09/2012	0.42
33*	25/06/2010	1.31	66	19/10/2011	0.79	99*	6/12/2012	0.22

* denotes missing events which are predicted based on the event peak flow rating.

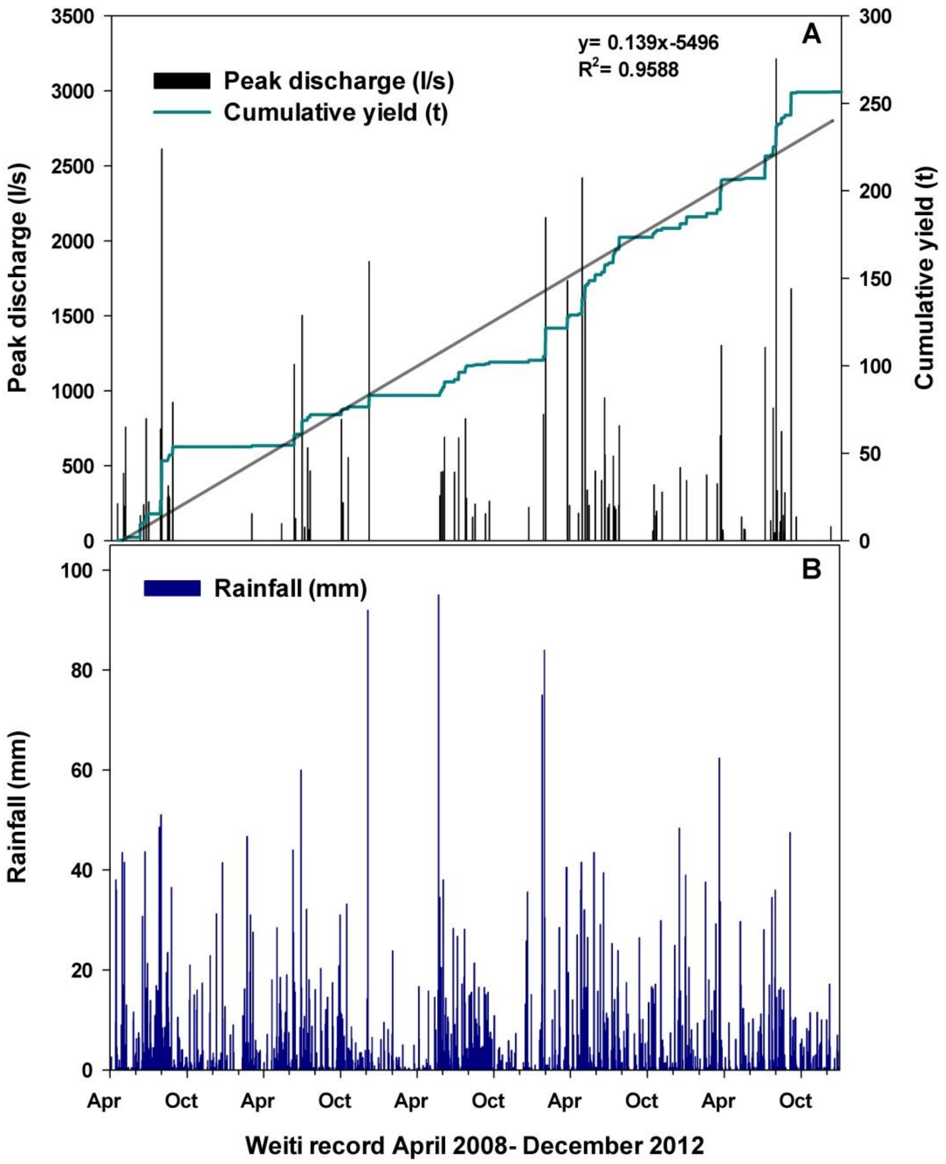

Figure 11. Cumulative sediment yields and peak discharge (A) and rainfall (B) for the Weiti sediment monitoring record from April 2008-December 2012.

Table 21. Sediment yield summary for the Weiti catchment.

Description	Value (unit)
Total sediment across all events	257 t
Total sediment across sampled events	159 t
Total predicted sediment using rating	98 t
Error of predicted sediment yield	14 t
% total error of predicted sediment yield	5 %
% total sediment yield sampled	62 %
Length of record	4.7 yr
Catchment area	1.7 km^2
Specific sediment yield	32.1 $t/km^2/yr$
Yield trend	0.14 t/day
Specific yield trend	37.3 $t/km^2/yr$

4.10 West Hoe

The West Hoe site was established in 2012 to act as a reference site whereby change in sediment loss is driven solely by climatic conditions in order to determine background conditions. The majority of the catchment (97%) is covered by broadleaved indigenous hardwoods and manuka/kanuka, and 100% of the catchment is Waitemata geology and Ultic soils (Table 3). The site is predominantly (74%) moderately steep with the rest (26%) being strongly rolling (Figure 13).

As stated in section 3.1.3, a TSS-turbidity relationship was created to develop a rating for this site. Although SSC is also being analysed for the site, the rating was stronger and appeared more sensible using this relationship than it was for SSC- turbidity but the SSC data will be used in time once more events are captured and the site better established.

The sediment yield for the TSS-turbidity one year record was calculated as 13.95 t, equating to a specific sediment yield of 26.3 t/km^2/yr (Figure 12). A sediment yield summary will be derived for the West Hoe catchment over time.

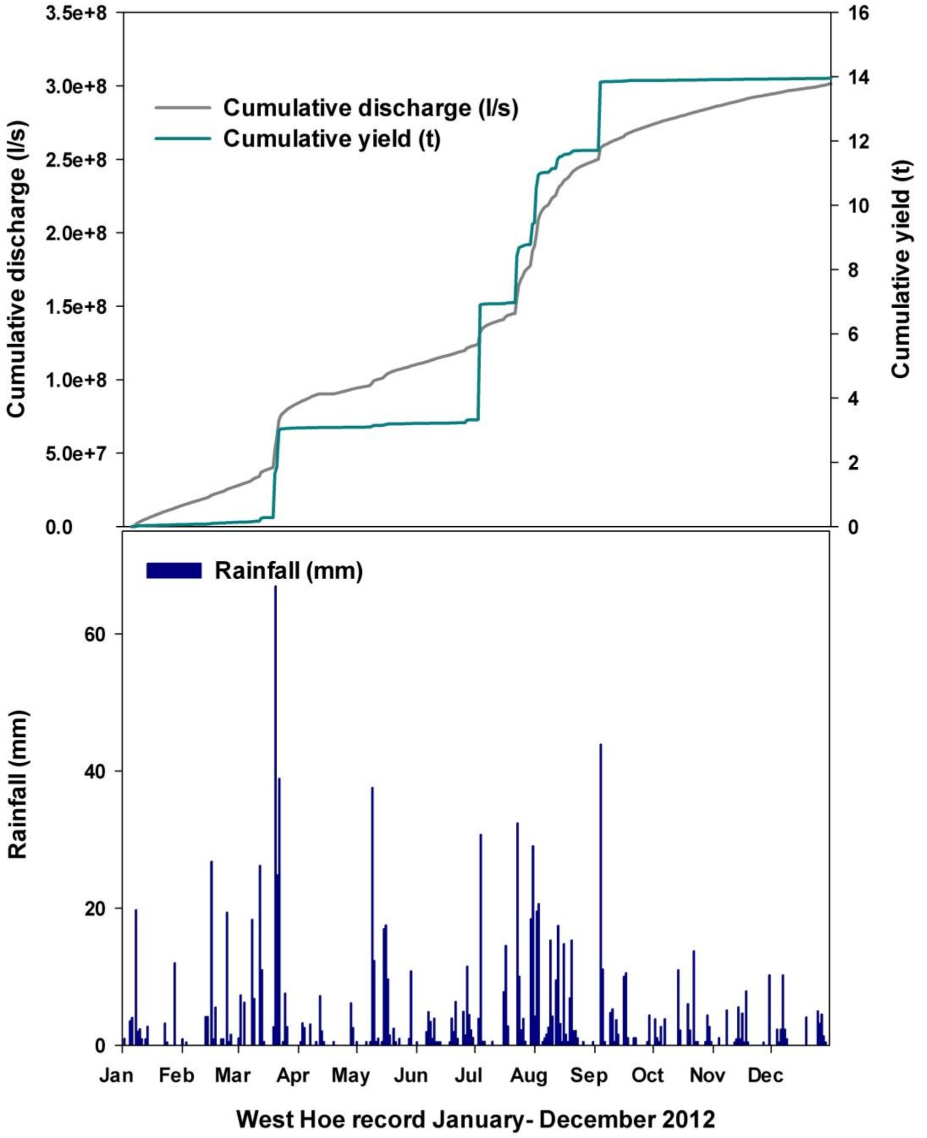

Figure 12. Cumulative sediment yields and discharge (A) and rainfall (B) for the West Hoe sediment monitoring record from January 2012 to December 2012.

5.0 Discussion

5.1 Sediment yield comparisons between current sites and wider studies

The specific sediment yield (SSY) across the ten sites averaged 62.9 t/km^2/yr and ranged from 26 to 167 t/km^2/yr (Figure 14). The SSY was by far the greatest for the Mangemangeroa catchment which was almost double the SSY to the second greatest yielding site, Orewa (80 t/km^2/yr). Although the surrounding land use is not fully provided for the Mangemangeroa catchment, as a result of some patchy AgriBase data for the area, the dominant land uses include lifestyle blocks, beef cattle and sheep farming (AssureQuality 2012). The event occurring in 24-26/7/12 at the Mangemangeroa catchment contributed to over one third of the annual yield recorded at this site, and such an event has a return period of about 1:10 year, in terms of flow (m^3/s). Although there was a greater rainfall event in and around March 2012, generating a yield of 76 t, the July event occurred at a time of year when soil moisture was at field capacity and the storm event contributed to saturated excess runoff (Curran Cournane *et al.* 2011; Srinivasan and McDowell 2007; Srinivasan *et al.* 2007).

A call for caution is suggested when interpreting the sediment yield and SSY for the Mangemangeroa catchment because of its late establishment as a sediment monitoring site, particularly given the influence of one large event over a short monitoring record span. A longer record will allow us to determine if the site continues to record high sediment yield, indicating a highly erosive catchment, or whether reduced yields will be recorded over time. For example, Hicks *et al.* (2009b) calculated a SSY of 89 t/km^2/yr for Mangemangeroa using data collected between November 2000 and March 2004 by Andrew Swales, NIWA Hamilton, and the then Auckland Regional Council Environmental Services. It is also worth noting that particular attention should focus on the approach used for calculating SSY. The 89 t/km^2/yr calculated for Mangemangeroa in Hicks *et al.* (2009b) is the mean of three SSY approaches calculated for this site. The three rating approaches include: 1) a SSC vs peak discharge approach; 2) an event yield vs peak discharge approach; and 3) a Monte Carlo approach. Whichever of approaches 1 and 2 has the lowest standard error tends to be the approach opted for. The Monte Carlo approach is based on an event sediment yield rating using a probability distribution of event peak discharges. The SSY ranged from 81-94 t/km^2/yr across all three approaches used for the Mangemangeroa catchment (Hicks *et al.* 2009b) and, hence, particular attention should note the approach used to calculate SSY.

Unsurprisingly, the West Hoe site generated the least SSY across all sites - supporting its appropriateness as a reference site. A call for caution also applies when interpreting the sediment yield and SSY for the West Hoe and Kaipara catchments because of the shorter length of the sediment record at these sites, albeit having longer flow and rainfall records (Figure 14). The sediment rating for these sites will improve over time as more storm events are sampled.

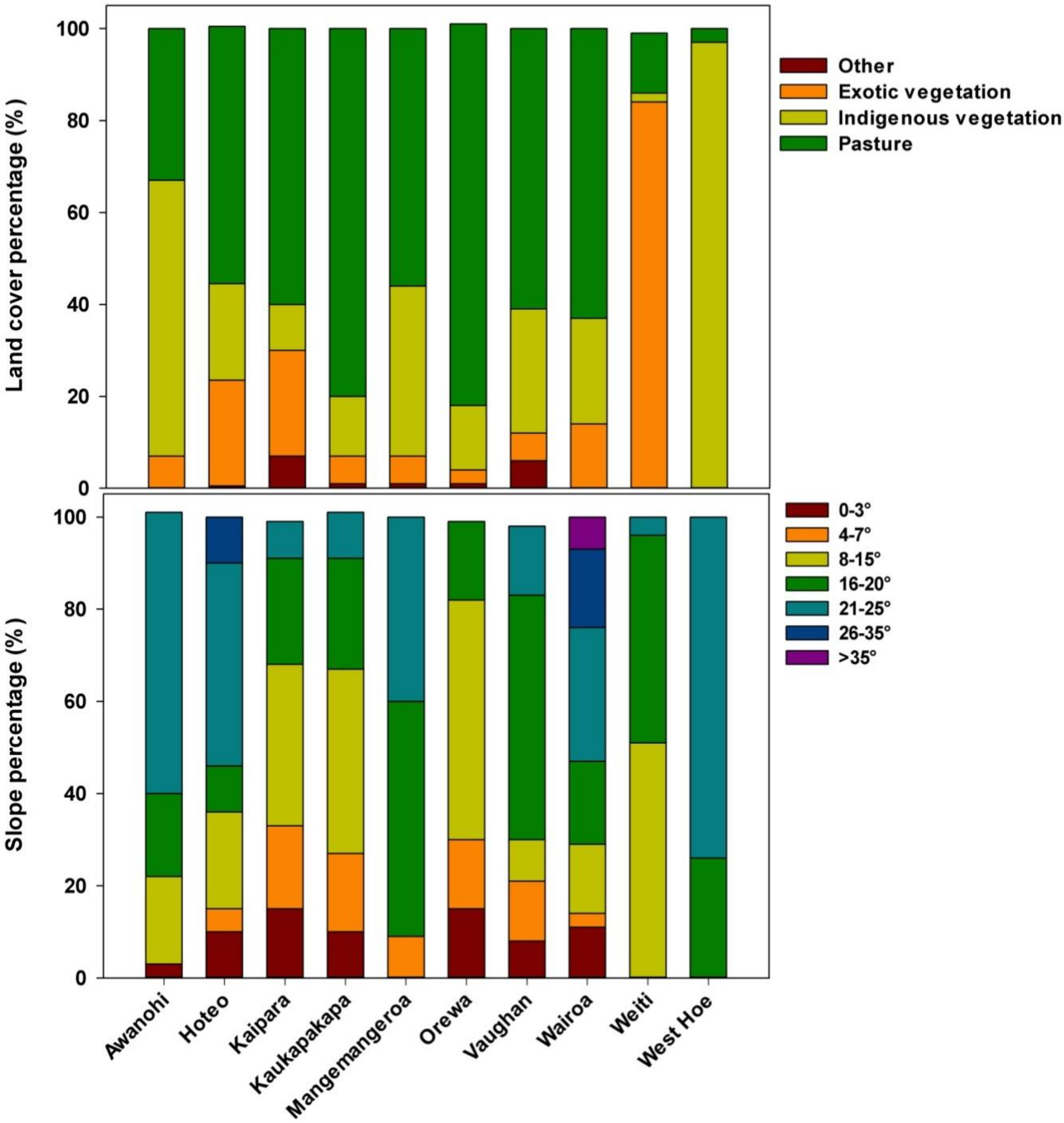

Figure 13. Comparison of land cover and slope at study catchments.

Mean SSY for the longer established sites (>1year sediment record) was 57.7 t/km^2/yr, and the SSY are all clustered in the range 32-80 t/km^2/yr – a tight range for sediment yields from multiple catchments (Hicks *et al.* 2009b). The majority of these catchments were predominantly pasture catchments except for Awanohi and Weiti which were predominantly indigenous vegetation and plantation forest, respectively (Figure 13). In contrast to Hicks *et al.* (2009b) who reported a SSY of 172 ± 19 t/km^2/yr for pre-harvest conditions at Redwood Forest in the Mahurangi, pre-harvest SSY were recorded as 32 t/km^2/yr in the current study at Weiti Forest. The Redwood Forest site was the steepest of all sites reported by Hicks *et al.* (2009b) and post-harvest activity at Redwood Forest yielded the greatest SSY across all sites.

When sediment yield from pastoral farming was compared with yield from plantation forestry over a full forest rotation (pre-, during- and post-harvest) in the Hawke's Bay, it was reported that sediment yield was likely to be less under forestry than pasture (Fahey *et al.* 2003). Over the seven year sediment monitoring period: pre-harvest yields were 7.6 t/km^2 and 21.2 t/km^2 for the forested and pasture catchments, respectively; 4.9 t/km^2 and 22 t/km^2, respectively, during the road construction phase; 84.4 t/km^2 and 43.8 t/km^2, respectively, during the logging phase; and 176.8 t/km^2 and 129 t/km^2, respectively, during the post harvesting phase (Fahey *et al.* 2003).
In the current study, Weiti Forest is undergoing harvesting activity and it will be interesting to both determine how the sediment yield will vary across the full rotation cycle and how long it takes for post-harvest yields to return to pre-harvest conditions. It is also worth noting that Hicks *et al.* (2009b) reported a SSY of 82 ± 13 t/km^2/yr at the Weiti Forest site (vs 32 t/km^2/yr in the current report). The former SSY was derived using a sediment record only 0.56 years in length which has now been extended to 4.7 years and used to update the current SSY results. This example again reiterates to interpret short term records with caution and the importance of establishing long term records as they provide more meaningful results and are less sensitive to erratic storm events.

Sediment yields calculated for 23 monitored sites in the Waikato region ranged from 8 t/km^2/yr to 230 t/km^2/yr, with the majority of sites falling within the 40-100 t/km^2/yr range (Hoyle *et al.* 2012). The site that generated the greatest yields was a pasture dominated site. For the nine auto-sampled sites in the latter report, SSYs ranged from 36 to 195 t/km^2/yr, calculated using the event yield rating approach for unsampled events. The majority of these nine sites reported by Hoyle *et al.* (2012) were pasture dominated sites (n=6) and similarly, seven out of the ten sites in the current report (excluding Awanohi, Weiti and West Hoe) were predominantly pasture. The mean SSY for pastoral sites reported in the Waikato analysis using the event rating approach was 90 t/km^2/yr versus 75 t/km^2/yr in the current report, representing only a 17% difference in sediment yields generated from pastoral catchments between the two regions.

Although not currently being monitored for sediment, Hicks *et al.* (2009b) reported SSY (mean across the three analysis approaches) of 200 ± 2 t/km^2/yr, 88 ± 19 t/km^2/yr and 40 ± 11 t/km^2/yr for Wylie Road, Mahurangi College and lower Awaruku-Long Bay, respectively, in Auckland. The former two sites were predominantly pasture sites and the latter site a predominantly urban site. These authors also calculated that for a given rainfall x slope product, sediment yields from forested areas were 2/3 of those from pasture areas, while sediment yields from urbanised areas were ¼ of those from pasture areas.

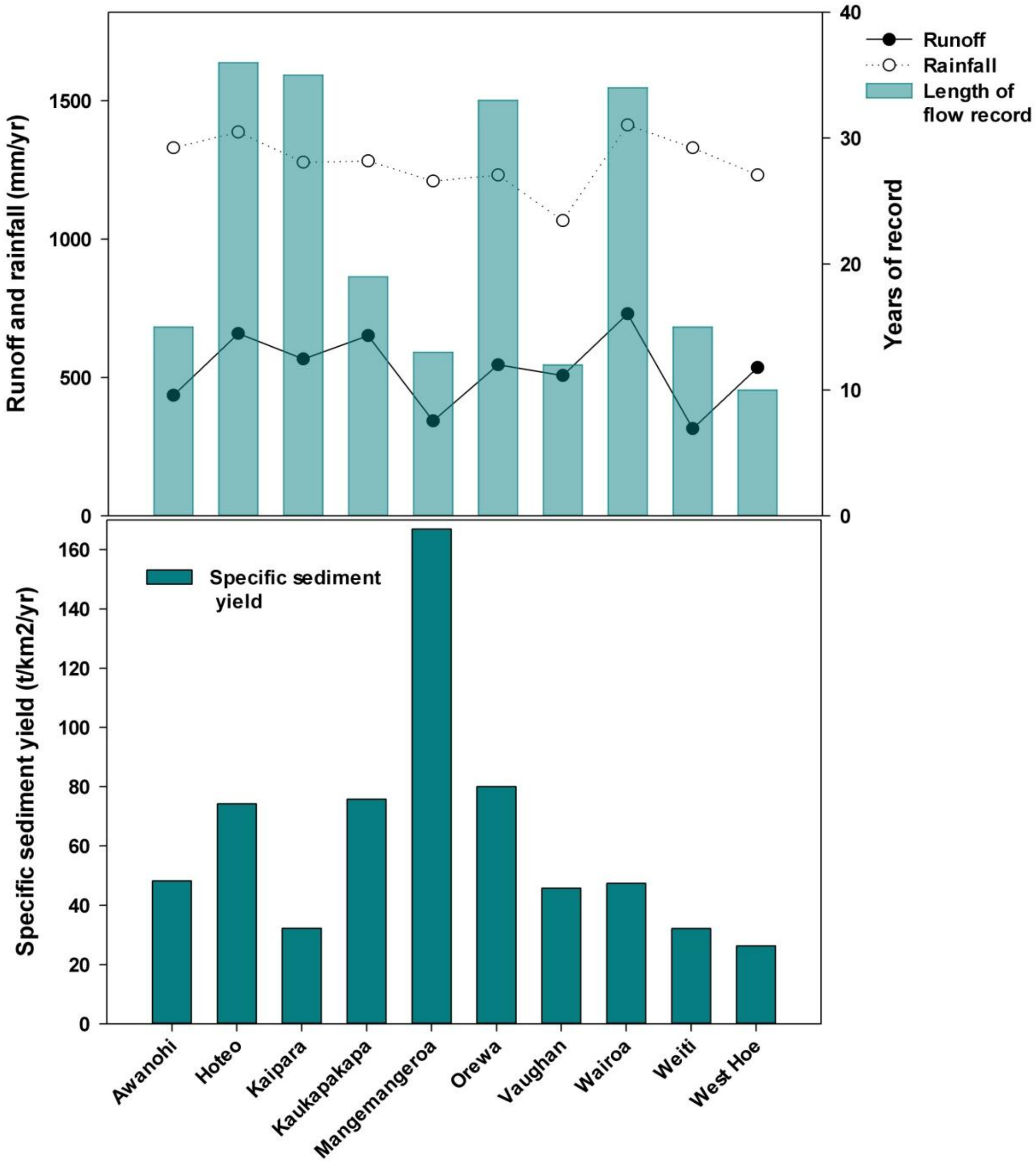

Figure 14. Comparison of hydrological characteristics and specific sediment yields at study sites.

There tends to be a bias towards monitoring sediment in pastoral dominated catchments, reflecting the prevalence of this land cover in both Auckland and Waikato. Basher *et al.* (1997) reported a SSY of 49 t/km^2/yr over a 3 year monitoring period for a predominantly intensive market gardening catchment in Pukekohe. The dominant soil types in South Auckland are classified as well structured Granular soils, representing about 17% of land area in Auckland (NZLRI 2010b). Interestingly, these yields recorded by Basher *et al.* (1997) were described as being very low in absolute terms compared to the amount of soil movement that was being measured within paddocks and deposited in drains close to the source. This was attributed to the relatively strong aggregated nature of the soils making them resistant to slaking and dispersion mechanisms that would otherwise break them up into primary soil particles which would be transported as suspended load in surface runoff (Basher *et al.* 1997; Basher and Ross 2002). These authors also reported that the bulk of sediment is generated in winter/early spring and that efforts to reduce sediment load and soil movement should be concentrated during this period. It has been recommended that sediment stations are set up in and around West Auckland, Auckland city and the Manukau/Pukekohe areas (Semadeni-Davies *et al.* 2013) to provide a broader geographical representation of sediment yield data. This will also take into account broader geologies, land cover and climate, increasing the diversity of the dataset.

5.2 Sediment modelling considerations

It is timely to start considering using the sediment data reported in the current study, Hicks *et al.* (2009b), Hoyle *et al.* (2012) and Basher *et al.* (1997) to calibrate an empirical model for predicting sediment yield that is spatially sensitive and responsive to catchment hydrology, slope, land cover and geology. The CLUES (Catchment Land Use for Environmental Sustainability) model was recently investigated for data reported in the current study and that of Hicks *et al.* (2009b) (Semadeni-Davies *et al.* 2013). In general, the relationship between CLUES-predicted yields and observation-based sediment yield estimates was poor. The lack of agreement indicates that there is a need for local calibration of the CLUES model for Auckland and pooling the various studies highlighted above, as well as any studies in neighbouring regions such as Northland, will be a good starting point. However, the CLUES model does not taken into account hydrological variation which has been reported in the current and other studies as being highly variable. When choosing the empirical model it will be important to consider what the model will to be used for, whether it is fit for purpose and having appropriate data to validate the model. The Orewa and Wairoa catchments are looking like very promising sites for the purposes of model validation, both having sampled 87% of the recorded sediment yield, and in time the other validation, calibration and reference sites will become good candidates. It is recommended that future work explores the model options appropriate for Auckland Council's sediment monitoring requirements.

5.3 Auckland Plan target

Strategic Direction 7 in the Auckland Plan has a target to *'reduce the overall yield of suspended sediment to priority marine receiving environments from 2012 levels by 15% by 2040'* (AC 2012). Specific sediment yields for 2012 for the ten catchments in the current study are illustrated in Figure 15 which demonstrates how variable SSY are across individual sites in Auckland. The numbers in parentheses (in Figure 15) illustrate whether 2012 total rainfall is above or below the long term mean rainfall for each site indicating the spatial variability of rainfall patterns from year to year that also needs to be considered. This is important because a reduction of sediment by 15% by 2040 from 2012 levels could purely be by chance depending on how wet or dry these two physical years are. That said, a wet or dry year is not the only driver contributing to high yields. One large event in a dry year (for example, the January 2011 event with a 1:25 return period for the Hoteo and Wairoa catchments) can have a greater effect than an above normal wet year on the SSY.

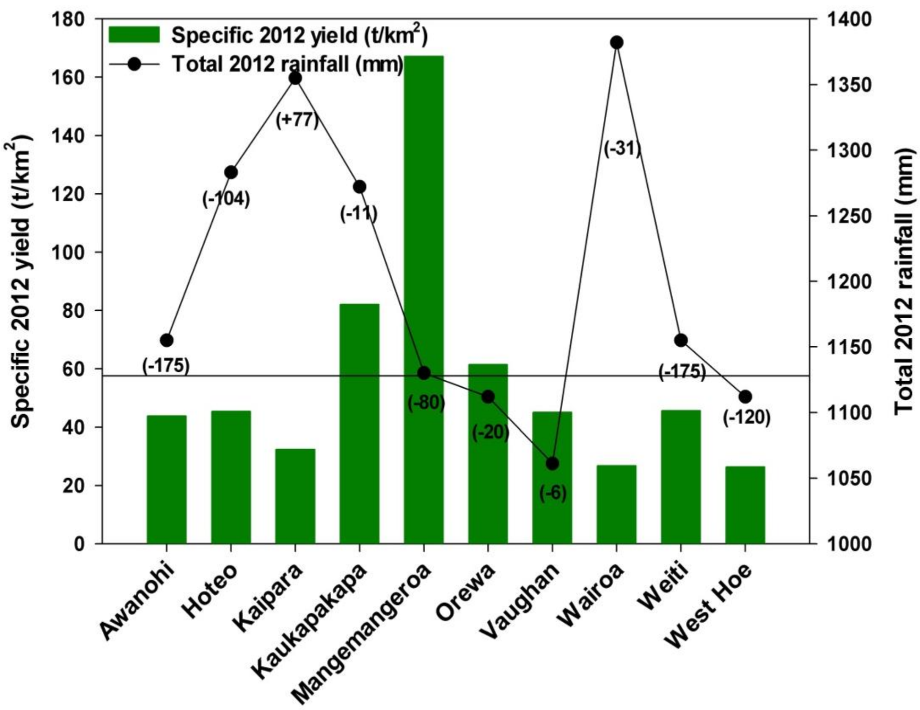

Figure 15. Specific yield (t/km^2) and total rainfall for 2012 all sites [numbers in parentheses illustrate by how much rainfall (mm) was above (+) or below (-) the long term mean rainfall for each site].

A lot of research highlights the annual variability in sediment yield that is to be expected from year to year variability in weather e.g. Basher *et al.* (2011) and Hicks *et al.* (2011). This is illustrated in Figure 16 for the Vaughan site. It is therefore important to consider this sampling issue when determining if a SSY reduction has occurred between 2012 and 2040, as per the Auckland Plan target.

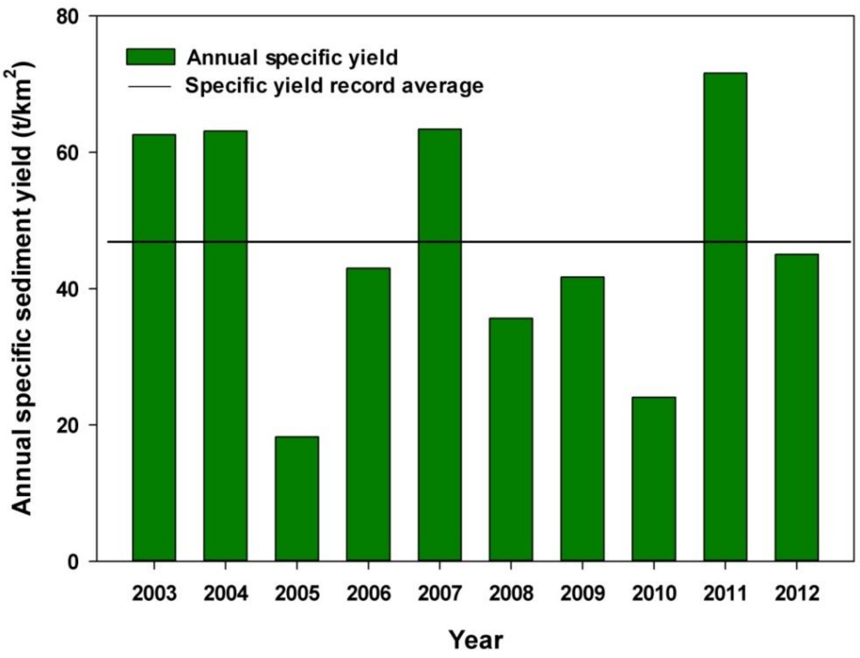

Figure 16. Specific annual sediment yields and mean SSY for the Vaughan 2003-2012 record.

- One way forward is to compare running mean yields over several years (e.g. 2010-2012, vs 2038-2040). The averaging period is not clear at present – we need one wherein the standard error on the mean yield is < 15% - otherwise a change within the target level won't be detected. This will become clearer as time progresses and the sediment datasets continue to extend.

- Another approach could involve the comparison of similar sized peak discharge events for years 2010-2012 vs 2038-2040. However, land use changes within catchments for similar sized peak discharge events will need to be considered when making temporal comparisons.

- It will also be important to nominate what sites will be used to determine the Auckland Plan sediment target. For example, the West Hoe reference site is the most stable of sites that is envisaged to remain so which would make a good candidate. Being a reference site whereby sediment is driven by climatic conditions, future climate change might mean that even West Hoe's yield increases or decreases. Therefore, the West Hoe sediment record could be used to normalise the yield trend, removing the effects of climate change (which should affect every catchment). This could also apply to the Awanohi catchment being 60% native bush. In contrast, if harvesting were to occur at Weiti forest or urbanisation of any of the pastoral catchments (e.g. Vaughan) in and around 2040 it would be imprudent to use such sites or caution would be warranted.

  Furthermore, priority marine-receiving environments will also need to be identified for the latter to be determined.

- An alternative approach is to look at drift in the event yield vs Qpeak rating. This removes the interannual variability. So (assuming the rating slope remained constant), the approach would be to look for a 15% reduction in the rating offset.

Therefore, as well as serving SoE purposes, sediment monitoring needs to continue in order to measure if a sediment reduction has occurred, as per the Auckland Plan. The method used to measure change will be determined by the performance of individual sites which are envisaged to improve over time as more events are captured and the rating improved. It is recommended that future work concentrate on the approach used to determine the sediment target in the Auckland Plan when sediment data becomes more refined and reliable for all sites over time.

6.0 Conclusion

The main conclusions reported in this study of sediment yields from ten catchments in Auckland include:

- Specific sediment yields (SSY) ranged from 26 $t/km^2/yr$ at the West Hoe reference catchment to 167 $t/km^2/yr$ at the Mangemangeroa predominantly pastoral catchment. Both these two sites and the Kaipara catchment should be interpreted or viewed with caution owing to their short 1 year monitoring record. For example, the Mangemangeroa catchment yielded the greatest SSY of all sites but this was largely influenced by a 1:10 year return period event based on flow. A longer record will allow us to determine if the site continues to record high sediment yield, indicating a highly erosive catchment, or whether the SSY will reduce over time as the impact of this event on the time-averaged yield wanes.

- The mean SSY across all ten sites was 62.9 $t/km^2/yr$ calculated using the sampled storm events and the sediment event yield (kg) vs Qpeak (l/s) rating for missing events. Excluding sites with only a year's data, the SSY range across catchments (32-80 $t/km^2/yr$) was relatively tight. The SSY reported for sites in the current study were similar in range, if not at the lower end, to Waikato yields which mostly fell within the 40-100 $t/km^2/yr$ range.

- Specific sediment yield was sensitive to large infrequent storm events, particularly for catchments with short spanning sediment records.

- It is recommended that future work explores an empirical model for predicting sediment yield for Auckland. Sediment yield analyses from previous studies in Auckland, Waikato and Northland can potentially be pooled together to locally calibrate the chosen model.

- Several considerations and approaches to measure the Auckland Plan target, which is to reduce sediment yields from 2012 levels by 15% by 2040, have been discussed. It is recommended that future work concentrate on the approach used to measure change when sediment data becomes more refined and reliable for all sites over time.

7.0 Acknowledgements

The Environmental Strategy and Policy team are thanked for supporting this study, particularly Roger Bannister. The Environmental Monitoring team in the Research Investigation and Monitoring Unit are thanked for their fieldwork contribution. Dr Murray Hicks from NIWA is thanked for analytical assistance and peer reviewing the report which has improved its quality. This report has also undergone an internal peer review and the peer review panel, review manager and reviewer, Nick Reid, are thanked for their valuable comments and suggestions.

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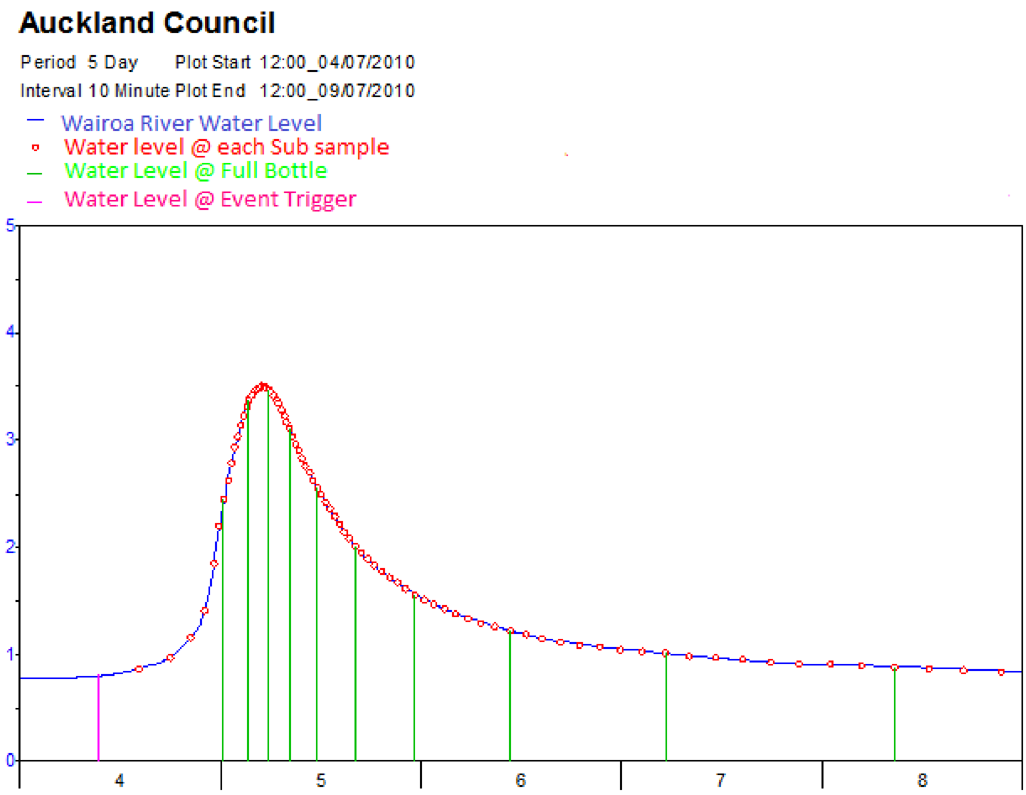
9.0 Appendices

9.1 Appendix A: Schematic example of hydrograph



Appendix A. Schematic example of hydrograph illustrating water level trace, volume, trigger level to trigger sub sampling (composite) and bottle sampling.
Y axis is Water Level height in meters X axis is Day of the Month.

9.2 Appendix B: SSC and TSS background for individual sites

Site	SSC and TSS relationship
Awanohi	All data pre 22/07/2012 = TSS
Hoteo	All data is TSS
Kaipara	SSC= 0.984*TSS
Kaukapakapa	SSC= 1.0064*TSS
Mangemangeroa	All 2012 data is SSC
Orewa	SSC = 0.998*TSS
Vaughan	All data pre 03/07/2012 is TSS
Wairoa	SSC = 1.077*TSS
Weiti	SSC= 0.8214*TSS (Hoyle 2012)
West Hoe	All data TSS/Turbidity relationship

9.3 Appendix C: Gauging results including Cmean/Cpoint values for the various sites

Site	Date and Time	Cmean	Cpoint	Ratio	Rated Discharge m^3/s
Hoteo	20/03/2012 13:32	120.0	102.8	1.17	76.87
Kaipara	23/07/2012 10:51	107.8	105.9	1.02	29.87
	02/08/2012 10:21	117.5	132.18	0.89	47.55
Kaukapakapa	19/03/2012 15:43	115.85	206.25	0.56	15.11
	20/03/2012 09:27	92.17	120.00	0.77	22.75
Mangemangeroa	16/07/2012 10:57	195.75	210.15	0.93	0.83
	26/07/2012 12:47	27.54	35.51	0.78	0.23
	31/07/2012 18:48	76.66	75.75	1.01	0.56
Orewa	07/09/2010 11:46	147.82	229.90	0.64	1.47
	29/01/2011 06:05	87.73	100.80	0.87	5.50
	23/07/2012 11:32	40.48	56.30	0.72	1.65
Wairoa	26/05/2011 00:00	380.13	439.03	0.87	83.34
	27/05/2011 01:04	266.56	316.40	0.84	73.58
	22/03/2012 10:25	157.00	154.12	1.02	20.11
	22/03/2012 12:39	117.40	126.90	0.93	15.19
	16/07/2012 12:20:00	333.46	292.47	1.14	50.60
	16/07/2012 14:37	397.53	371.80	1.07	60.05

9.4 Appendix D: Event sediment yield ratings for individual sites

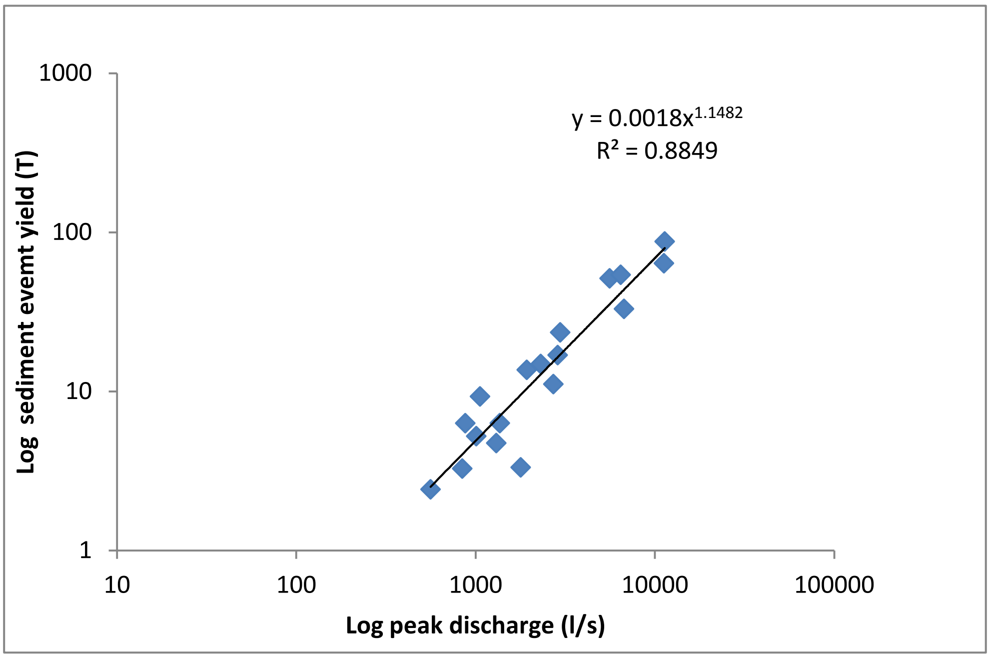


Figure D1. Awanohi rating. The % estimate error in rating-estimated yield is 16%.

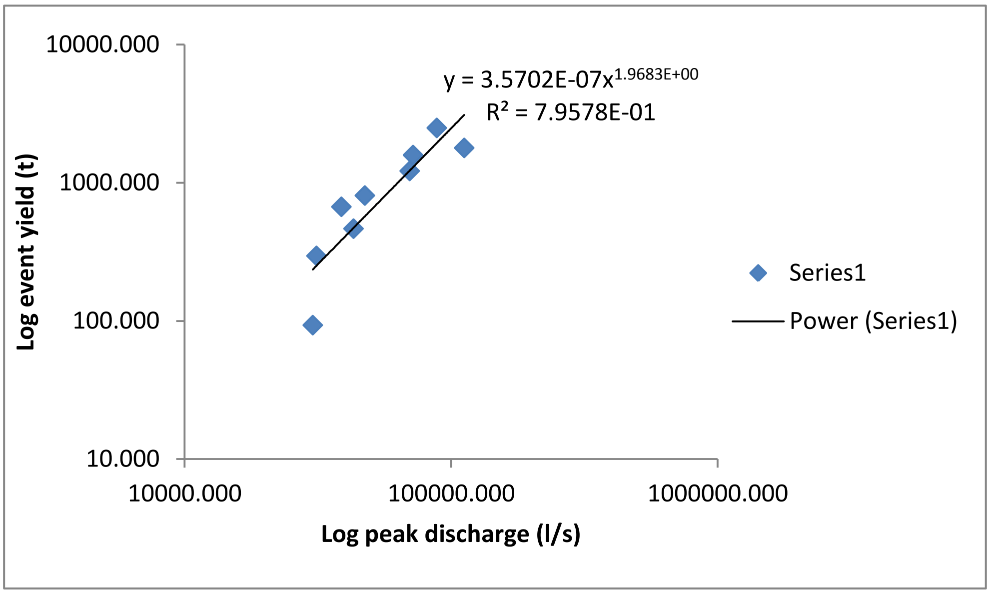


Figure D2. Hoteo rating. The % estimate error in rating-estimated yield is 26%.

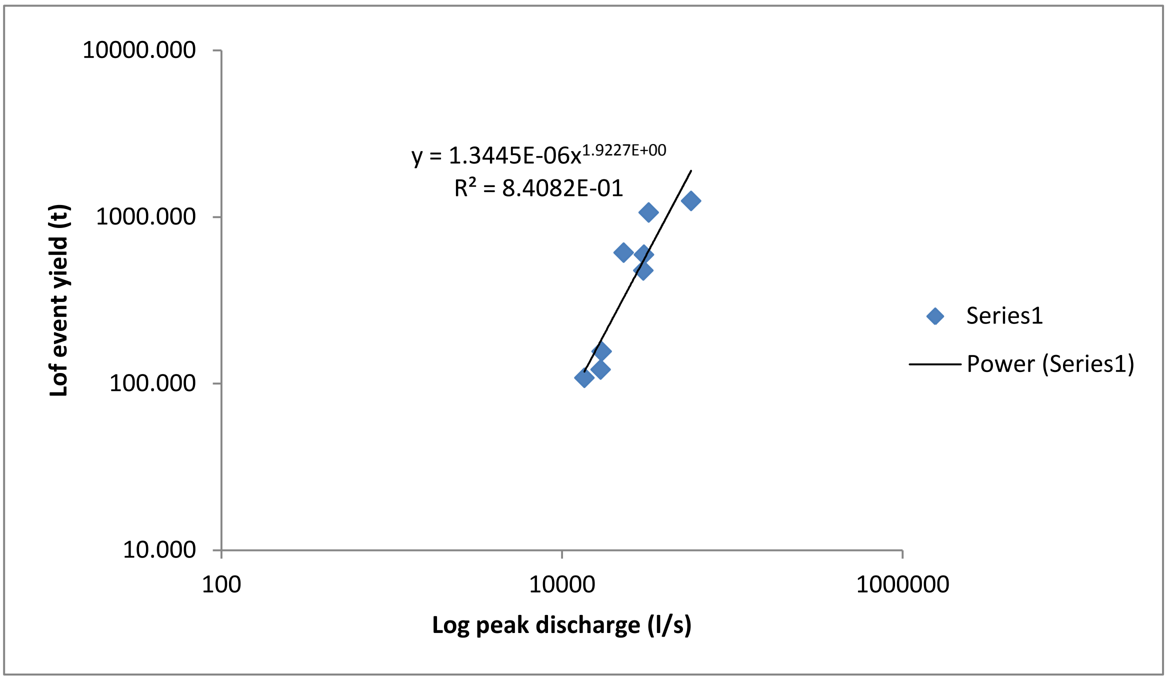


Figure D3. Kaipara rating. The % estimate error in rating-estimated yield is 23%.

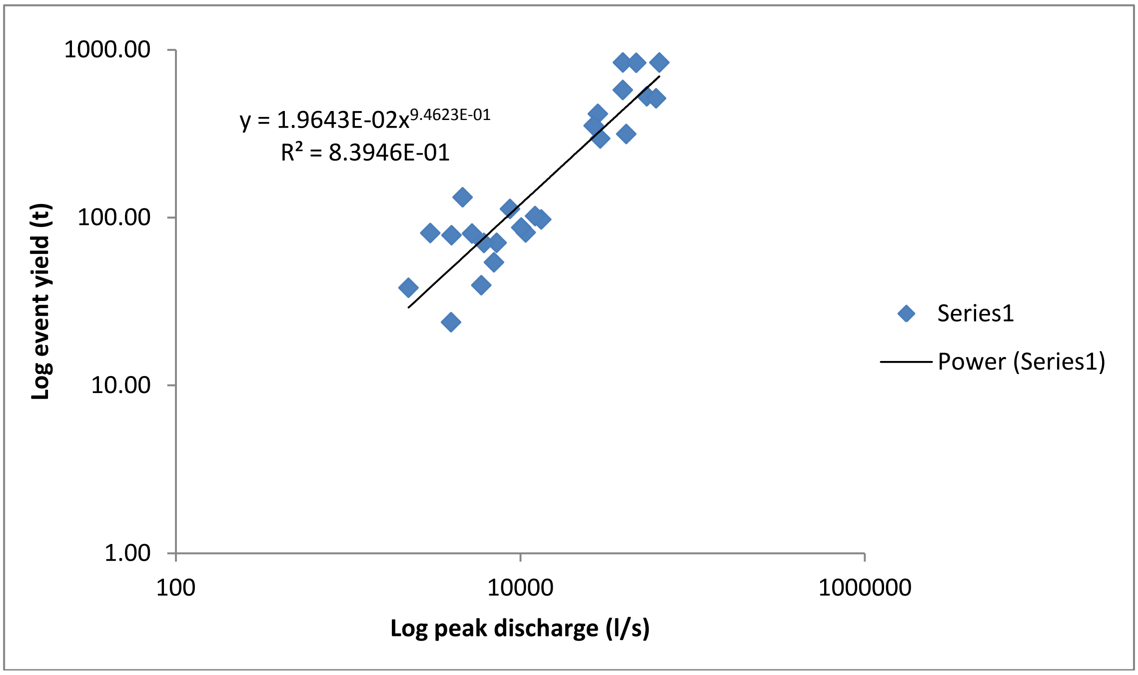


Figure D4. Kaukapakapa rating. The % estimate error in rating-estimated yield is 14%.

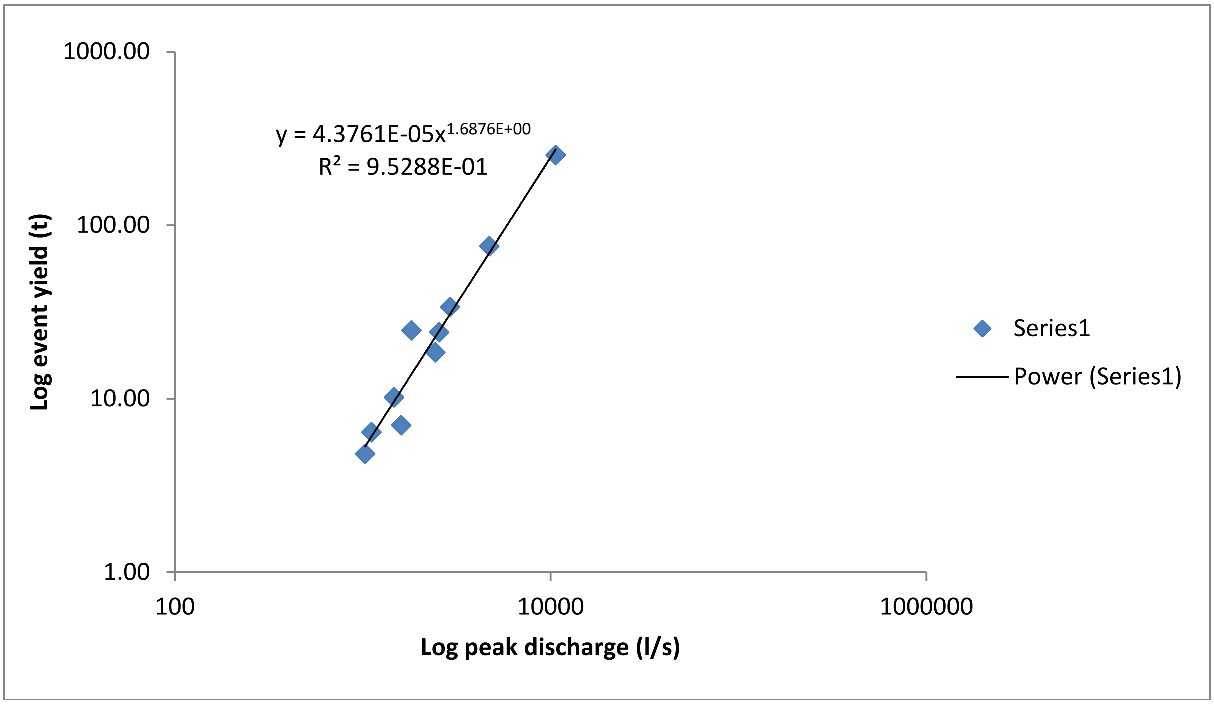


Figure D5. Mangemangeroa rating. The % estimate error in rating-estimated yield is 18.6%.

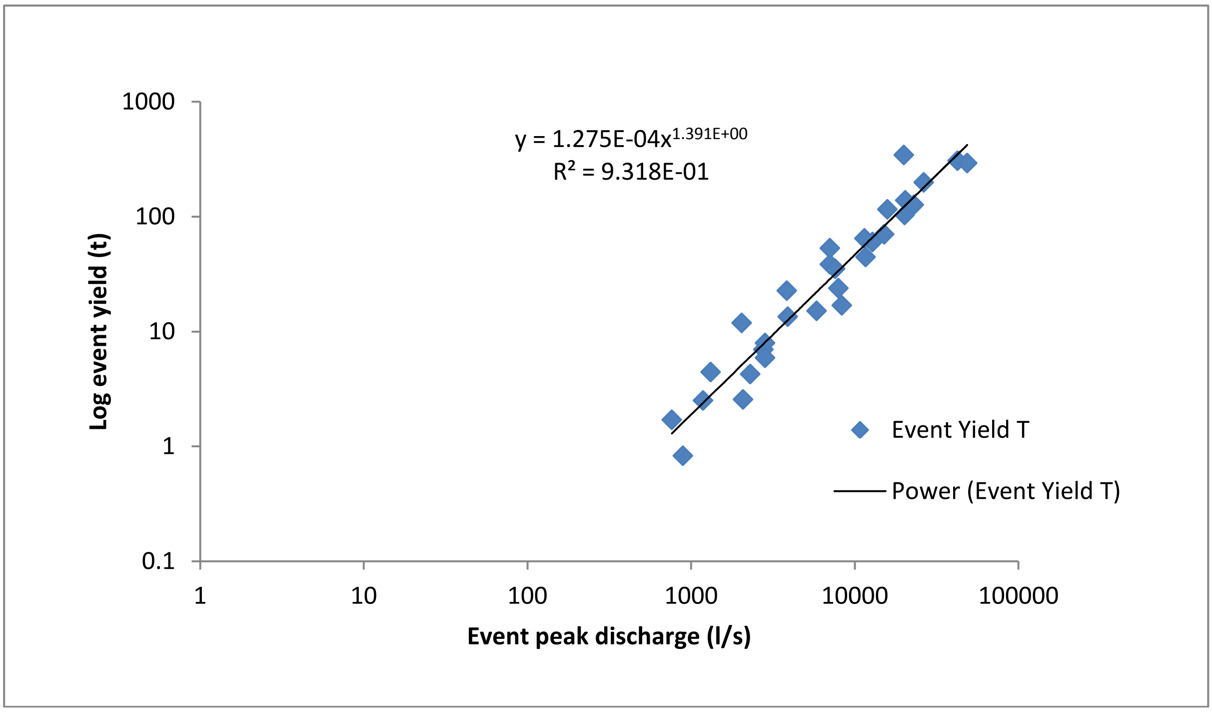


Figure D6. Orewa rating. The % estimate error in rating-estimated yield is 17.1%.

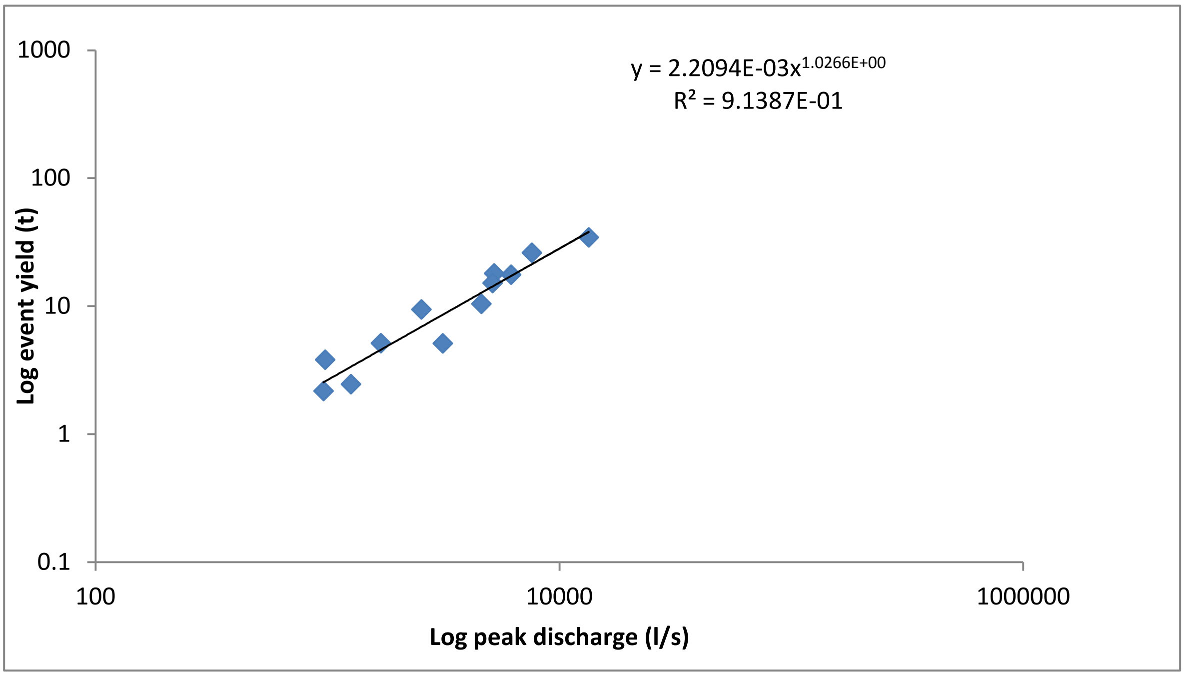


Figure D7. Vaughan rating. The % estimate error in rating-estimated yield is 10.2%.

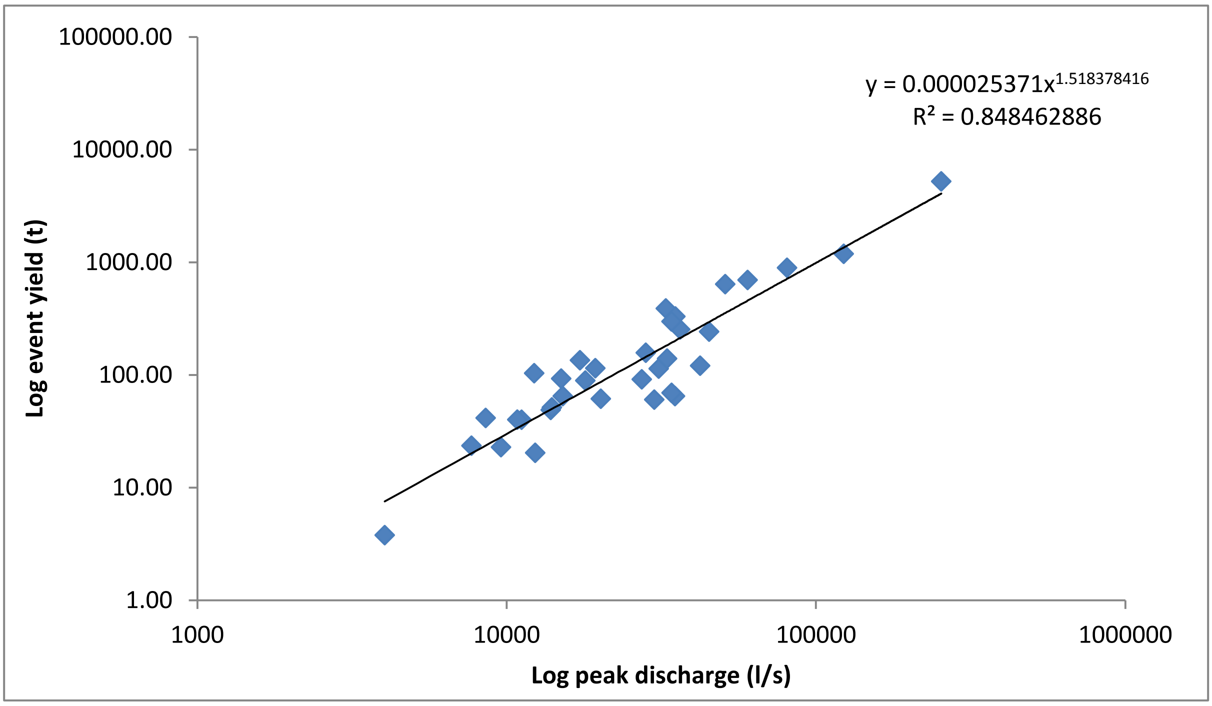


Figure D8. Wairoa rating. The % estimate error in rating-estimated yield is 30.5%.

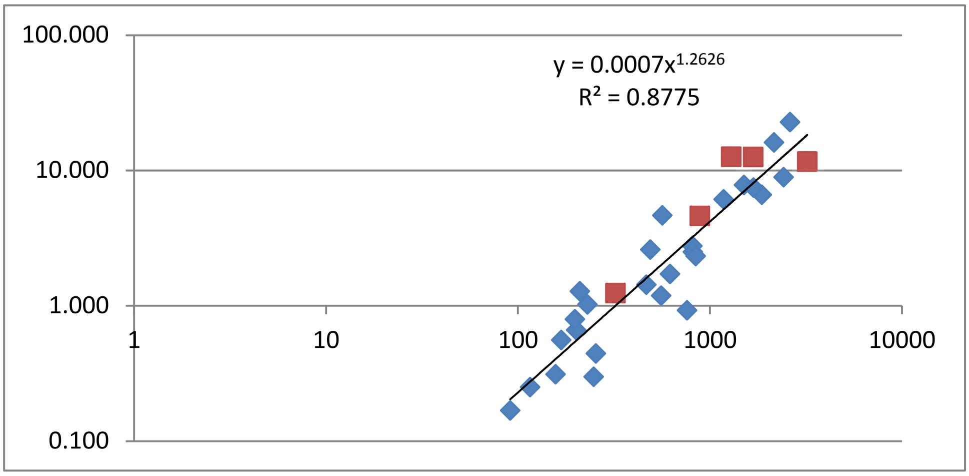


Figure D9. Weiti rating. The %estimate error in rating-estimated yield is 4.0%.The blue squares are rating events taken from Hoyle et al. (2012) up to March 2012 and the red squares are events used to develop the rating from March-December 2012.

9.5 Appendix E: Return period distributions

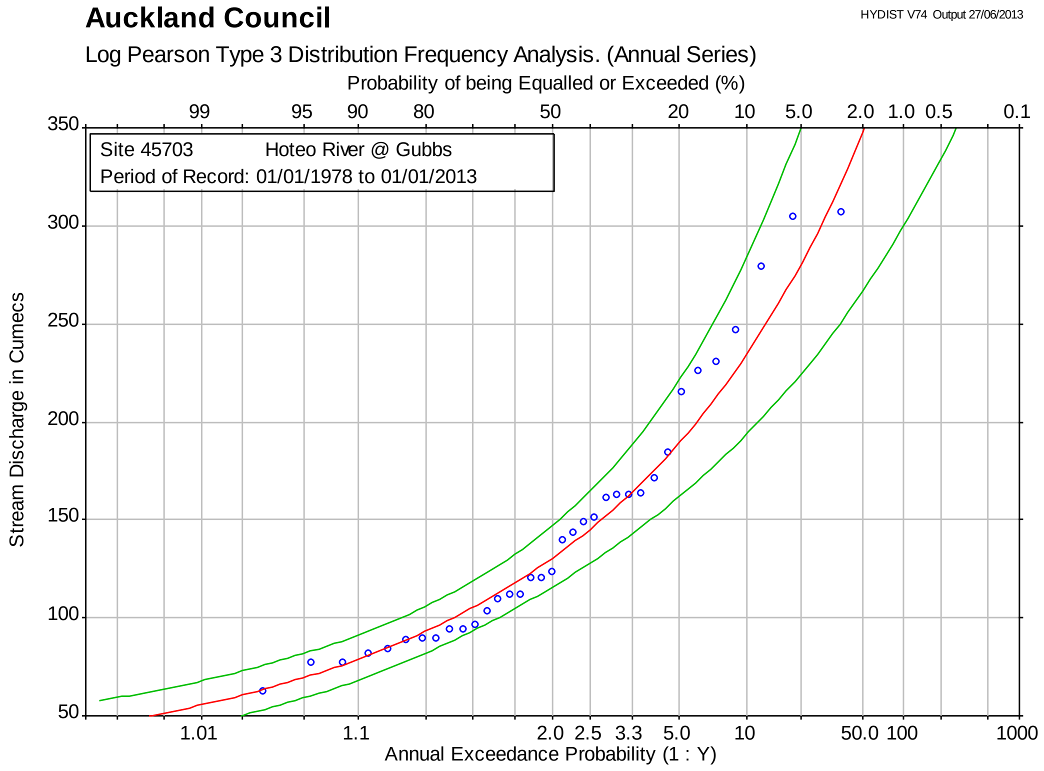


Figure E1. Return period distribution for the Hoteo catchment based on flow record.

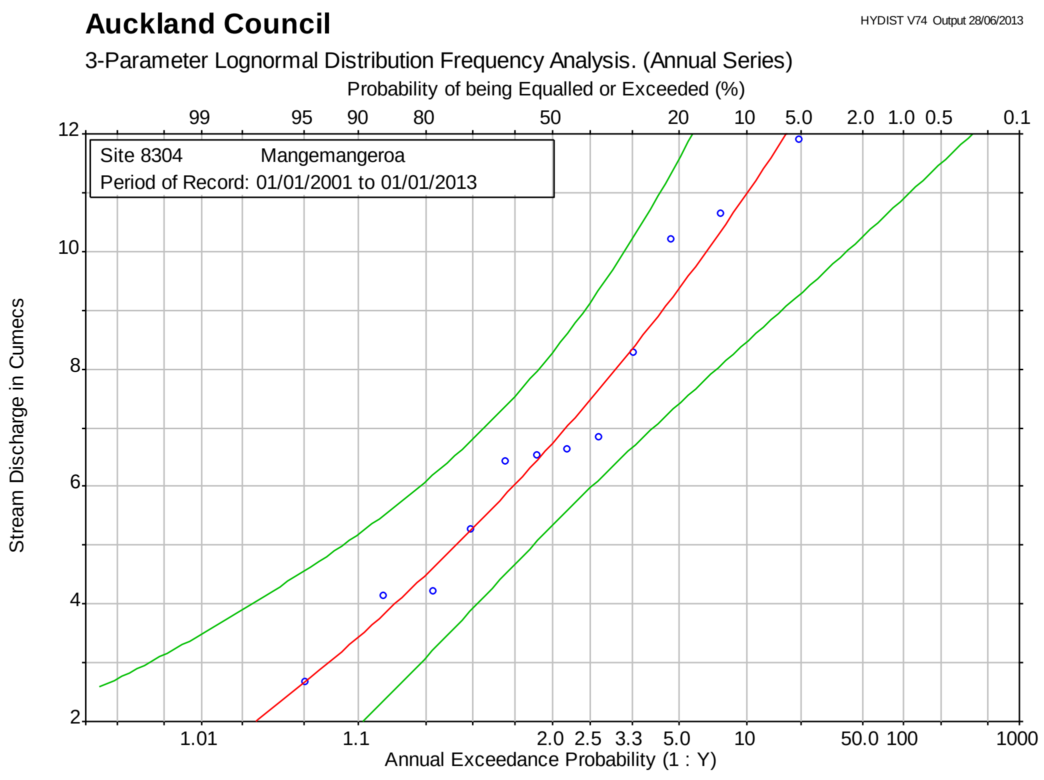


Figure E2. Return period distribution for the Mangemnageroa catchment based on flow record.

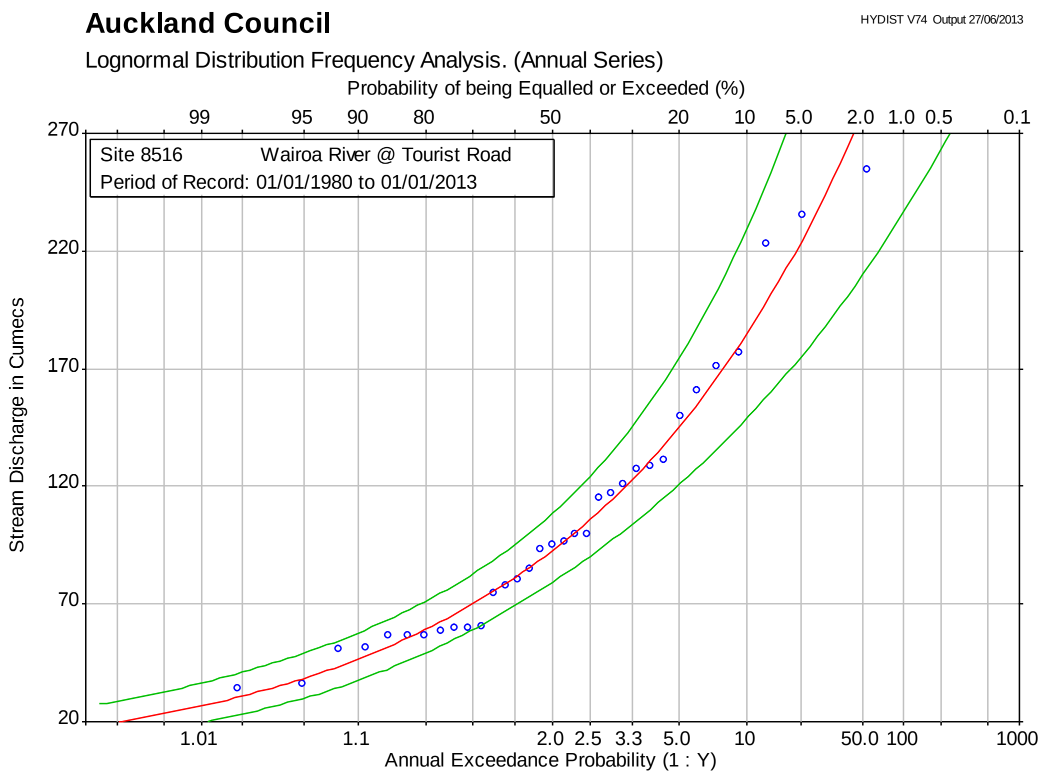


Figure E3. Return period distribution for the Wairoa catchment based on flow record.

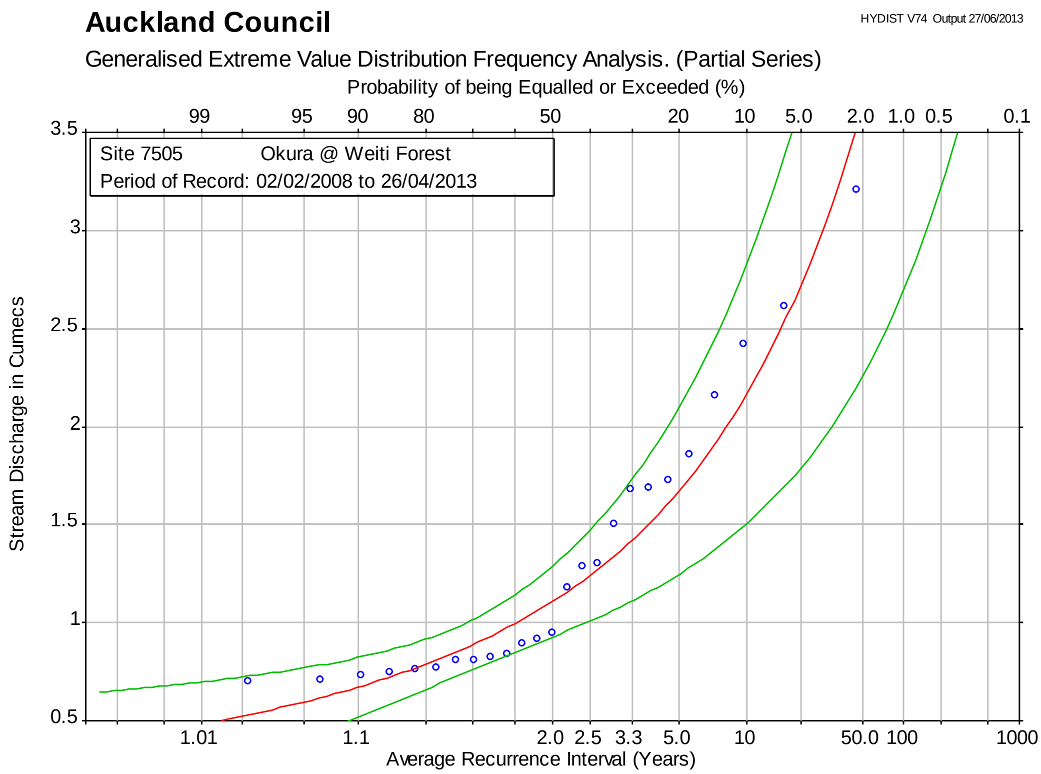


Figure E4. Return period distribution for the Weiti catchment based on flow record.