# Rural Catchment Sediment Yields from the Auckland Region. State of the Environment Reporting

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Research and Evaluation Unit RIMU

Auckland Council
Te Kaunihera o Tāmaki Makaurau

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The Hōteo River in flood during a storm event, photograph by Nicholas Holwerda (RIMU).

# Executive summary

The many rivers, streams, estuaries and harbours in the Auckland region provide extensive recreational, cultural, food harvesting and aesthetic values, but they can be degraded by elevated delivery of sediment from the land and from stream channel erosion during storm event runoff. Concern with sediment impacts on Auckland's coastal receiving environments has spanned the past several decades. For example, with targets set for reduction in coastal sediment delivery to priority marine receiving environments under the previous Auckland Plan[1]. More recently the Ministry for the Environment's National Policy Statement for Freshwater Management[2] has drawn attention to also limiting sediment impacts in in-stream environments.

Acknowledging ongoing sediment management issues and drivers, over the past decade Auckland Council has pursued a programme (the "Auckland Council event-based sediment monitoring network") to monitor predominantly rural stream sediment yields (derived from storm events) at a selection of river sites across the region. This knowledge will provide scientifically robust and defensible information to service multiple planning instruments and forms part of the state of the environment sediment management assessment through time. This programme supports Auckland Council's role in managing rural catchments to create a sustainable balance between environmental protection and rural production.

This report provides updated results to 31 December 2019 on sediment yields from 10 state of the environment sites across the rural Auckland landscape (information from an additional three sites outside this programme is also presented). At these sites, suspended sediment loads are sampled continuously during storm runoff events using automatic samplers operated on a flow-proportional basis. 'Rating' relationships between event sediment yield and event peak water discharge are used to estimate the sediment yields of any unsampled or inadequately sampled events.

The main findings are as follows:

On average, 71 per cent of the sediment yields of all 13 sites were well measured by flow-proportional auto-sampling during catchment runoff events.

The study confirms the importance of using the American Society for Testing and Materials (ASTM) method for laboratory analysis of suspended sediment concentration and of checking that auto-sampler-collected samples represent the average sediment concentration passing through the stream cross-section. It is recommended that further manual gaugings of the full cross-section suspended load are programmed at all sites, with priority given to those sites presently without any gaugings.

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[1] *The Auckland Plan*, March 2012. Auckland Council, Auckland.

[2] National Policy Statement for Freshwater Management 2020, New Zealand Government, Wellington August 2020.

There was an eight-year reference period (2012-2019) for which there were overlapping sediment records for eight of the 10 state of the environment sites. Over this period, specific suspended sediment yield from these eight catchments ranged from 19 t/km$^2$/y at the native-forested West Hoe reference catchment to 120 t/km$^2$/y at the largely pasture-covered Mangemangeroa catchment. Higher specific yields were recorded for several other sites (Te Muri and Oratia), but those sediment yields reflect their shorter periods of record, which encompassed several very wet years.

Further analysis of these eight sites over the reference period showed that the variation in their specific yields can be explained reasonably well in terms of predominant land cover and terrain steepness.

Four sites showed statistically significant trends through time in their event yield rating relationships across their full periods of sediment record, with Wairoa and Orewa showing increasing event yields for given sized floods, while Kaipara and Mangemangeroa showed decreasing event yields. The trend for increasing event yields observed at the Wairoa, despite erosion mitigation efforts, is likely an artefact of the extreme flood event that occurred there in March 2017. This flood delivered almost three times the mean annual sediment yield and likely activated erosion sites that persisted through 2019.

For the period 2012-2018, over which land cover change was surveyed, three of the study catchments experienced land cover change on more than one per cent of their area. These three all showed significant time trends in their event yield ratings over the same epoch. Vaughan and Orewa, with six to eight per cent of their areas urbanised from pasture over 2012-2018, both showed event yields increasing by about 12-16 per cent per year. Mangemangeroa, with about five per cent of its area converted from exotic forest to pasture, showed event yields reducing by about six per cent per year.

The large variability in annual sediment yields observed across the Auckland region limits the temporal resolution and precision of any programme to monitor progress on sediment yield reduction. This variability indicates that averaging windows in the order of 10 years are required to detect changes of 40 per cent or greater.

Monitoring change in the event yield rating provides finer temporal resolution because the variability of data occurs between events, not between years. However, it effectively only monitors changes in catchment erodibility and sediment availability for given sized hydrological events. Thus it may not capture changes in yields driven by the more frequent extreme rainfall and runoff events anticipated (at least across the southern part of the Auckland region) with future climate change[3].

[3] See: Pearce, P., Bell, R., Bostock, H., Carey-Smith, T., Collins, D., Fedaeff, N., Kachhara, A., Macara, G., Mullan, B., Paulik, R., Somervell, E., Sood, A., Tait, A., Wadhwa, S. and J-M. Woolley (2020*). Auckland Region climate change projections and impacts.* Auckland Council technical report, TR2017/030-3.

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# 1.0 Introduction

The many streams, estuaries and harbours in the Auckland region provide extensive recreational, cultural, food harvesting and aesthetic values. However, these water bodies can be degraded by elevated delivery of sediment from land and stream bank erosion during storm runoff. This sediment increases water turbidity and sediment mass concentration, binds gravelly substrates, and deposits drapes of mud on stream and estuary beds, adversely impacting ecosystem health and biodiversity (Bilotta and Brazier 2008; Davies-Colley et al. 2015). Moreover, transported sediment can act as a vector for other pollutants such as phosphorus, heavy metals and polycyclic aromatic hydrocarbons (Haygarth et al. 2006; Mills et al. 2012). Soils in themselves are a non-renewable and essential resource for food production.

The concern with sediment impacts on Auckland's coastal receiving environments has spanned the past several decades. For example, with targets previously set for reduction in coastal sediment delivery under the Auckland Plan (Auckland Council 2012). More recently, the National Policy Statement for Freshwater Management (NPS-FM) 2020 (MfE 2020) has drawn attention to also limiting sediment impacts in in-stream environments.

The primary metrics of interest for coastal sediment delivery relate to event and longer-term average suspended sediment yields, which are dominated by storm runoff. Acknowledging this, Auckland Council has, over the past decade, pursued a programme to monitor rural stream sediment yields from storm events at a network of sites across the region (the "Auckland Council event-based sediment monitoring network"). The original aim of this programme was to provide scientifically robust and defensible information to service multiple planning instruments and state of the environment evaluation requirements. To that may now be added the aim of providing information to help set catchment-wide sediment yield reduction targets to achieve NPS-FM objectives.

NPS-FM in-stream compliance is assessed through two graded attributes relating to fine sediment: water clarity (as a proxy for suspended fine sediment concentration) and deposited fine sediment cover on streambeds. Both of these attributes require being defined in terms of median values derived from discrete monthly state of the environment monitoring. By virtue of their sampling strategies, the monitoring of these in-stream sediment attributes is biased towards river baseflows and their link with event and mean annual yields is only indirect – insofar as there is an implicit expectation that improvements in sediment attribute metrics will relate linearly to reductions in mean annual sediment yields caused by catchment management to inhibit erosion (e.g., Dymond et al. 2017). In this framework, the Auckland Council event based sediment monitoring network also provides a valuable strategic resource for helping set catchment-wide sediment yield reduction targets to achieve NPS-FM objectives, complementing the regular discrete state of the environment monitoring which provides the tactical monitoring of the sediment-related attributes to check in-stream compliance. Further, adaptive soil erosion management strategies at a regional scale require a robust understanding of inter-annual variability of sediment yield.

The Auckland Council event-based sediment monitoring network was designed to be regionally representative (because we can't monitor every catchment) and stratified by catchment geology, climate and land cover (Hicks et al. 2009b), with sites intended to service one of four primary purposes:

- Calibration/baseline sites require catchments with relatively uniform land use and are intended to provide data on mean annual sediment yields and event yields for the purpose of calibrating predictive models, thus they are intended for short-term monitoring. They may also provide baseline data to demonstrate the effectiveness of sediment management policies.
- Validation sites are for monitoring sediment yields from larger catchments with sediment management schemes in place or with particularly sensitive downstream receiving environments, providing information to gauge the efficacy of management schemes and to validate predictions from catchment erosion models.
- Reference sites are those remaining relatively pristine in the long-term, so that their long-term monitoring can identify changes driven only by climate, without the confusing effects of land use change.
- Compliance sites are those in typically small catchments subject to development or activity where monitoring is required for evaluative purposes (e.g. forest harvesting).

Ten sites were drawn into or established for this network, with catchment sediment yield results up to 2012 reported by Curran-Cournane et al. (2013). At most of these 10 sites, a further seven years (2013-2019) of data has now been collected since Curran-Cournane et al. (2013) reported.

This report updates the data analysis from the Auckland Council event-based sediment monitoring network up to 31 December 2019 (10 sites). It also includes additional yield information from three sites from the upper Henderson catchment (Alley 2016), collected in support of a historical operational catchment management programme and reported here for completeness[4].

The length of the monitoring record covered by these 13 sites varies between catchments, spanning the period of 2008 to 2019, with a maximum record length of nine years and a minimum record length of three years at any given catchment. A standardized reference period of 2012-2019 was able to be assessed for eight of the 13 catchments to facilitate comparisons.

This report:

- Analyses the annual and spatial variability among the 13 monitored catchments.
- Provides baseline information on inter-annual variability in catchment sediment yields from the Auckland region.
- Considers relevant metrics to estimate changes in sediment yields over time and potential applications for setting targets over relevant time frames.
- Considers the impact of changes in land cover on suspended sediment yields over the reference period.

[4] Suspended sediment monitoring was also undertaken between 2012 and 2015 at two Auckland Council monitoring sites on the Waiteitei and Waiwhiu Streams (tributaries of the Hōteo River) for a NIWA-led research project. Sediment yield results for those sites are reported in Hughes et al. (2016).

## 1.1 Scope and objectives

The scope of this reporting was to analyse and report on suspended sediment yield results for the 13 sites monitored continuously for suspended sediment load as listed in Table 2-1, covering their full period of sediment record through to 31 December 2019.

This included:

- Quality-checking the data supplied by Auckland Council's Research and Evaluation Unit, RIMU.
- Adjusting the results for the use of different laboratory procedures.
- Adjusting point-sampling based loads to those representing the load carried over the whole stream cross-section.
- Developing 'rating' relationships between sediment yield and peak discharge for runoff events, using these to estimate yields during unsampled events and to explore for trends in yields through time.
- Generating records of event sediment yield matched with event peak flows and rainfall.
- Deriving annual and mean sediment yields, examining variability in annual sediment yields.
- Exploring for a suitable target statistic for monitoring in-stream and coastal outcomes resilient to interannual variability.
- Relating mean sediment yields to catchment land cover, with a focus on explaining differences in yields measured through a reference period over which as many sites as possible had consistent records.
- Correlating any land cover change over the monitoring period with observed temporal change in mean sediment yield.

# 2.0 Monitored rivers and catchments

## 2.1 River sites

The 13 river sites monitored for suspended sediment (Table 2-1) and river discharge drain catchments distributed across the Auckland region (Figure 2-1) and are predominantly in the northern half of the region.

**Table 2-1: Summary of suspended sediment monitoring sites.**
Suspended sediment and river discharge monitoring sites, associated rainfall sites, sediment data collection periods, and current site status. *Sites in italics are not part of the Auckland Council event-based sediment monitoring network.*

| Primary Purpose | River site and site no. | NZTM Easting | NZTM Northing | Rainfall site no. | Sediment monitoring site status | First sampling date | Last sampling date |
|---|---|---|---|---|---|---|---|
| Calibration/ baseline | Kaukapakapa River at Taylors – 45415 | 1735809 | 5945031 | 645519 | Open | 21/05/2010 | 18/12/2019 |
| Validation | Hōteo River at Gubbs – 45703 | 1735424 | 5972357 | 643510 | Open | 21/05/2010 | 16/10/2019 |
| | Kaipara River at Waimauku – 45311 | 1733345 | 5930348 | 647510 | Open | 12/03/2012 | 18/12/2019 |
| | Mangemangeroa Stream at Craigs – 8304 | 1772261 | 5910514 | 649941 | Open | 3/07/2012 | 16/10/2019 |
| | Orewa Stream at Kowhai Ave – 7202 | 1748295 | 5948502 | 646619 | Open | 5/07/2009 | 10/11/2019 |
| | Te Muri Stream at Te Muri Farm – 6995 | 1752915 | 5957910 | 645714 | Open | 29/12/2013 | 15/10/2019 |
| | Vaughan Stream at Lower Weir – 7506 | 1755442 | 5938731 | 647739 | Open | 3/07/2012* | 17/12/2019 |
| | Wairoa River at Tourist Road – 8516 | 1782663 | 5901676 | 750010 | Open | 21/05/2010 | 17/10/2019 |
| Compliance | Weiti Stream at Weiti Forest – 7505 | 1751872 | 5940969 | 646622 | *Closed* | 15/04/2008 | 6/12/2016 |
| Reference | West Hoe Stream at Hall Farm – 7206 | 1748302 | 5950580 | 646619 | Open | 9/05/2012 | 15/10/2019 |
| *Upper Henderson Catchment Management Programme* | *Opanuku Stream at Candia – 7904* | *1742162* | *5915566* | *648517* | *Closed* | *2/01/2016* | *26/12/2018* |
| | *Oratia Stream at Parrs Cross – 7955* | *1735424* | *5972357* | *649636* | *Closed* | *27/01/2016* | *26/12/2018* |
| | *Swanson Stream at Woodside Reserve – 7907* | *1743783* | *5919897* | *648516* | *Closed* | *8/01/2016* | *26/12/2018* |

*There was a short period of monitoring at Vaughan Stream from 2001-2005 and then a break until 03/07/2012. The 2001-2005 data were analysed by Curran-Cournane et al. (2013). This report focusses on the data from July 2012.

All but Opanuku Stream at Candia, Oratia Stream at Parrs Cross, Swanson Stream at Woodside Reserve, and Weiti Stream at Weiti Forest currently remain operational.


**Figure 2-1: The 13 storm-event sediment monitoring sites and their catchments, with associated rainfall monitoring sites.**

## 2.2 Catchment characteristics

River catchment characteristics are summarised in Table 2-2. As described in Curran-Cournane et al. (2013), catchment area, geology, slope, soils and land cover were determined by Auckland Council staff using ArcGIS. Geology, soil order and slope were extracted from the New Zealand Land Resource Inventory (NZLRI 2010a, 2010b, 2010c).

Catchment areas range between 0.3 $km^2$ (Te Muri) and 268 $km^2$ (Hōteo), with nine catchments having areas less than 23 $km^2$ and two less than 1 $km^2$.

Geology varies, but with Waitematā Formation (interbedded sandstone and mudstone) prevalent in most catchments. Exceptions are the three Henderson Creek tributaries (Opanuku, Oratia and Swanson, which have bedrock of volcanic origin), Wairoa (greywacke), and Kaukapakapa, Orewa and Weiti (predominantly mudstone).

Ultic soils generally predominate, except in the three Henderson Creek tributaries and the Wairoa, which have mainly granular soils by virtue of their different geologies. Dominant slope types are typically rolling to strongly rolling, but are moderately steep to steep at Hōteo, Opanuku, Wairoa and West Hoe.

Land cover[5] (Figure 2-2) is predominantly rural pasture at Hōteo, Kaipara, Kaukapakapa, Mangemangeroa, Orewa, Te Muri, Vaughan and Wairoa. Native forest dominates at Opanuku, Oratia, Swanson and West Hoe, while exotic forest dominates at Weiti. Land cover change between 2012 and 2018 (which spans most of the sediment monitoring period at most sites) is discussed in Section 5.4.

Catchment mean annual rainfall was calculated from the automatic rain-gauge associated with each river site (Table 2-1) for the full calendar years associated with the period of storm-event sediment monitoring (i.e. if sediment monitoring spanned May 2012 through December 2019, then the rainfall is averaged over all of 2012-2019). Mean annual runoff (equal to mean water discharge in l/s multiplied by the number of seconds in a year and divided by catchment area in $m^2$) at the river sediment monitoring site was determined for the same period.

Mean annual rainfall associated with the river sediment monitoring ranged from 1,159 mm at Orewa (2009-2019) up to 1,883 mm at Opanuku (2016-2018). Long-term average rainfall patterns across the Auckland region (Figure 2-3) show areas of higher rainfall in the region's north-east (over the Hōteo-Kaipara catchments), in the south-

[5] Several hierarchical land cover classifications are available for the Auckland region. The one used in this report is derived from the New Zealand Land Cover Database V5.0 (Manaaki Whenua – Landcare Research) and aggregated as per Table A-1, Appendix A.

east (over the Wairoa), and in the south-west (over the Henderson tributaries). These patterns are reflected in the figures for the storm-event sediment monitoring period (Table 2-2), but it is of note that the three-year sediment monitoring period at the three Henderson tributaries (Opanuku, Oratia and Swanson) spanned a wetter than average period, so their average rainfalls listed in Table 2-2 will exceed their long-term averages.

Mean annual catchment runoff ranged between 366 mm at Vaughan Stream (2012-2019) and 1,302 mm at Oratia Stream (2016-2018) – again with the latter determined by the wetter-than-average 2016-18 period. Catchment runoff ratios (i.e. runoff divided by rainfall) ranged between 0.31 (exotic forest dominated Weiti and mixed land cover Vaughan) and 0.72 (native forest dominated Oratia). This variation primarily reflects the influences of vegetation cover (on rainfall interception and evapotranspiration) and catchment geology (on catchment permeability and hence runoff losses to groundwater) but will also be influenced by how well each rain-gauge represents the average rainfall over the catchment.

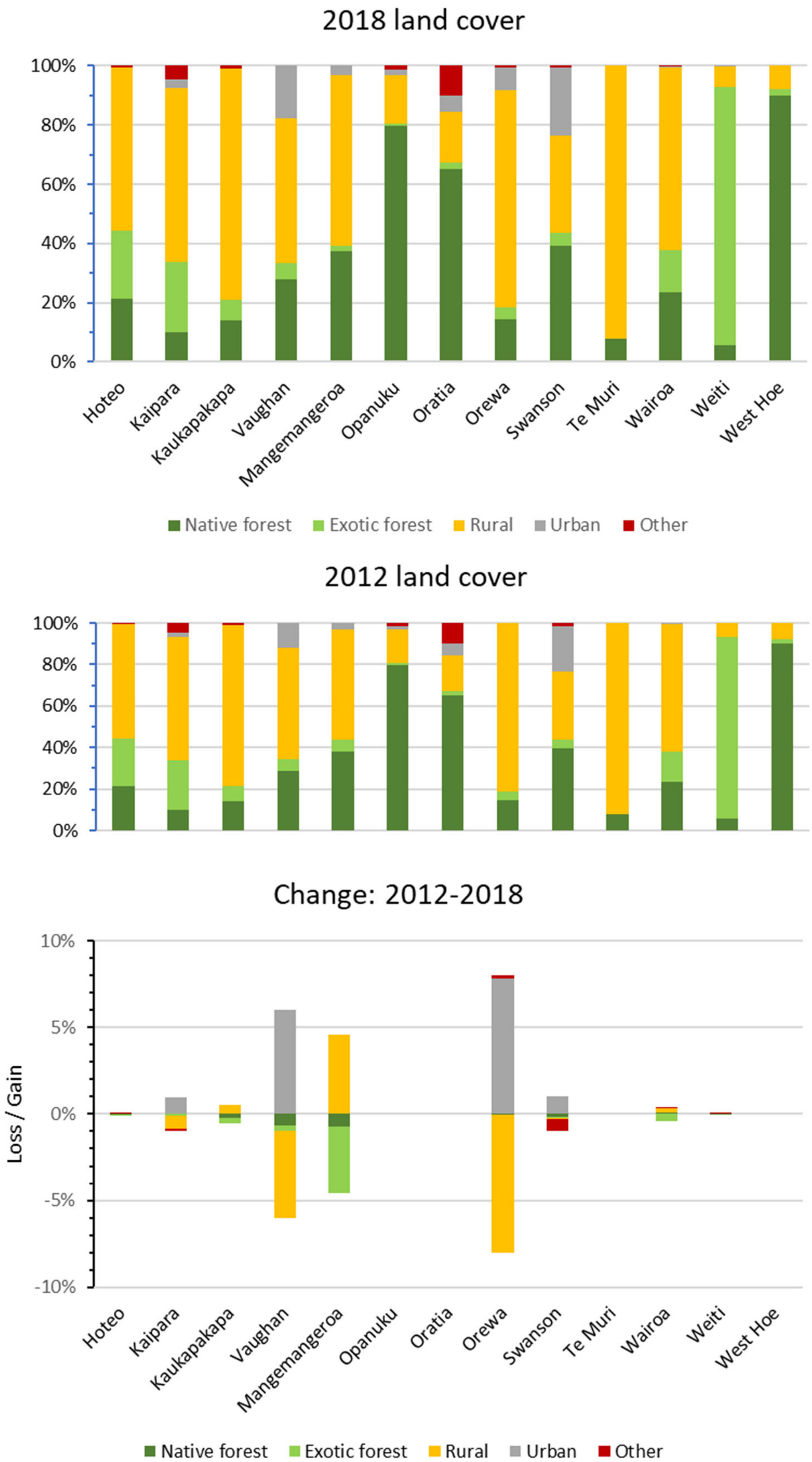


**Figure 2-2: Land cover and land cover change for the study catchments, 2012 and 2018.**

**Table 2-2: River catchment characteristics summary.**

| Site | Area ($km^2$) | Geology (top 3 components listed) | Land cover (2018, components >5% listed) | Soil order (dominant) | Slope (dominant) [2] | Mean annual rainfall (mm/y)[3] | Mean annual runoff (mm/y)[4] | Runoff ratio |
|---|---|---|---|---|---|---|---|---|
| Hōteo River | 268 | Waitematā (77%)<br>Mudstone (8%)<br>Alluvium (8%) | Rural (55%)<br>Exotic forest (23%)<br>Native forest (21%) | Ultic (75%)<br>Recent (16%) | Moderately steep (44%) | 1383 | 684 | 0.49 |
| Kaipara River | 163 | Waitematā (45%)<br>Alluvium (34%)<br>Sand/dune (10%) | Rural (59%)<br>Exotic forest (24%)<br>Native forest (10%) | Ultic (43%)<br>Allophanic (25%) | Rolling (35%) | 1373 | 647 | 0.47 |
| Kaukapakapa River | 62 | Mudstone (33%)<br>Waitematā (25%)<br>Alluvium (23%) | Rural (78%)<br>Native forest (14%)<br>Exotic forest (7%) | Ultic (74%)<br>Allophanic (13%) | Rolling (39%) | 1319 | 542 | 0.41 |
| Mangemangeroa Stream | 4.5 | Waitematā (100%) | Rural (57%)<br>Native forest (37%) | Ultic (100%) | Strongly rolling (51%) | 1251 | 468 | 0.37 |
| Opanuku Stream | 15.8 | Volcanic-sandstone (50%)<br>Turbidite (21%)<br>Andesite (11%) | Native forest (80%)<br>Rural (17%) | Granular (67%)<br>Brown (32%) | Steep (32%)<br>Moderately steep (34%) | 1883 | 993 | 0.53 |
| Oratia Stream | 16.8 | Volcanic-sandstone (45%)<br>Turbidite (39%) | Native forest (65%)<br>Rural (17%)<br>Urban (6%) | Granular (88%)<br>Allophanic (6%) | Strongly rolling (37%)<br>Rolling (46%) | 1807 | 1302 | 0.72 |
| Orewa Stream | 9.7 | Mudstone (50%)<br>Waitematā (26%)<br>Alluvium (23%) | Rural (73%)<br>Native forest (14%)<br>Urban (8%) | Ultic (89%)<br>Gley (11%) | Rolling (52%) | 1159 | 586 | 0.51 |
| Swanson Stream | 22.6 | Volcanic-sandstone (40%)<br>Turbidite (39%) | Native forest (39%)<br>Rural (33%)<br>Urban (23%) | Granular (40%)<br>Ultic (32%)<br>Allophanic (20%) | Strongly rolling (23%)<br>Rolling (49%) | 1760 | 924 | 0.53 |
| Te Muri Stream | 0.3 | Waitematā (99%)<br>Alluvium (1%) | Rural (92%)<br>Native forest (8%) | Ultic 100% | Moderately Steep (100%) | 1252 | 469 | 0.37 |

| Site | Area ($km^2$) | Geology (top 3 components listed) | Land cover (2018, components >5% listed) | Soil order (dominant) | Slope (dominant) [2] | Mean annual rainfall (mm/y)[3] | Mean annual runoff (mm/y)[4] | Runoff ratio |
|---|---|---|---|---|---|---|---|---|
| Vaughan Stream | 2.3 | Waitematā (97%)<br>Limestone (3%) | Rural (49%)<br>Native forest (28%)<br>Urban (18%)<br>Exotic forest (6%) | Ultic (90%) | Strongly rolling (53%) | 1176 | 366 | 0.31 |
| Wairoa River | 114 | Greywacke (58%)<br>Waitematā (33%)<br>Alluvium (6%) | Rural (70%)<br>Native forest (15%)<br>Exotic forest (15%)<br>Other (2%) | Granular (36%)<br>Ultic (28%) | Moderately steep (29%) | 1491 | 730 | 0.49 |
| Weiti Stream | 1.7 | Mudstone (51%)<br>Limestone (42%) | Exotic forest (87%)<br>Rural (7%)<br>Native forest (6%) | Ultic (100%) | Rolling (51%) | 1271 | 394 | 0.31 |
| West Hoe Stream | 0.5 | Waitematā (100%) | Native forest (90%)<br>Rural (8%) | Ultic (100%) | Moderately steep (74%) | 1159 | 466 | 0.40 |

[1] Other includes cropping, bare ground and water body.

[2] Slope types defined in Appendix A, Table A-2.

[3] Measured at sites listed in Table 2-1 for full calendar years spanning sediment record in Table 2-1.

[4] Measured at sediment site for full calendar years spanning sediment record in Table 2-1.

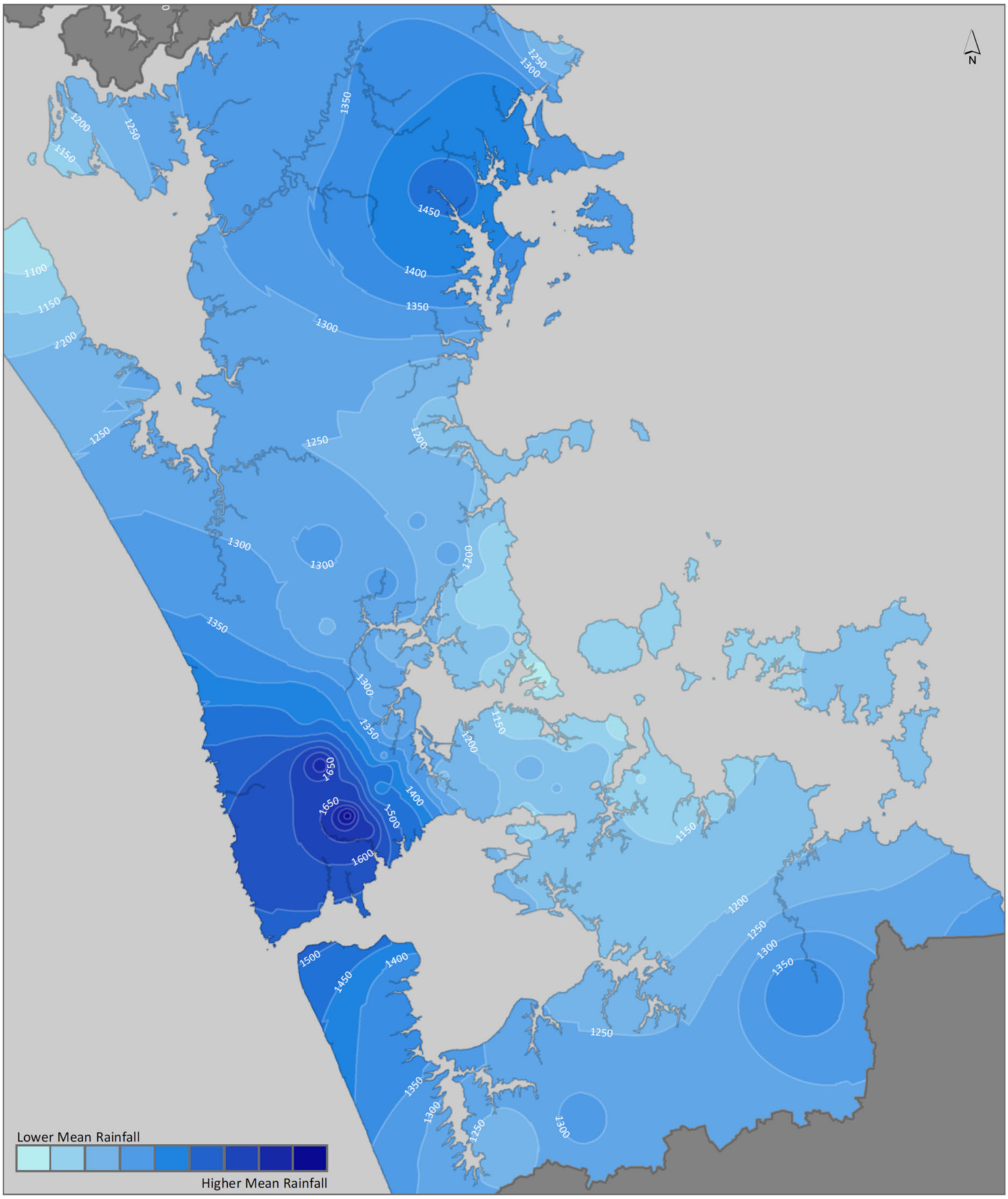


**Figure 2-3: Long-term mean annual rainfall patterns across the Auckland region[6].**

[6] Rainfall sites in the Auckland Council Hydstra database were ranked according to the length of record. All sites with a starting date on or before 1 January 2000 were selected for further use, comprising a total of 55 sites. Hydstra data analytics were used to generate seasonal statistics for each rainfall site, including the median, mean, min, and max. Rainfall isohyet maps were generated using inverse distance weighted (IDW) interpolation of mean rainfall depths.

# 3.0 Data collection and analysis methods

## 3.1 River discharge and rainfall

River discharge and rainfall are monitored in each study catchment by Auckland Council's Research and Evaluation Unit (RIMU) staff. By necessity, river discharge is monitored at the same location as the sediment monitoring (since the river discharge is required to both schedule sediment samples and calculate the sediment load), hence the site name and number for the river discharge and sediment records coincide. The matching rainfall site is listed in Table 2-1 and located on Figure 2-1. Rainfall is monitored using automated "tipping-bucket" gauges that typically record when each approximately 0.5 mm of rain has fallen.

## 3.2 Suspended sediment auto-sampling

The suspended sediment load at the study sites was monitored continuously during storm runoff events using automatic samplers (ISCO model 3700s, with 24 sample bottles). At most river sites, the auto-samplers were operated in flow-proportional compositing mode, that is, the rate of sampling was proportional to the stream flow rate (four to eight samples were composited into each sampler bottle; see Figure B-1, Appendix B for an example). At Hōteo and Weiti, the automated samples were collected flow-proportionally but not composited. At West Hoe, compositing occurred after 1 September 2017. Sampling was controlled by the data-logger that monitors the stream stage (i.e. water level above a known point). Sampling was activated during events when a stage threshold was passed and water samples were triggered when a fixed volume of water had passed the monitoring point, as calculated by the data logger which is programmed with the site's stage-discharge rating. The higher the flow rate the shorter the time interval between collection of water samples. With compositing, the suspended sediment concentration (SSC, mg/l) in a filled sample bottle, multiplied by the water volume discharged while the sample was accumulated (l), determines the mass load of sediment (mg) carried by the stream over this period. Adding the transported sediment mass associated with each bottle filled over a catchment runoff event provides the mass yield over the event. Compositing samples increases the endurance of a sampler (allowing collection of up to 24x8 = 192 samples before bottle replacement, compared with just 24 samples without compositing) and so increases the temporal resolution of the sampling. It also reduces laboratory costs for analysing SSC. Without compositing, bottle SSCs are instantaneous values and the sediment load over the time interval between consecutive samples is determined by multiplying their average SSC by the water volume discharged over that interval.

The stage threshold to initiate storm event sampling was site-specific and set based on winter base-flow levels. The sampling trigger volume was also site-specific and was set so that whole events were typically well sampled. RIMU staff remotely monitored the status of the auto-samplers so that bottles could be changed expediently.

This flow-proportional composite auto-sampling followed protocols now detailed in the National Environmental Monitoring Standard for suspended sediment (NEMS 2020).

On occasion, auto-samplers suffered mechanical break-down or the auto-sampler's bottle supply was exhausted before the storm event ran its course and it was not possible to replace the bottles. Less often, there were periods (typically several months) when the auto-samplers were "off-line" or absent. In such cases, event sediment yields were either only partly sampled or not sampled at all. In either case, gaps in the event yield record have been "patched" using the event yield rating curve with the recorded event peak discharge to estimate the unsampled event yields (Section 3.6.2).

## 3.3 Periods of record

The period of suspended sediment data collection covered in this report varies among river sites (Table 3-1). Commencement of data collection ranged from 15 April 2008 at Weiti Stream to 27 January 2016 at Oratia Stream. At most sites, data collection continued through until late 2019 (whenever the last storm runoff event occurred, which ranged between October and December for different sites); however, data collection ceased on 26 December 2018 at Opanuku, Oratia and Swanson Streams and on 6 December 2016 at Weiti Stream. The sediment records of all 13 sites overlapped only in 2016. Eight sites had overlapping records between 2012 and 2019, and this has been the focus of the comparison reported here.

**Table 3-1: Duration of suspended sediment record at study sites.**
**X** – full calendar year monitored; x – part calendar year monitored. Start and end dates for monitoring listed in Table 2-1.

| Stream | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hōteo | | | x | **X** | **X** | **X** | **X** | **X** | **X** | **X** | **X** | x |
| Kaipara | | | | | x | **X** | **X** | **X** | **X** | **X** | **X** | **X** |
| Kaukapakapa | | | x | **X** | **X** | **X** | **X** | **X** | **X** | **X** | **X** | **X** |
| Mangemangeroa | | | | | x | **X** | **X** | **X** | **X** | **X** | **X** | x |
| Orewa | | x | **X** | **X** | **X** | **X** | **X** | **X** | **X** | **X** | **X** | x |
| Te Muri | | | | | | | **X** | **X** | **X** | **X** | **X** | x |
| Vaughan | | | | | x | **X** | **X** | **X** | **X** | **X** | **X** | **X** |
| Wairoa | | | x | **X** | **X** | **X** | **X** | **X** | **X** | **X** | **X** | x |
| Weiti | x | **X** | **X** | **X** | **X** | **X** | **X** | **X** | x | | | |
| West Hoe | | | | | x | **X** | **X** | **X** | **X** | **X** | **X** | x |
| *Opanuku* | | | | | | | | | *x* | ***X*** | *x* | |
| *Oratia* | | | | | | | | | *x* | ***X*** | *x* | |
| *Swanson* | | | | | | | | | *x* | ***X*** | *x* | |

## 3.4 Laboratory analysis

All water samples collected were sent to an ISO (International Organisation for Standardisation) accredited laboratory for analysis of suspended sediment concentration (SSC).

Generally, after mid-2012, water samples were analysed in the laboratory for SSC using the ASTM D 3977-97 method (ASTM 2007), which analyses the full sample returned from the field. Prior to mid-2012, samples were analysed for total suspended solids (TSS) using the TSS laboratory method (APHA 2005), which analyses only a sub-sample of the field-collected sample. The laboratory method was changed in 2012 in acknowledgment that numerous studies had shown that the TSS approach performs erratically and is prone to bias, particularly when sand content is >25% (Gray et al. 2000). United States Geological Survey (USGS) studies have concluded that the only practical way of correcting historical TSS results to SSC is by collecting duplicate samples for analysis by both methods, then developing site-specific empirical relationships between TSS and SSC (Glysson et al 2000; Ward 2000).

Of the sites where sampling began before mid-2012 (Kaipara, Kaukapakapa, Orewa, Wairoa and Weiti), the TSS results compiled before mid-2011 to mid-2012 (depending on the site) have been corrected to SSC-equivalent values using site-specific relationships derived from paired analysis of samples using the SSC and TSS methods (Appendix C). This was not done for the Hōteo and Vaughan sites, but given that most of the other sites showed near 1:1 relationships, it is reasonable to assume 1:1

relationships held at those two sites also. Moreover, both catchments have predominantly clay-rich Ultic soils which are expected to render a suspended load that is predominantly mud-grade and therefore less prone to TSS bias. Where the TSS method remains in use for the purpose of measuring suspended sediment load, it is important to check (and if need be correct) for systematic differences between TSS and SSC results.

All samples from Mangemangeroa, Opanuku, Oratia, Swanson, Te Muri and West Hoe were analysed with the SSC method.

## 3.5 Data quality checks

Data quality checks for this study involved reviewing the river flow records and the sediment data. Details are provided in Appendix D.

In brief:

- The flow records were checked for gaps, particularly to identify periods of missing flow record that contained significant runoff events. When such gaps were identified, RIMU staff provided "infill" runoff event peak discharges that were estimated from flow records from nearby sites.
- The raw sediment data were scanned and corrected for erratic data, point-SSC to cross-section-averaged relationships were applied where available and needed, and the suitability of sampled events for determining event sediment yield and for developing the event yield rating was checked.
- The event yield ratings were checked and corrected for time-trends as needed.
- The master lists of events were checked for missing events and correct application of the event rating when needed.

## 3.6 Sediment yield calculation

### 3.6.1 Correction to cross-section average SSC

Incomplete sediment mixing over the stream cross-section can mean that the SSC of auto-sampler-collected water samples ($C_p$), which are collected at a typically-bankside point, may not be the same as the discharge-weighted cross-section average SSC ($C_m$), which is the parameter required to determine the stream sediment load (NEMS 2020). Accordingly, as detailed in Appendix E, manual sediment gaugings were undertaken and matched with auto-sampled SSC during storm flows at nine of the study sites, and corrective relations were developed as needed. Mostly, there was no significant relationship between $C_m/C_p$ and discharge, nor was $C_m/C_p$ significantly different from 1, so no corrective action was required. Therefore, auto-samplers appear to provide a reasonable representation of the cross-section mean SSC at most of the sites in the RIMU network, likely by virtue of a predominantly mud-grade suspended load across much of the region. However, a correction function was required at Kaukapakapa and Orewa (Appendix E, Table E-1).

### 3.6.2 Event yields and ratings

Event sediment yields from well-sampled events were used to compile event yield "ratings" for each site. These rate event yields against event peak discharge and are used for two purposes. The first purpose is to estimate the yield from events that were either poorly sampled or not sampled at all, which can occur due to auto-sampler breakdown or simply because the sampler has run out of bottles. The second purpose is to identify temporal change in sediment availability in the catchment. For example, a "lift" in the sediment rating function indicates that more sediment is delivered from a given-sized hydrological event (as indexed by peak discharge), such as might occur with a change from forest to pasture land-cover.

The events used to compile the event yield ratings were all single-peak events chosen when inspection by RIMU staff of the event hydrograph and distribution of samples showed that samples had been collected over the majority of the event "quickflow". Quickflow is the portion of the total hydrograph associated with relatively rapid storm runoff, as against that which stems from "delayed" flow and is separated on hydrographs using a site-specific separation slope that was fitted by RIMU staff by visual inspection. Multi-peak quickflow events were avoided in the rating because these can induce a wide range of sediment yields.

The event yield ratings were defined by power law functions of the form $S = aQ_p^b$, where S is the event sediment yield (t), $Q_p$ is the event peak discharge (l/s), and a and b are coefficients. These were fitted in Excel using linear regression to the log-transformed data. The coefficient 'a' was adjusted with Duan's (1983) "smearing estimator" to remove the bias that results from the log transformation of S (this factor is the average ratio of observed/predicted event yield, $S_{obs}/S_{pred}$, across the rating dataset).

The error on any event yield predicted by the event rating, $S_e$, expressed as a proportion, was determined as:

$$S_e = e^{se} - 1$$

where the exponential constant e = 2.71828, $se = s(1 + 1/n + (Q_{pt} - Q_{pm})^2/\Sigma_i(Q_{pi} - Q_{pm})^2)^{0.5}$, s is the standard error of the regression estimate (as fitted in log-log space), n is the number of data pairs used to fit the rating, $Q_{pt}$ is the peak discharge of the event being predicted, $Q_{pm}$ is the mean peak discharge across the rating dataset, and $Q_{pi}$ is the peak discharge of each event in the rating dataset.

### 3.6.3 Time-trends shown by event yield ratings

The “residuals” of the observed event yields and those predicted by the event ratings in natural log-space (i.e. $\log_e S_{obs} - \log_e S_{pred}$ which is the same as $\log_e S_{obs}/S_{pred}$) were examined for a time-trend by regressing $\log_e S_{obs}/S_{pred}$ against event date. The resulting function was $S_{obs}/S_{pred} = e^{cDate}.e^{d}$, where c and d are regression coefficients and Date is the date of the event in Excel date format (i.e. days since 1 January 1900). A trend was identified if the slope of this regression relation (defined by the c coefficient in log space) was significantly different from zero (at the 5% significance level using a two-tailed t-test). In such cases, this time-trend function was combined with the event rating function to make the rating time-dependent. The coefficient c enables the rate at which $S_{obs}$ diverges from $S_{pred}$ on a yearly basis to be determined. For example, if c = -0.00016 (as was determined at Mangemangeroa), then this indicates that each year from 2012-2020 the observed event yield (for a given sized event peak discharge) reduced by 5.7% from the previous year.

### 3.6.4 Accumulated yield, mean yield, and specific yield

The accumulated sediment yield over the record period was the sum of the sediment yields of all events, sampled and unsampled (i.e. predicted).

The error in the accumulated sum of predicted event yields was determined by the root-sum-square approach. That is, if $(S_e \times S_{pred})_j$ is the error in the jth predicted event, then the accumulated error in the yield summed over all predicted events is $(\Sigma_j (S_e \times S_{pred})_j^2)^{0.5}$. This approach assumes that the errors in the predicted event yields of sequential events are independent. The error in sampled events was assumed negligible compared to the error in the unsampled/predicted events.

The mean sediment yield (also termed the mean annual sediment yield) over the record period was the accumulated yield divided by the record period duration (years). The specific sediment yield is the mean sediment yield divided by catchment area.

Note that this accumulated yield is for storm events only. It assumes that the sediment yields during baseflows (i.e. at stages lower than the trigger stage for auto-sampling) are small compared to those carried during storm runoff. Support for this approximation is provided by Hicks et al. (2009a), who used relationships between instantaneous SSC and water discharge to estimate both base flow and storm flow yields at eight sites in the Auckland region. They found that storm flows carried 74-93% of the total yield, depending on the site.

# 4.0 Site-by-site results

## 4.1 Overview

This section presents information and results from the 13 study catchments in a common format that covers:

- Catchment description.
- Record period.
- Corrections made to convert auto-sampled SSC to equivalent cross-section average SSC.
- The event sediment yield vs event peak discharge “rating” curve, developed from well-sampled, single-peak events and used to estimate the yield of un-sampled or poorly-sampled events.
- Analysis of the event rating “residuals” to assess if there is a time trend shown by the ratio of observed/predicted event yield.
- Results on sediment yield, mean yield over the record period, specific yield, and uncertainty estimates.

Key information/results are tabled, and Table 4-1 provides guidance on interpreting these items. Plots are provided of the event rating and its associated observed/predicted time trend and of the time-cumulative sediment load aligned with time-series plots of runoff event peak discharge and daily rainfall.

Supplementary data files of sediment yields for all events over the record period, sampled or rating-estimated, as presented in this report are also available on Knowledge Auckland, www.knowledgeauckland.org.nz. For further enquiries and data supply, email environmentaldata@aucklandcouncil.govt.nz.

Results-by-site are grouped according to catchment monitoring purpose (validation and reference, calibration, compliance, and Upper Henderson).

**Table 4-1: Guidance for interpreting site-by-site information and results.**
Key results identified by bold font.

| Description (units) | Explanation |
|---|---|
| Catchment area ($km^2$) | Area of catchment upstream of monitoring site. |
| Start date | Date sediment record analysed from. |
| End date | Date sediment record analysed to. |
| **Duration (y)** | Duration of period for which sediment yield determined. |
| Maximum unsampled discharge (l/s) | The largest peak discharge used to estimate the yield of an unsampled event. This should be compared with the peak discharge of the largest sampled event used to define the event yield rating. |
| Maximum sampled peak discharge on rating (l/s) | Estimated yields for events with peak discharges larger than this value require extrapolation of the event yield rating, with greater uncertainty. |
| Total sediment yield across all events (t) | Sediment yield totalled for all events, sampled or rating-predicted, over duration. |
| Total sediment yield across sampled events (t) | Sediment yield totalled only for sampled events over duration. |
| Total sediment yield predicted using rating (t) | Sediment yield totalled only for un-sampled, rating-predicted events over duration. |
| Standard error of regression (%) | Provides an estimate of the uncertainty in the event yield predicted with the event yield rating (±%). |
| Error on predicted sediment yield (t) | Error on total yield over all predicted events, determined as the root-sum-of-squares of the errors in the individual event yields. |
| **Error on total sediment yield (%)** | Proportional error on total yield (sampled + predicted). This % error also applies to the yield and specific yield. |
| **Proportion total sediment yield sampled (%)** | Proportion of total yield sampled. 100% would indicate that no event yields had to be predicted using the event rating. |
| **Mean yield (t/y)** | The total sediment yield across all events divided by the duration of yield accumulation. |
| **Specific yield (t/km$^2$/y)** | The yield divided by catchment area – this should be used to compare catchments of different size. |

| Description (units) | Explanation |
|---|---|
| Cumulative yield trend (t/d) | Determined from the slope of a linear-regression trend-line fitted to the cumulative-yield vs time plot[7]. It differs slightly from the yield, which effectively is the slope of a line drawn from the start to end of the cumulative-yield curve. The cumulative yield trend is therefore less sensitive to the events at the start and end of the record. |
| Cumulative specific yield trend (t/km$^2$/y) | The cumulative yield trend per unit catchment area. |
| **Time trend on event yields (%/y)** | Assesses if there is a statistically significant (at 5% level) trend with time shown by the residuals (observed/predicted ratio) of the event yield rating. "NS" signifies that no such trend was observed. If a significant trend was observed, the result shows the proportional yearly change in yield for a given sized peak discharge event. No result is provided if the monitoring period is three years or less. |

[7] In Excel, time has day units so this trend slope has units t/d but can be converted to t/y by multiplying by 365.25.

## 4.2 Reference and validation catchments

In overview for the reference and validation catchments, the greatest mean sediment yield was from the Hōteo River, which has the largest catchment monitored, although the greatest level of uncertainty was also associated with this site.

The greatest specific yield was at Te Muri Stream (172 $t/km^2/y$); however, this is likely associated with the limited monitoring period at this site, as discussed further in Section 5.0. Across the 2012-2019 reference period, the greatest specific yield was at Mangemangeroa Stream (120 $t/km^2/y$).

No significant time trends were observed in the event yield ratings at the only reference catchment of West Hoe Stream and at three of the validation catchments; however, significant time trends for increasing event sediment yields (for the same sized hydrological event) were observed in the Wairoa River and Orewa River, while time trends for decreasing event yields were observed at Mangemangeroa Stream and Kaipara River. Time trends on annual yields are discussed in Section 5.

Further details on each catchment are outlined below.

**Table 4-2: Sediment yield result summary for the reference and validation sites for their entire monitoring periods.**

| | Reference | Validation (ordered by decreasing catchment slope) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Description (units)** | **West Hoe** | **Te Muri** | **Hōteo River** | **Wairoa River** | **Mangemangeroa Stream** | **Vaughan Stream** | **Orewa River** | **Kaipara River** |
| Catchment area ($km^2$) | 0.5 | 0.3 | 268 | 114 | 4.5 | 2.3 | 9.7 | 163 |
| Start date | 1/01/2012 | 1/01/2014 | 21/05/2010 | 21/05/2010 | 1/01/2012 | 1/01/2012 | 29/06/2009 | 1/01/2012 |
| End date | 31/12/2019 | 31/12/2019 | 31/12/2019 | 31/12/2019 | 31/12/2019 | 31/12/2019 | 31/12/2019 | 31/12/2019 |
| **Duration (y)** | **8.0** | **6** | **9.61** | **9.6** | **8** | **8** | **10.5** | **8** |
| Maximum unsampled discharge (l/s) | 1528 | 1720 | 306600 | 236443 | 13225 | 10067 | 46728 | 124015 |
| Maximum sampled peak discharge on rating (l/s) | 1805 | 2163 | 206400 | 360725 | 11285 | 7610 | 48598 | 100257 |
| Total sediment yield across all events (t) | 75.8 | 310 | 206644 | 78760 | 4308 | 771 | 6402.1 | 39597 |
| Total sediment yield across sampled events (t) | 55.9 | 195 | 95470 | 58658 | 3004 | 408 | 4606.8 | 26573 |
| Total sediment yield predicted using rating (t) | 19.9 | 116 | 111174 | 20101 | 1304 | 364 | 1795.3 | 13024 |
| Standard error of regression (%) | 45.0% | 25.2% | 63% | 59.0% | 31.0% | 58.0% | 59.0% | 47.3% |
| Error on predicted sediment yield (t) | 3.1 | 7 | 31853 | 8163 | 178 | 49.4 | 439.6 | 2114 |
| **Error on total sediment yield (%)** | **4.1%** | **2.4%** | **15.4%** | **10.4%** | **4.1%** | **6.4%** | **6.9%** | **5.5%** |
| **Proportion total sediment yield sampled (%)** | **74%** | **62.8%** | **46%** | **74%** | **69.7%** | **52.9%** | **72%** | **69%** |
| **Mean yield (t/y)** | **9.5** | **51.7** | **21497** | **8193** | **539** | **96.5** | **609.4** | **4950** |
| **Specific yield ($t/km^2/y$)** | **19.0** | **172** | **80.2** | **71.9** | **120** | **41.9** | **62.8** | **30.4** |
| Cumulative yield trend (t/d) | 0.025 | 0.174 | 57.7 | 22.9 | 1.439 | 0.307 | 1.466 | 13.7 |
| Cumulative specific yield trend ($t/km^2/y$) | 18.3 | 212 | 78.7 | 73.5 | 117 | 48.7 | 55.2 | 30.6 |
| **Time trend on event yields (%/y)** | **NS** | **NS** | NS | **+13.1%** | **-5.7%** | **NS** | **+6.3%** | **-9.4%** |

### 4.2.1 West Hoe Stream

The 0.5 $km^2$ West Hoe Stream catchment, monitored at the Hall Farm site, is formed in Waitematā Formation bedrock and has Ultic catchment soils, predominantly moderately steep slopes, and largely indigenous forest cover (Table 2-2). Its primary monitoring purpose is as a reference site, whereby change in sediment yield is expected to be driven only by climatic conditions.

Sediment data collection at West Hoe Stream began on 9 May 2012 and continued through until 8 October 2019. With "padding-back"[8] to 1 January 2012 and "padding-out" until 31 December 2019, this provides eight years of record. Event sediment yields were determined for 116 events over this period.

No suspended sediment gaugings have been done at West Hoe Stream, so we have assumed $C_m/C_p$ = 1 for all discharges. It is recommended that priority be given to undertaking some manual depth integrated sediment gaugings to validate this assumption.

The event yield rating, developed from 23 well-sampled single-peak events (Figure 4-1A), was $S = 1.80 \times 10^{-5} Q_p^{1.671}$, where the coefficient $1.80 \times 10^{-5}$ incorporates a log bias correction factor of 1.07. The highest peak discharge at which this rating was applied (1,528 l/s) is less than the highest peak discharge used to derive the rating (1,806 l/s), hence there was no rating extrapolation required.

The residual ratios from the rating relation (i.e. observed/predicted) showed no significant (at the 5% significance level) monotonic time trend over the monitoring period (Figure 4-1B).

As summarised in Table 4-2, the total sediment yield from storm events over the eight-year period was 75.8 t, equating to a specific yield of 19.0 $t/km^2/y$ – the lowest observed across the dataset. This confirms the suitability of this site as a reference site, which is expected to respond as would a pristine, totally natural site.

Of the total yield, 74% was captured by sampled events; the remainder from unsampled events was predicted using the event rating and resulted in a ± 4.1% uncertainty in the total yield over all events.

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[8] "Padding-back" is where the event sediment yield record was extended back in time before sediment monitoring commenced. This was done by applying the event rating curve to event peak discharges occurring over this time. Similarly, "padding-out" is where the event rating is applied to peak discharges recorded beyond the most recent sediment measurements. This "padding" provides complete calendar years of event yields at the beginning and end of the sediment record.

The largest event (in terms of peak discharge) occurred over 24-25/12/2018 with a peak discharge of 1,806 l/s (Figure 4-2A) and a well sampled yield of 5.15 t (equating to 54% of the mean annual yield and 29% of the 2018 yield).

The cumulative specific yield trend, derived from the time-cumulative yield plot (Figure 4-2A), was 18.3 t/km$^2$/y, which is close to the specific yield of 19.0 t/km$^2$/y derived by dividing the total specific yield by the record period.

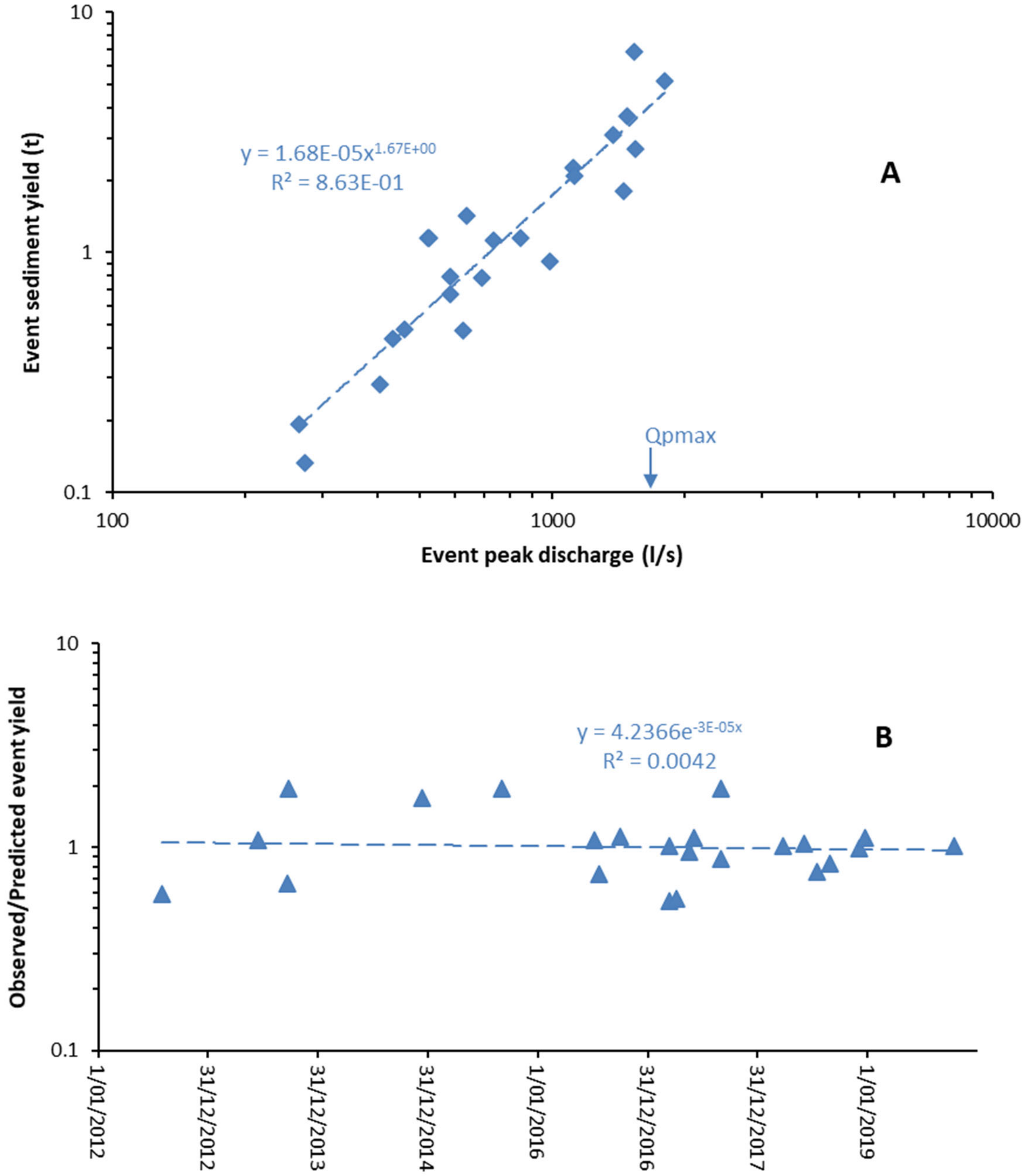



**Figure 4-1: Rating between event sediment yield and event peak discharge for West Hoe Stream at Hall Farm, 2012-2019.**
A: rating. Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. B: Observed/Predicted event yield vs. time. Time-trend is not significant at 5% level.

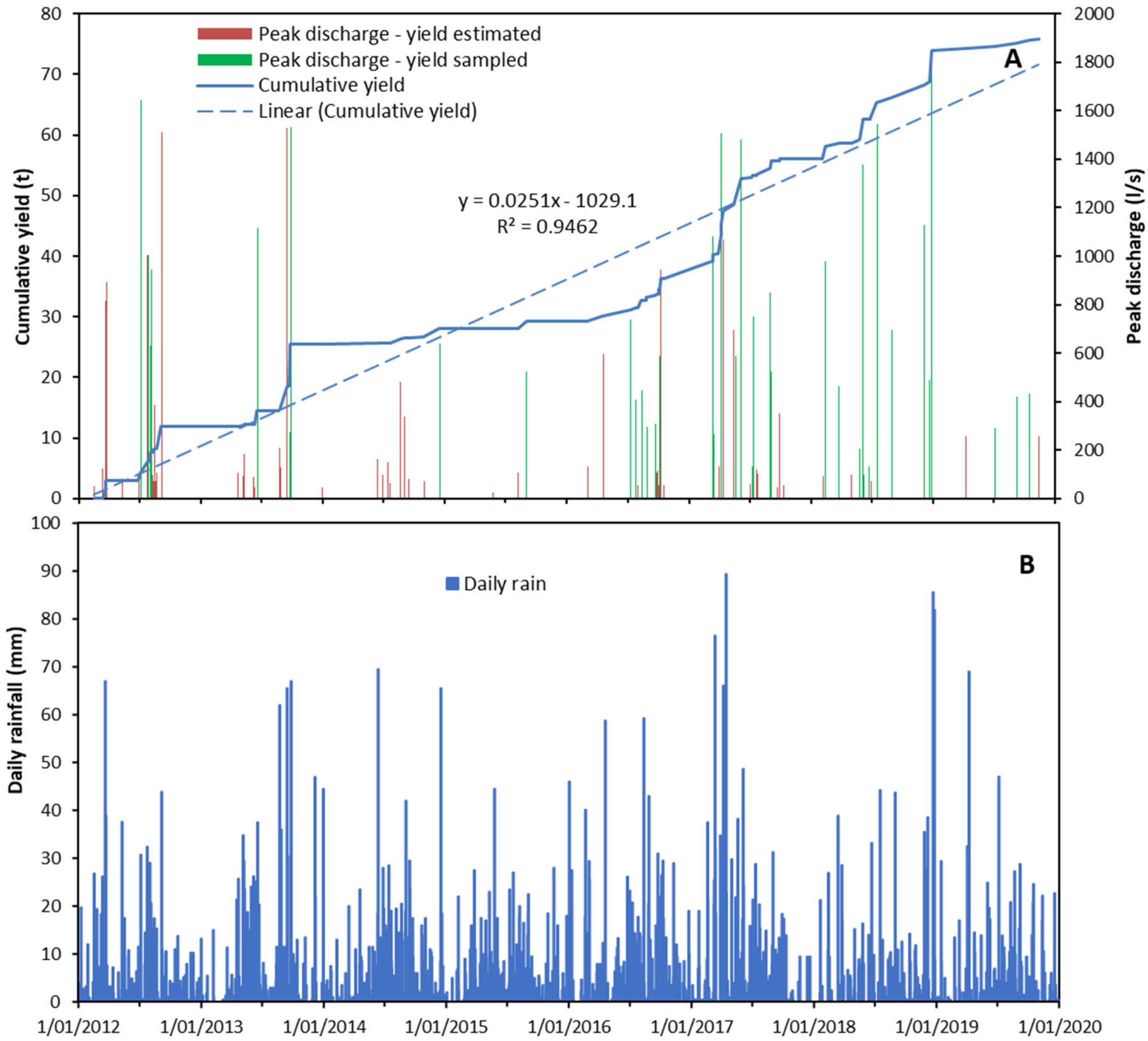



**Figure 4-2: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for West Hoe Stream at Hall Farm, 15/2/2012-11/11/2019.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red.

### 4.2.2 Te Muri Stream

The 0.3 km$^2$ Te Muri Stream sub-catchment, monitored at the Te Muri Regional Park – Farm site, is formed in mainly Waitematā Formation bedrock and has dominantly Ultic catchment soils, predominantly moderately steep slopes, and predominantly pasture cover albeit with ~ 7% indigenous forest (Table 2-2). Te Muri is a validation site which is being used to secure evidence on the effect of stock exclusion from a moderately steep catchment via adaptive farm management practices. This evaluation is ongoing.

The sediment record at Te Muri Stream spans from 29 December 2013 to 15 October 2019, enabling a record of six years after “padding-out” to 31 December 2019. Event sediment yields were determined for 205 events over this period.

No suspended sediment gaugings have been done at Te Muri, so we have assumed $C_m/C_p$ = 1 for all discharges.

The event yield rating, developed from 18 well-sampled single-peak events (Figure 4-3A), was $S = 8.22 \times 10^{-3} Q_p^{0.988}$, where the coefficient $8.22 \times 10^{-3}$ incorporates a log bias correction factor of 1.03. The highest peak discharge at which the rating was applied (1,720 l/s) is less than the highest peak discharge used to derive the rating (2,163 l/s), hence there was no rating extrapolation required. The residuals ratio from the rating relation (i.e. observed/predicted) showed no significant (at the 5% significance level) monotonic time trend (Figure 4-3B).

As summarised in Table 4-2, the total sediment yield from storm events over the monitoring period was 310 t, equating to a specific sediment yield of 172 t/km$^2$/year.

Of the total yield, 63% was captured by sampled events, the remainder from unsampled events was predicted using the event rating and resulted in a ± 2.4% uncertainty in the total yield over all events.

The largest recorded event (in terms of peak discharge) was 5227 l/s on 29/08/2018. (Figure 4-4A). This event was well sampled with a yield of 29.4 t (equating to 57% of the mean annual yield and 41% of the 2018 yield). The stage-discharge rating is extrapolated to estimate this peak flow value, therefore, when future validation gaugings are completed this value could change. Most other large events also had well sampled yields. It is noted that the high rainfall event of 18 February 2016 (when over 100 mm of rain fell – Figure 4-4B), which was not sampled, did not produce a particularly high event yield when applying the peak discharge to the event rating (Figure 4-4A). This was because the rain was quasi-steady through the day, resulting in a broad multi-peak hydrograph, the maximum peak at about 300 l/s. The rating-estimated yield from this multi-peak event (2.5 t) was estimated off the single highest peak and so likely underestimates the true event yield. Nonetheless, this is captured by the estimation error and the impact on the long-term average yield is considered to be minor.

The cumulative specific yield trend, derived from the time-cumulative yield plot (Figure 4-4A), was 100.1 t/km$^2$/y, which is 11% larger than the specific yield of 90.3 t/km$^2$/y.

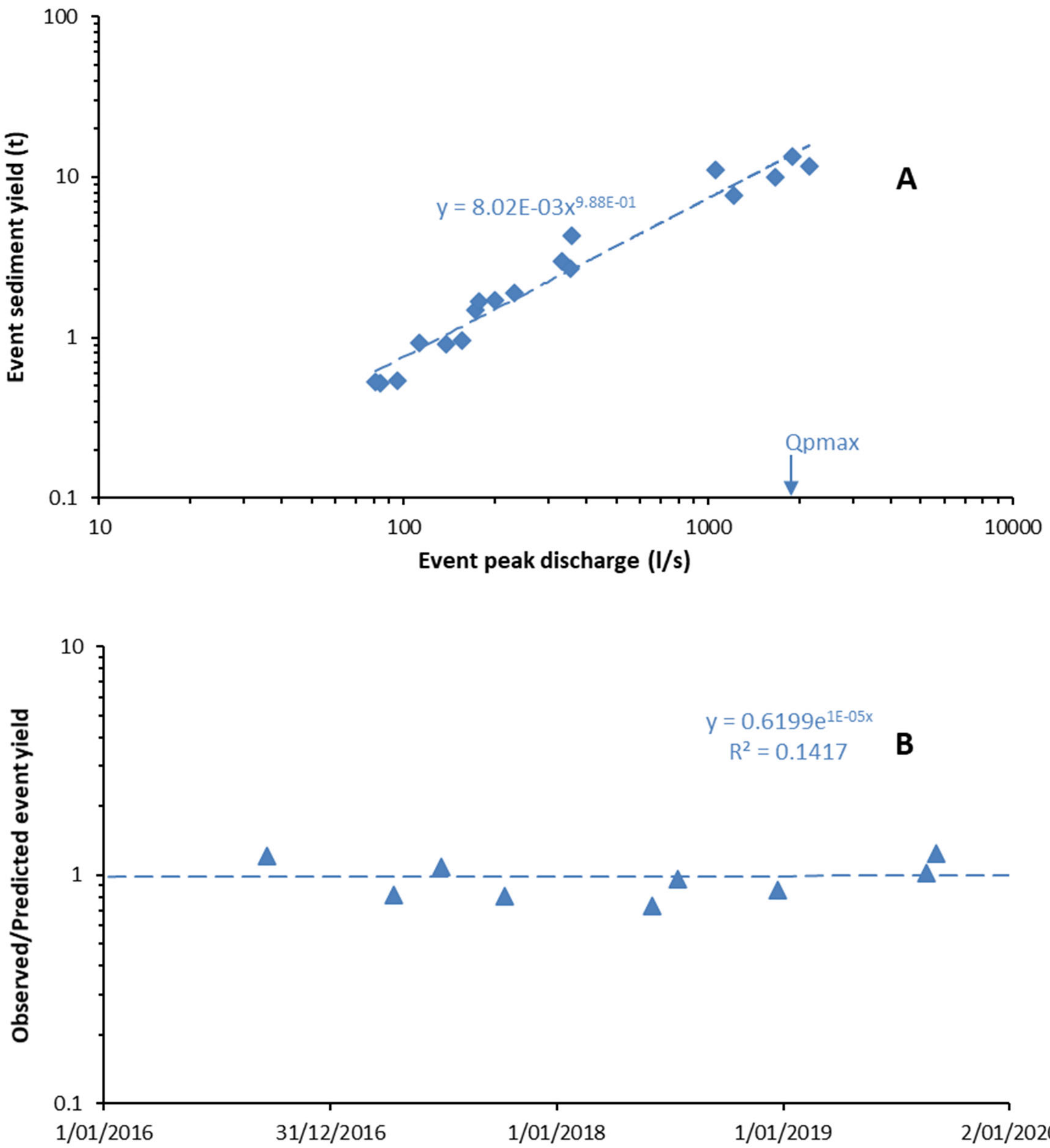



**Figure 4-3: Rating between event sediment yield and event peak discharge for Te Muri Stream at Te Muri Farm, 2014-2019.**

A: rating. Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. B: Observed/Predicted event yield vs. time. Time-trend is not significant at 5% level.

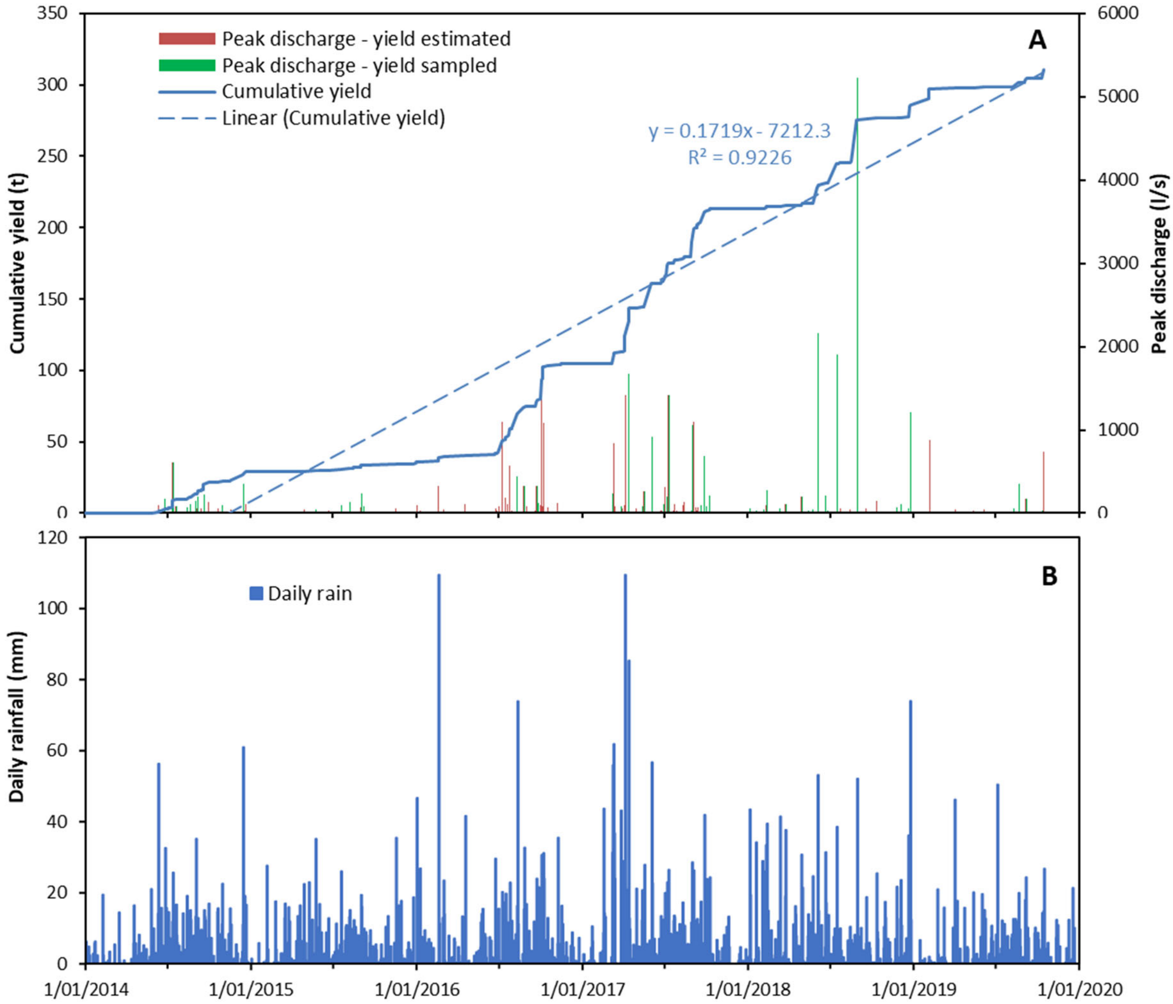



**Figure 4-4: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Te Muri Stream at Te Muri Farm, 1/1/2014-31/12/2019.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red.

### 4.2.3 Hōteo River

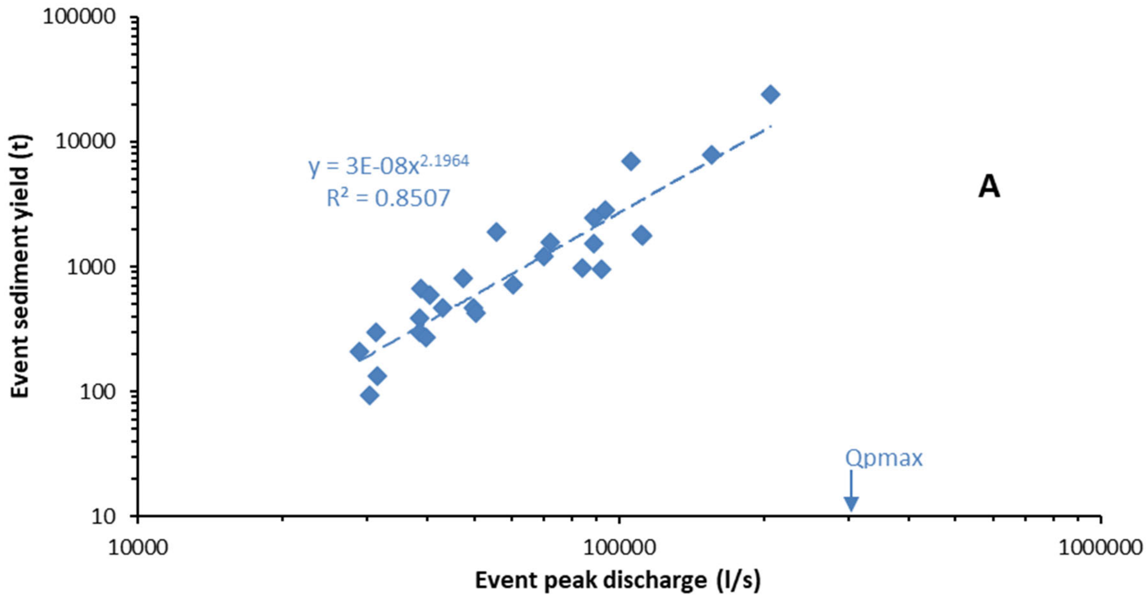
The 268 km$^2$ Hōteo River catchment, monitored at the Gubbs site, is formed in Waitematā bedrock and has dominantly Ultic catchment soils, predominantly moderately steep slopes, and predominantly pasture land cover (Table 2-2). Its primary monitoring purpose is as a validation site (to validate the efficacy of sediment management policy).

The sediment record at Hōteo River spans from 21 May 2010 to 16 October 2019, although for the purpose of this study the record has been "padded-out" to 31 December 2019 using the event rating to complete the 2019 calendar year, enabling a record of 9.6 years. Event sediment yields were determined for 132 events over this period.

Seven suspended sediment gaugings were done between March 2012 and April 2017, covering a river discharge range of 77,000-193,000 l/s, for the purpose of establishing a relation between the SSC mixing ratio $C_m/C_p$ and discharge (Appendix E Table-1). Three of these data-points were discarded because of low $C_m/C_p$ values (0.34-0.59) that were likely due to the auto-sampler collecting sediment from a near-riverbed layer of mobile sandy bed material. The remaining data-points (Figure 4-6B) showed no significant deviation (at the 5% significance level) from a $C_m/C_p$ = 1 relation, irrespective of discharge, hence no $C_m/C_p$ adjustment was applied.

The event yield rating, developed from 27 well-sampled single-peak events (Figure 4-5A), was $S = 3.142 \times 10^{-8} Q_p^{2.196}$, where the coefficient ($3.142 \times 10^{-8}$) incorporates a log bias correction factor of 1.12. The highest peak discharge at which the rating was applied (306,600 l/s) exceeds the highest peak discharge used to derive the rating curve (206,400 l/s), hence the rating had to be extrapolated for that unsampled event, resulting in reduced confidence in the yield estimate for the event. The residuals ratio from the rating relation (i.e. observed/predicted) showed no significant monotonic time trend (at the 5% significance level, Figure 4-5B).

As summarised in Table 4-2, the total sediment yield from storm events over the monitoring period was 206,644 t, equating to a specific sediment yield of 80.2 t/km$^2$/y.



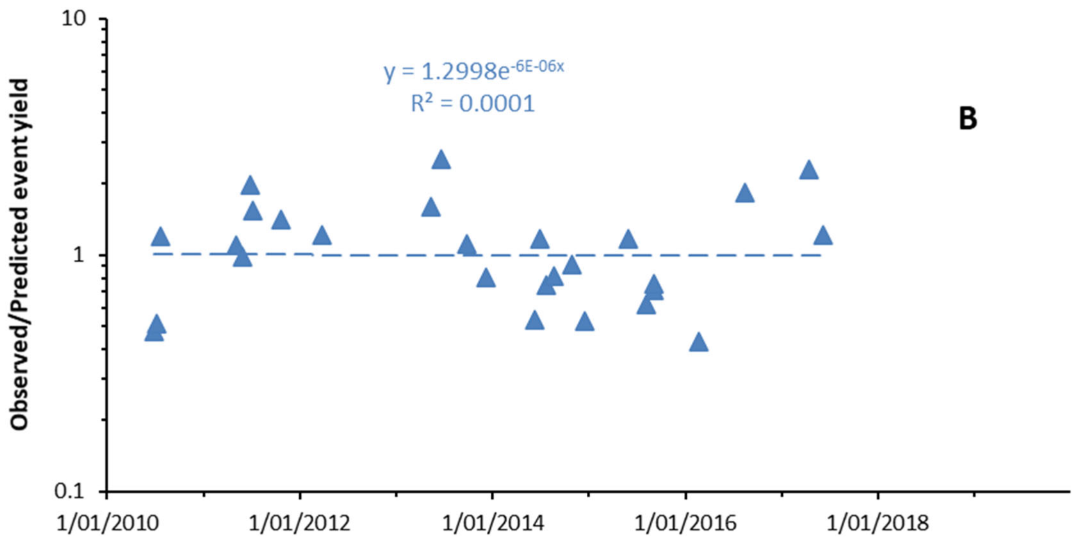




**Figure 4-5: Rating between event sediment yield and event peak discharge for Hōteo at Gubbs, 2010-2019.**
Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. A: rating. B: Observed/Predicted event yield vs. time. Time-trend is not significant at 5% level.

Of the total yield, only 46% was captured by sampled events; the remainder from unsampled events was predicted using the event rating and resulted in a ± 15.4% uncertainty in the total yield over all events. The largest event (in terms of peak discharge) across the entire record, which occurred over 23-31 January 2011 when the peak discharge was 306,600 l/s (Figure 4-6A), was unsampled. The auto-sampler failed during this event (1:25 year return period) because it was so large that floodwaters lifted and tipped the auto-sampler, spilling the sample bottles (Curran-

Cournane et al. 2013). The rating-estimated yield for this event was 35,000 t (equating to 160% of the mean annual yield and 79% of the 2011 yield). The next largest event, over 10-13 August 2016 and peaking at 206,400 l/s, had a well sampled yield of 24,200 t (113% of the mean annual yield and 50% of the 2016 yield). There has only been one well-sampled event since March 2018 which suggests that greater effort may be required to keep on top of monitoring at this site.

The time-cumulative yield plot (Figure 4-6A) shows steep "jumps" around the dates of these two large events in 2011 and 2016. The cumulative specific yield trend, derived from this plot, was 78.7 t/km$^2$/y, which is close to the specific yield of 80.2 t/km$^2$/y.

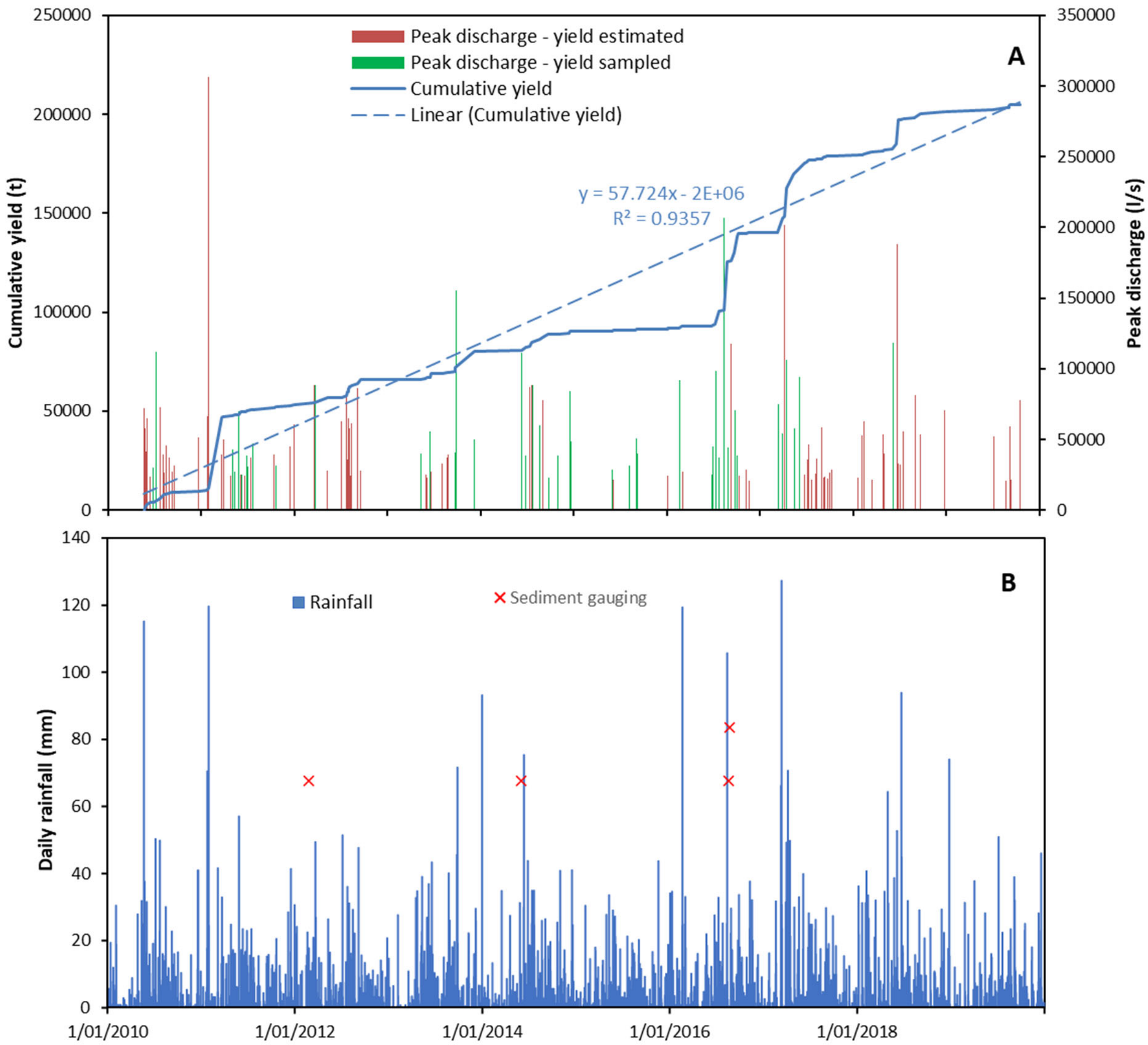



**Figure 4-6: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Hōteo at Gubbs, 21/5/2010-31/12/2019.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red. xs mark the four gaugings of cross-section mean SSC used to evaluate Cm/Cp.

### 4.2.4 Wairoa River

The Wairoa River catchment, monitored at the Tourist Road site and with an effective area of 114 $km^2$ downstream of dammed tributaries, is formed mainly in greywacke bedrock and has dominantly Granular, Ultic and Recent catchment soils, predominantly steep slopes, and mainly pasture land cover (Table 2-2). Its primary monitoring purpose is as a validation site.

The sediment record at Wairoa River spans from 21 May 2010 to 17 October 2019, although for the purpose of this study the record has been "padded-out" to 31 December 2019 using the event rating, enabling a record of 9.6 years. Event sediment yields were determined for 210 events over this period.

The monitoring and event yield analysis have focussed on natural runoff events. Flow releases from the water storage reservoirs to provide environmental compensation flows have not been specifically monitored (these are not expected to discharge much sediment since their runoff is not sourced from eroding hillslopes).

Eight suspended sediment gaugings were done between May 2011 and March 2017 (Figure 4-8B), covering a discharge range of 15,190-174,610 l/s, for the purpose of establishing a relation between $C_m/C_p$ and discharge (Appendix E, Table 1). The $C_m/C_p$ ratios ranged between 0.84 and 1.14 for all but the highest discharge, for which $C_m/C_p$ was 0.65. Including the high-discharge point there was a weak trend for $C_m/C_p$ to decrease with increasing discharge; excluding this point there was no trend with discharge and the average $C_m/C_p$ was not significantly different from 1. A sensitivity test comparing the total sampled yield over the monitoring period when the trend function was used to adjust the auto-sampled SSC with the total yield when no adjustment was made showed only a 6% difference, which was less than the error of the estimate of the trend function. On that basis, we assumed $C_m/C_p$ = 1 at all discharges.

The event yield rating, developed from 61 well-sampled single-peak events (Figure 4-7A), was $S = 7.96x10^{-6} Q_p^{1.657}$. The highest peak discharge at which the rating was applied 236,443 l/s) is less than the highest peak discharge used to derive the rating (360,725 l/s), hence the rating was not extrapolated. The residuals ratio from the rating relation (i.e. observed/predicted) showed a significant (at the 5% significance level) monotonic time trend (Figure 4-7B), defined by the function obs/pred = $3.581\ x10^{-4}$ D – 13.74, where D is the Excel date (days since 1 January 1900) and the coefficient $3.581x10^{-4}$ indicates a 13.1% per year increase in event yields at a given peak discharge. The event yield rating was multiplied by this time-trend function to correct for drift in the rating.

As summarised in Table 4-2, the total sediment yield from storm events over the monitoring period was 78,760 t, equating to a specific sediment yield of 89.5 t/km$^2$/y.

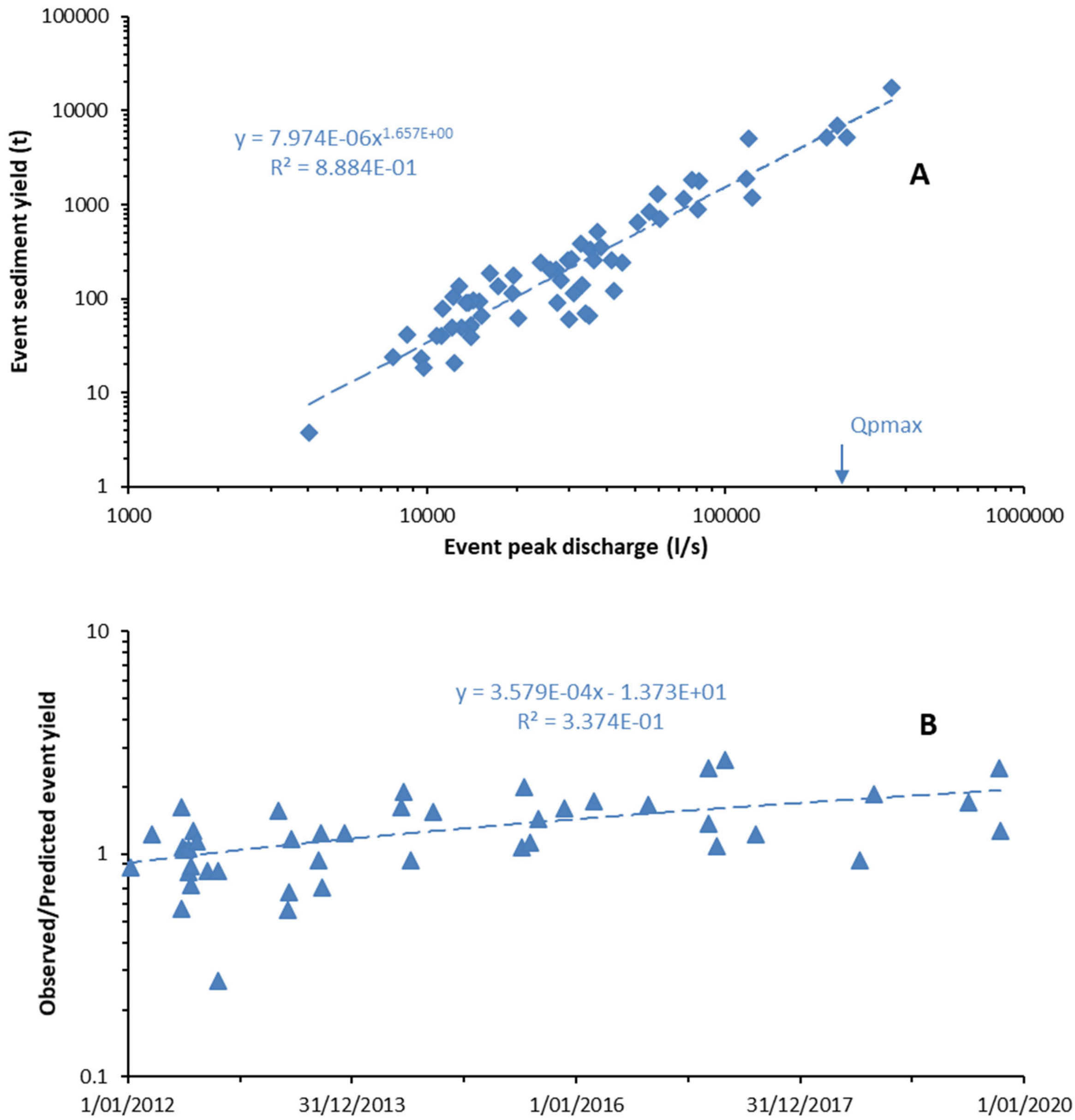



**Figure 4-7: Rating between event sediment yield and event peak discharge for Wairoa River at Tourist Road, 2010-2019.**
A: rating. Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. B: Observed/Predicted event yield vs. time. Time-trend is significant at 5% level.

Of the total yield, 74% was captured by sampled events, the remainder from unsampled events was predicted using the time-adjusted event rating and resulted in a ± 10.4% uncertainty in the total yield over all events.

The largest event (in terms of peak discharge) across the entire site flow record occurred over 4-9/3/2017 when the peak discharge was 360,725 l/s (Figure 4-8A) and the sampled yield was 22,670 t. This yield equates to 277% of the mean annual yield (and 59% of the 2017 yield), so this event had a substantial impact on the mean annual yield. Indeed, the time-cumulative yield plot (Figure 4-8A) shows its steepest "jump" associated with this March 2017 event.

The cumulative specific yield trend was 73.5 t/km$^2$/y, which is 2% larger than the specific yield of 71.9 t/km$^2$/y.

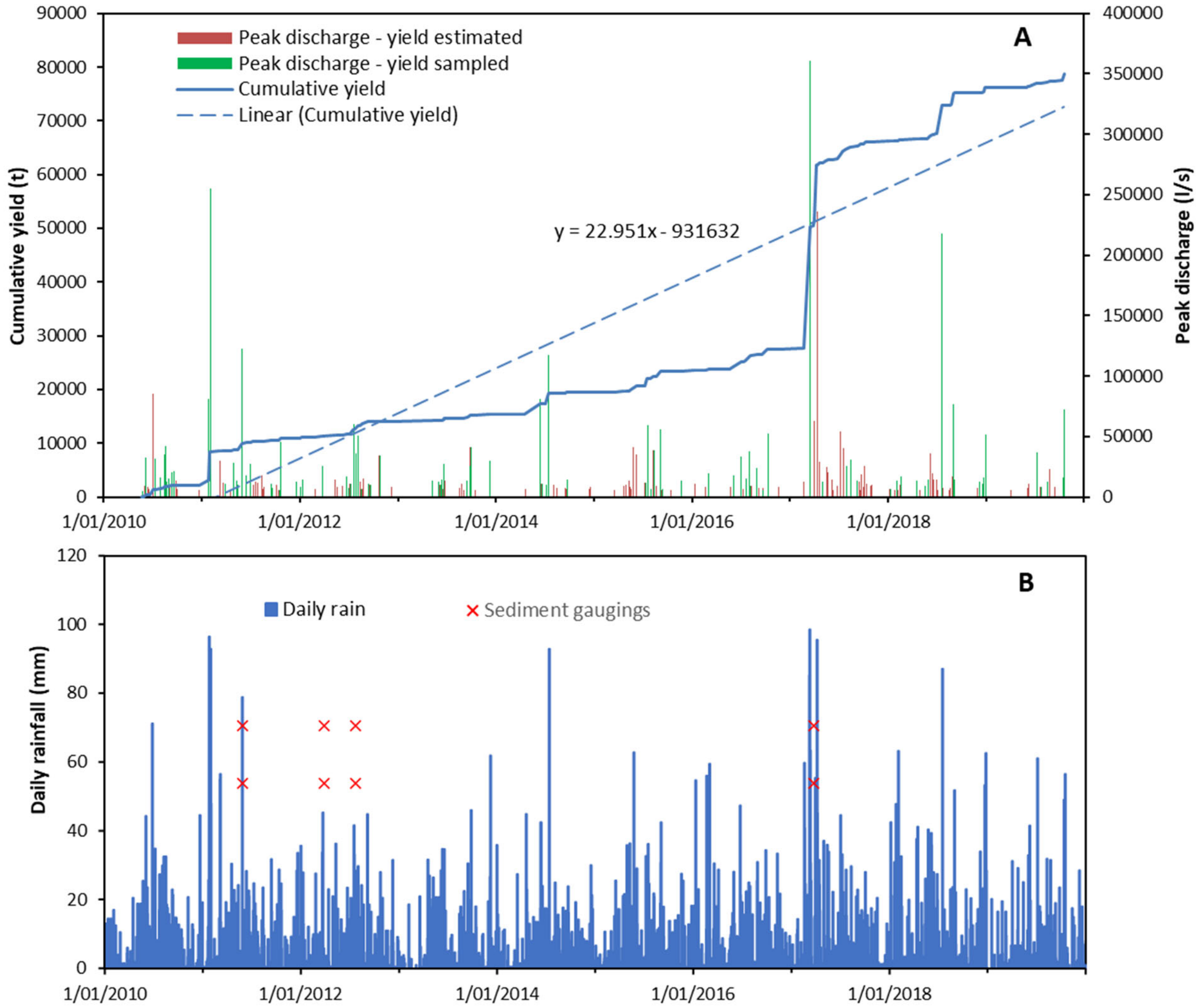



**Figure 4-8: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Wairoa River at Tourist Road, 21/5/2010-17/10/2019.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red. xs mark gaugings of cross-section mean SSC.

### 4.2.5 Mangemangeroa Stream

The 4.5 km$^2$ Mangemangeroa Stream catchment, monitored at the Craigs site, is formed mainly in Waitematā Formation bedrock and has dominantly Ultic catchment soils, predominantly moderately steep with lesser undulating slopes, and with a mixture of pasture and indigenous land cover (Table 2-2). Its primary monitoring purpose is as a validation site.

The sediment record at Mangemangeroa Stream spans from 3 July 2012 to 18 December 2019, although for the purpose of this study the record has been “padded-back” to 1 January 2012 and “padded-out” to 31 December 2019 using the event rating, enabling a record of eight years. Event sediment yields were determined for 139 events over this period.

Three suspended sediment gaugings were done in July 2012 (Figure 4-10B), covering a discharge range of 230-829 l/s, for the purpose of establishing a relation between $C_m/C_p$ and discharge (Appendix E, Table 1). The $C_m/C_p$ ratios ranged between 0.77 and 1.01 and trended up towards 1 as discharge increased (as expected as mixing should improve with increasing discharge). Given the few points, however, we chose to assume that $C_m/C_p = 1$ at all discharges, hence no $C_m/C_p$ adjustment was applied.

The event yield rating, developed from 25 well-sampled single-peak events (Figure 4-9A), was $S = 5.73x10^{-5}\ Q_p^{1.635}$. The highest peak discharge at which the rating was applied 13,300 l/s) exceeds the highest peak discharge used to derive the rating (11,300 l/s), hence the rating had to be extrapolated for that unsampled event, but not by much. The residuals ratio from the rating relation (i.e. observed/predicted) showed a small but significant (at the 5% significance level) monotonic time trend (Figure 4-9B) defined by the function obs/pred = 913 exp($-1.62x10^{-4}$D), where D is the Excel date (days since 1 January 1900), the coefficient 913 includes a log-bias correction factor of 1.03, and the exponential coefficient indicates a 5.7% per year reduction in event yields at a given peak discharge. The event yield rating was multiplied by this time-trend function to correct for drift in the rating.

As summarised in Table 4-2, the total sediment yield from storm events over the monitoring period was 4,308 t, equating to a specific sediment yield of 120 t/km$^2$/y.

Of the total yield, 69.7% was captured by sampled events; the remainder from unsampled events was predicted using the time-adjusted event rating and resulted in a ± 4.1% uncertainty in the total yield over all events.

The largest event (in terms of peak discharge) across the entire record, which occurred over 3-6/6/2018 when the peak discharge was 13,225 l/s (Figure 4-10A), was unsampled. The rating-estimated yield for this event was 377 t (equating to 70% of the mean annual yield and 32% of the 2018 yield). Most other large events had well sampled yields.

The time-cumulative yield plot (Figure 4-10A) shows its steepest “jump” associated with well sampled events occurring in March and April 2017. The cumulative specific yield trend, derived from this plot, was 117 t/km$^2$/y, which is close to the specific yield of 120 t/km$^2$/y.

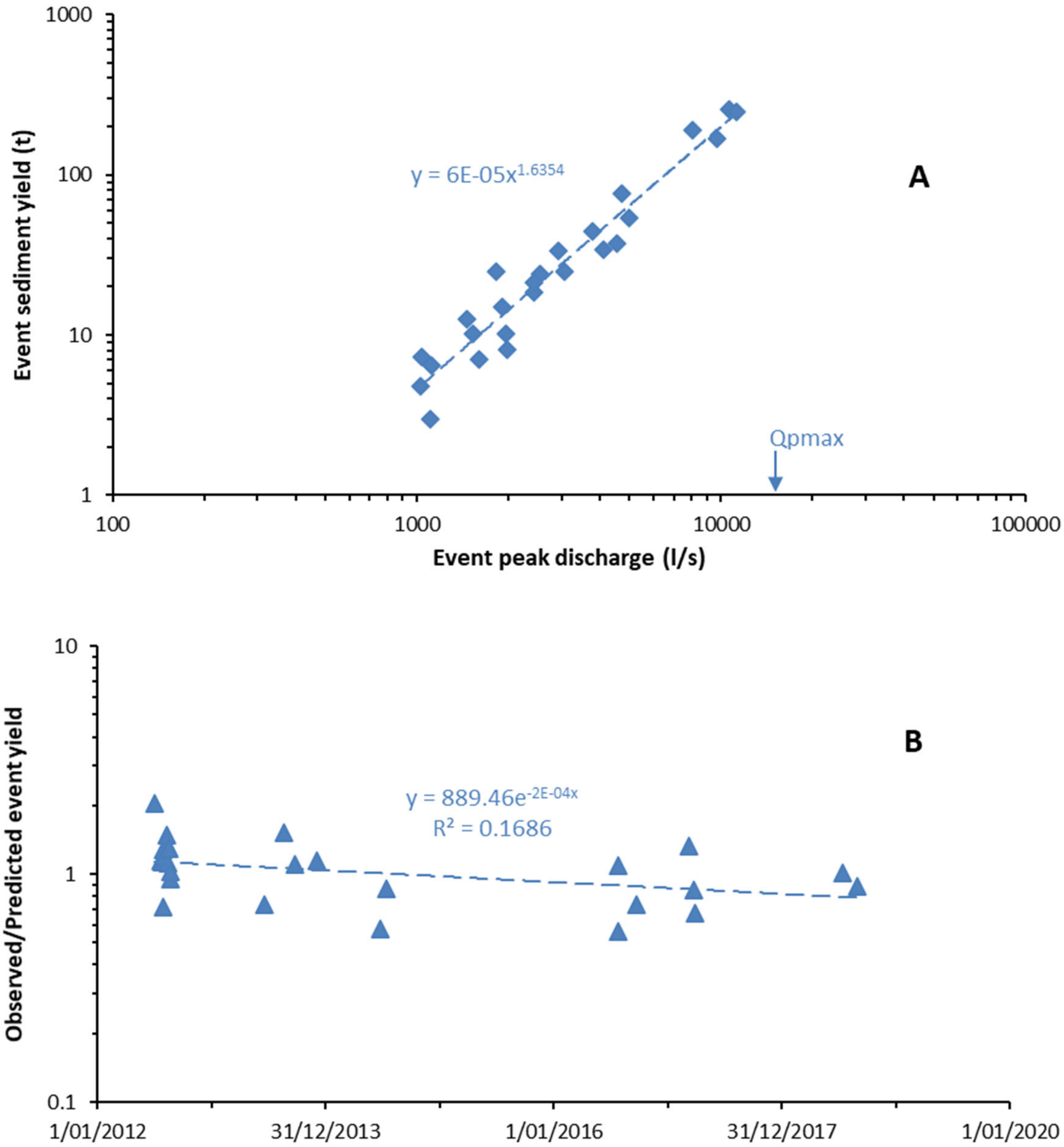



**Figure 4-9: Rating between event sediment yield and event peak discharge for Mangemangeroa Stream at Craigs, 2012-2019.**
Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. A: rating. B: Observed/Predicted event yield vs. time. Time-trend is significant at 5% level.

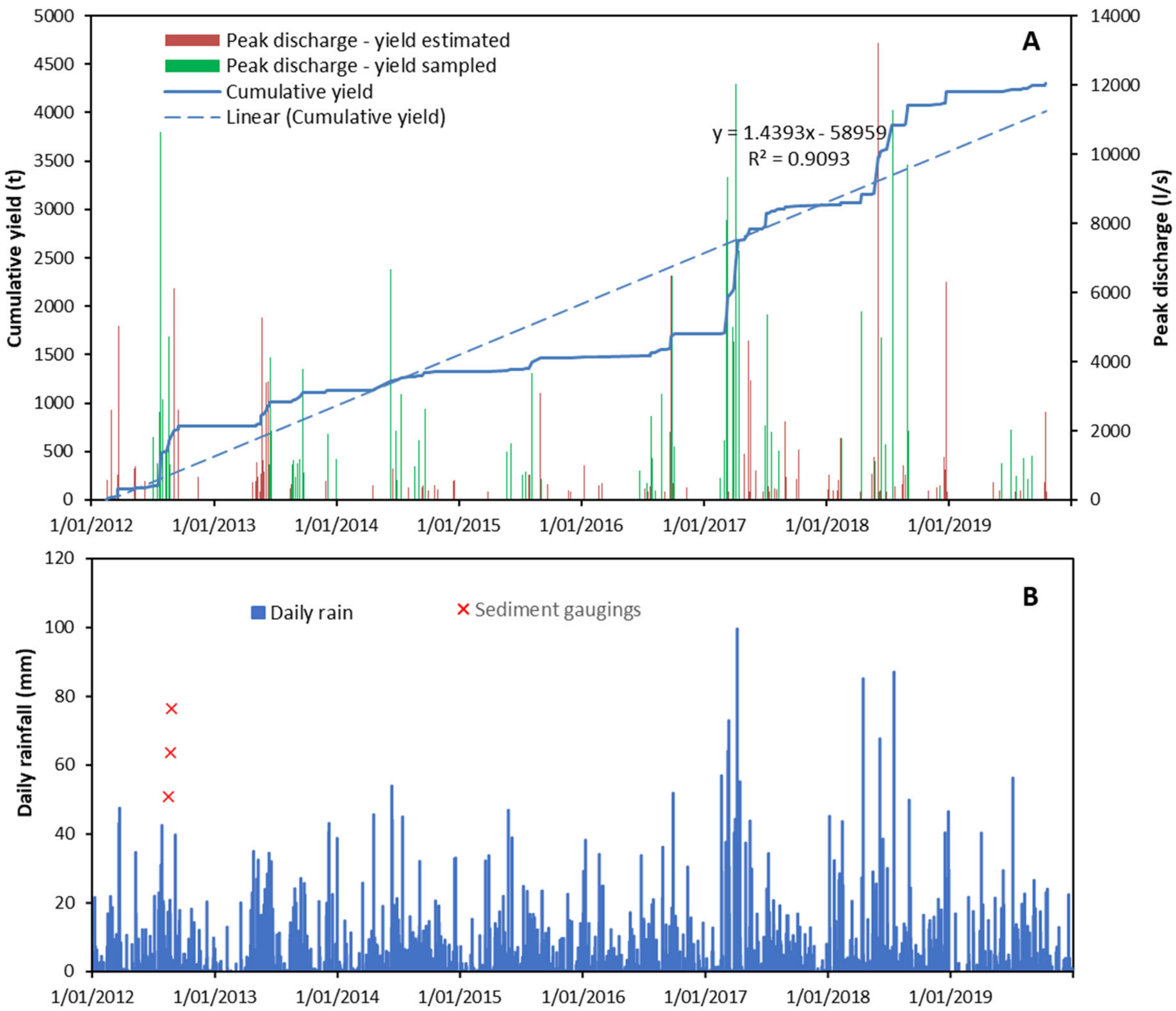



**Figure 4-10: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Mangemangeroa Stream at Craigs, 1/1/2012-31/12/2019.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red. xs mark gaugings of cross-section mean SSC.

It is of note that the mean annual specific yield reported here for Mangemangeroa (120 t/km$^2$/y) is less than the 167 t/km$^2$/y result derived by Curran-Cournane et al. (2013) based only on data collected during 2012. Since this included the yield from a large (approximately 10-year recurrence interval) flood, Curran-Cournane et al. (2013) queried whether that year was representative (indicating a highly erosive catchment) or whether the mean annual yield would reduce with further monitoring over time. This query can now be addressed (Figure 4-10, Table 5-1, Figure 5-1): the 2012 specific yield was higher than average but was not exceptional, as evidenced by the specific yields during 2017 (295 t/km$^2$) and 2018 (260 t/km$^2$) being higher than that of 2012 (169 t/km$^2$).

### 4.2.6 Vaughan Stream

The 2.3 $km^2$ Vaughan Stream catchment, monitored at the Lower Weir site, is formed in mainly Waitematā Formation bedrock and has dominantly Ultic and Organic catchment soils, predominantly rolling slopes, and predominantly pasture cover (Table 2-2). Its primary monitoring purpose is as a validation site.

Sediment data collection at Vaughan Stream spans two periods. Sampling first began on 11 January 2001 and 10 events were sampled from then until 7 October 2005. Sampling recommenced from 3 July 2012 and has continued though to 17 December 2019 with greater success (61 events were well sampled). This analysis focusses on the record from 2012 to 2019, which has been "padded-back" to 1 January 2012 using the event yield rating to provide an eight-year record. Event sediment yields were determined for 318 events over this period.

It is noted that this 2012-2019 period had two periods of missing flow record (01/03/2017-29/05/2017 and 24/01/2018-11/04/2018). The first one corresponds to a period when the weir was being rebuilt and unfortunately coincided with the largest rainstorm of the monitoring period (Figure 4-12B). The missing event peak stream discharges over these gap periods have been "patched" by scaling peak discharges recorded from the nearby Lucas at Gills Road site (3 km away and with a similar catchment area and land cover).

No suspended sediment gaugings have been done at Vaughan, so we have assumed $C_m/C_p = 1$ for all discharges.

The event yield rating for the 2012-19 period, from 23 well-sampled single-peak events (Figure 4-11A), was $S = 4.39 \times 10^{-4} Q_p^{1.248}$, where the coefficient $4.39 \times 10^{-4}$ incorporates a log bias correction factor of 1.10. The highest peak discharge at which this rating was applied (10,067 l/s) is 32% greater than the highest peak discharge used to derive the rating (7,610 l/s), hence there was some rating extrapolation required, which will have degraded the reliability of the estimated event yield. It is recommended that particular care is given to ensure that future events with peak discharges in this unrated range are well sampled, so that the rating may be extended.

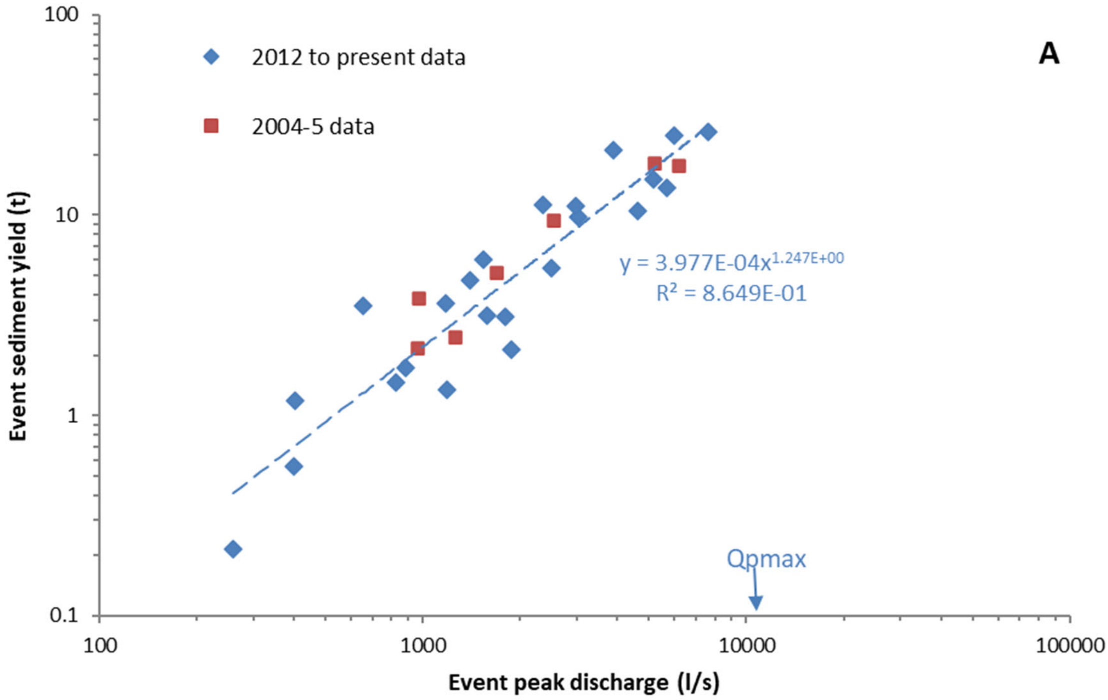
The residuals ratios from the rating relation (i.e. observed/predicted) showed no significant (at the 5% significance level) time trend over the 2012-19 period, although there is a suggestion of temporarily elevated residuals over the period 2016-18 (Figure 4-11B). It is of note that on Figure 4-11A the well-sampled event data from 2004-05 overplot the data from 2012-19, and on Figure 4-11B the 2004-2005 data plot on the trend-line fitted to the 2012-19 data. This indicates no longer-term time-trend in the event rating.

As summarised in Table 4-2, the total sediment yield from storm events over the 2012-2019 monitoring period was 771 t, equating to a specific sediment yield of 41.9 t/km$^2$/y.

Of the total yield, only 53% was captured by sampled events, the remainder from unsampled events was predicted using the event rating and resulted in a ± 6.4% uncertainty in the total yield over all events. This is the lowest performing site in regard to percentage of total yield sampled. As shown on Figure 4-11A, this relatively low percentage sampled stems mainly from the period January 2017 through April 2018, which included the interval while the weir was being rebuilt. Most events were well sampled before and after this period.

The largest event (in terms of peak discharge) across the entire record, which occurred over 24-27/09/2013 when the peak discharge was 11,066 l/s (Figure 4-12A), was well sampled with a yield of 20.1 t (equating to 21% of the mean annual yield and 28% of the 2013 yield).

The cumulative specific yield trend, derived from the time-cumulative yield plot (Figure 4-12A), was 48.7 t/km$^2$/y, which is 16% larger than the specific yield of 41.9 t/km$^2$/y.



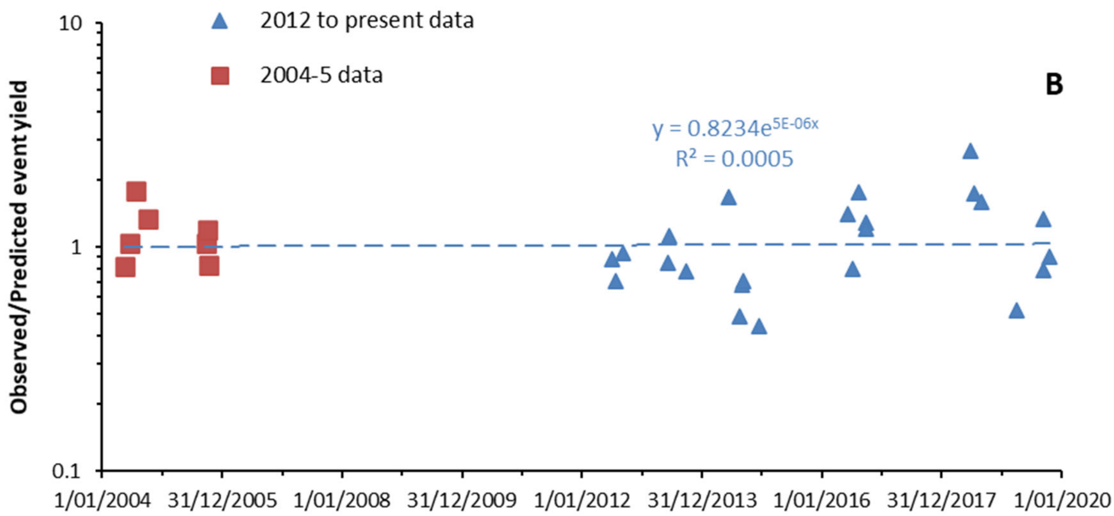




**Figure 4-11: Rating between event sediment yield and event peak discharge for Vaughan Stream at Lower Weir, 2004-2019.**
A: rating. Trend fitted to 2012-2019 data. Qpmax indicates maximum unsampled peak discharge 2012-2019. B: Observed/Predicted event yield vs. time. Time-trend is not significant at 5% level.

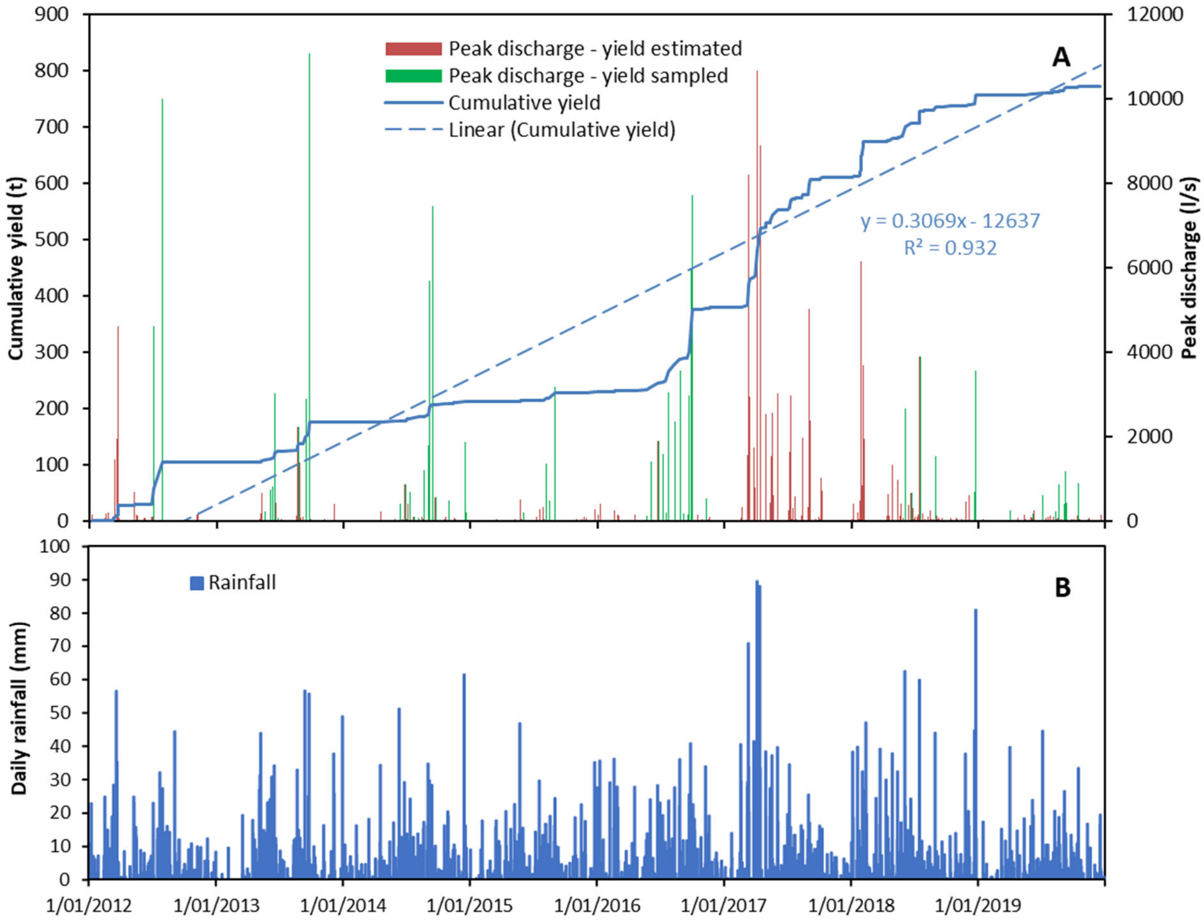



**Figure 4-12: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Vaughan Stream at Lower Weir, 3/7/2012-17/12/2019.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red.

### 4.2.7 Orewa River

The 9.7 km$^2$ Orewa River catchment, monitored at the Kowhai Avenue site, is formed mainly in Waitematā Formation bedrock and has dominantly Ultic and Gley catchment soils, predominantly rolling slopes, and with mainly pasture land cover (Table 2-2). Its primary monitoring purpose is as a validation site.

The sediment record at Orewa River spans from 5 July 2009 to 10 November 2019, although for the purpose of this study the record has been "padded-out" to 31 December 2019 using the event rating, enabling a record of 10.5 years. Event sediment yields were determined for 297 events over this period.

Four suspended sediment gaugings were done between September 2010 and August 2016 (Figure 4-14B), covering a discharge range of 1,470 – 9,088 l/s, for the purpose of establishing a relation between $C_m/C_p$ and discharge (Appendix E, Table 1). The

$C_m/C_p$ ratios ranged between 0.64 and 1.11 and showed a clear trend to increase towards 1 as discharge increased (as expected because mixing should improve with increasing discharge). As detailed in appendix E, the $C_m/C_p$ vs discharge (Q) relationship was fitted as a two-part function: for Q<7,350 l/s, $C_m/C_p = 0.0562Q + 0.587$; for Q>7,350 l/s, $C_m/C_p = 1$. These functions ensured that $C_m/C_p$ did not fall to too low a value at low sampled discharges nor increase to values substantially greater than 1 at high sampled discharges. The functions were used to adjust the auto-sampled SSC data.

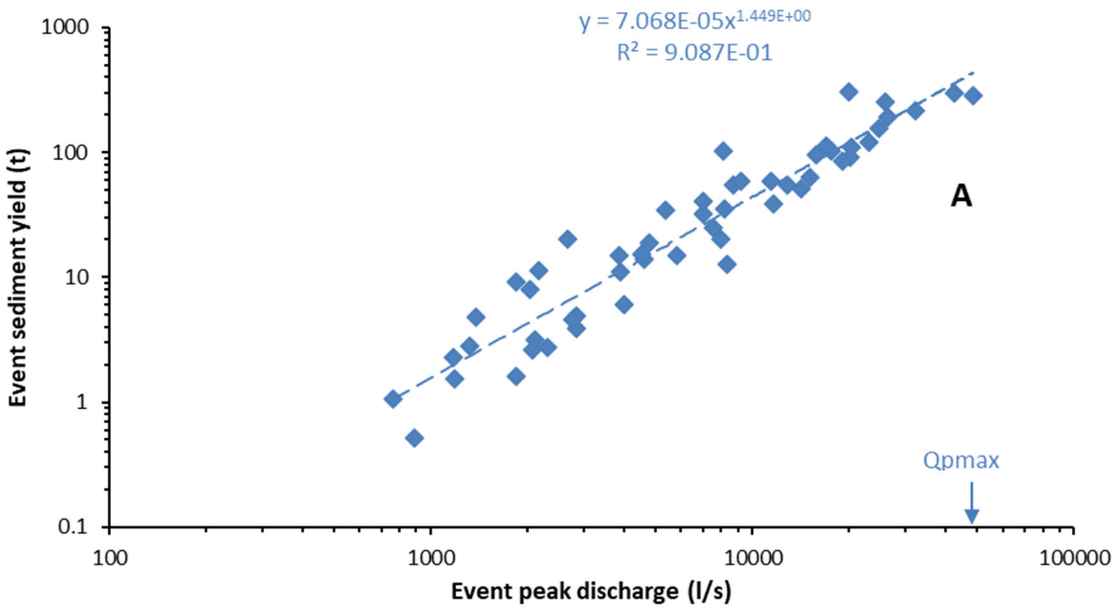
The event yield rating, developed from 53 well-sampled single-peak events (Figure 4-13A), was $S = 7.07\text{x}10^{-5}\ Q_p^{1.449}$. The highest peak discharge at which the rating was applied 46,728 l/s) is less than the highest peak discharge used to derive the rating (48,598 l/s), hence the rating was never extrapolated. The residuals ratio from the rating relation (i.e. observed/predicted) showed a significant (at the 5% significance level) monotonic time trend (Figure 4-13B), defined by the function obs/pred = $1.05\text{x}10^{-3}\ \exp(1.68\text{x}10^{-4}D)$, where D is the Excel date (days since 1 January 1900), the coefficient $1.05\text{x}10^{-3}$ includes a log-bias correction factor of 1.11, and the exponential coefficient indicates a 6.3% per year <u>increase</u> in event yields at a given peak discharge. The event yield rating was multiplied by this time-trend function to correct for drift in the rating.

As summarised in Table 4-2, the total sediment yield from storm events over the monitoring period was 6,402 t, equating to a specific sediment yield of 62.8 t/km$^2$/y.

Of the total yield, 72% was captured by sampled events, the remainder from unsampled events was predicted using the time-adjusted event rating and resulted in a ± 6.9% uncertainty in the total yield over all events.

The largest event (in terms of peak discharge) across the entire record occurred over 04-06/12/2009 when the peak discharge was 48,597 l/s (Figure 4-14A) and the sampled yield was 285 t (equating to 47% of the mean annual yield and 43% of the yield over the second half of 2009).

The time-cumulative yield plot (Figure 4-14A) shows its steepest "jump" associated with the unsampled event that occurred over 24-26/12/2018, when the peak discharge was 46,728 l/s and the rating-predicted yield was 646 t (equating to 106% of the mean annual yield). The cumulative specific yield trend, derived from this plot, was 55.2 t/km$^2$/y, which is 12% less than the specific yield of 62.8 t/km$^2$/y.



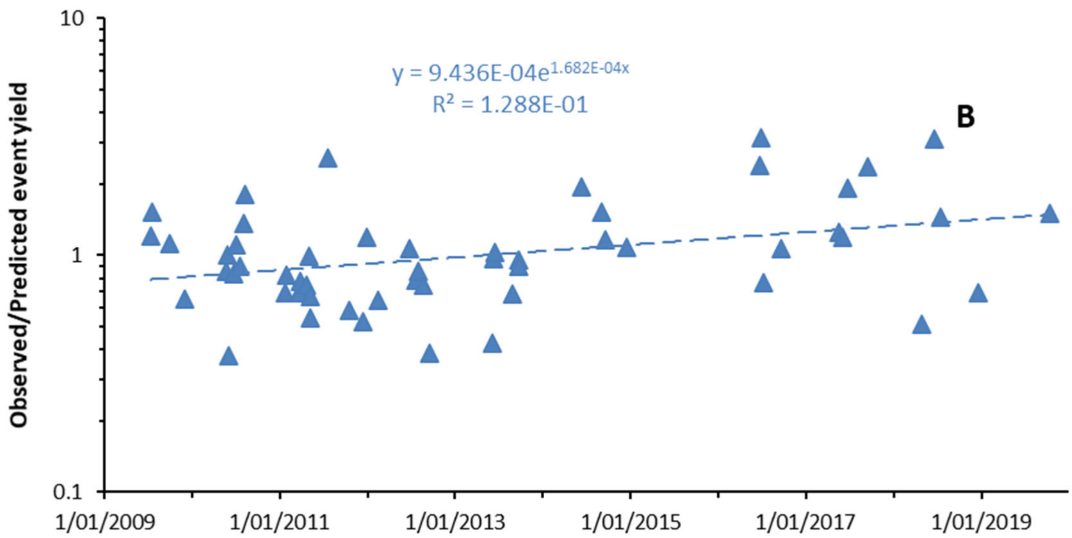




**Figure 4-13: Rating between event sediment yield and event peak discharge for Orewa River at Kowhai Ave, 2009-2019.**

Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. A: rating. B: Observed/Predicted event yield vs. time. Time-trend is significant at 5% level.

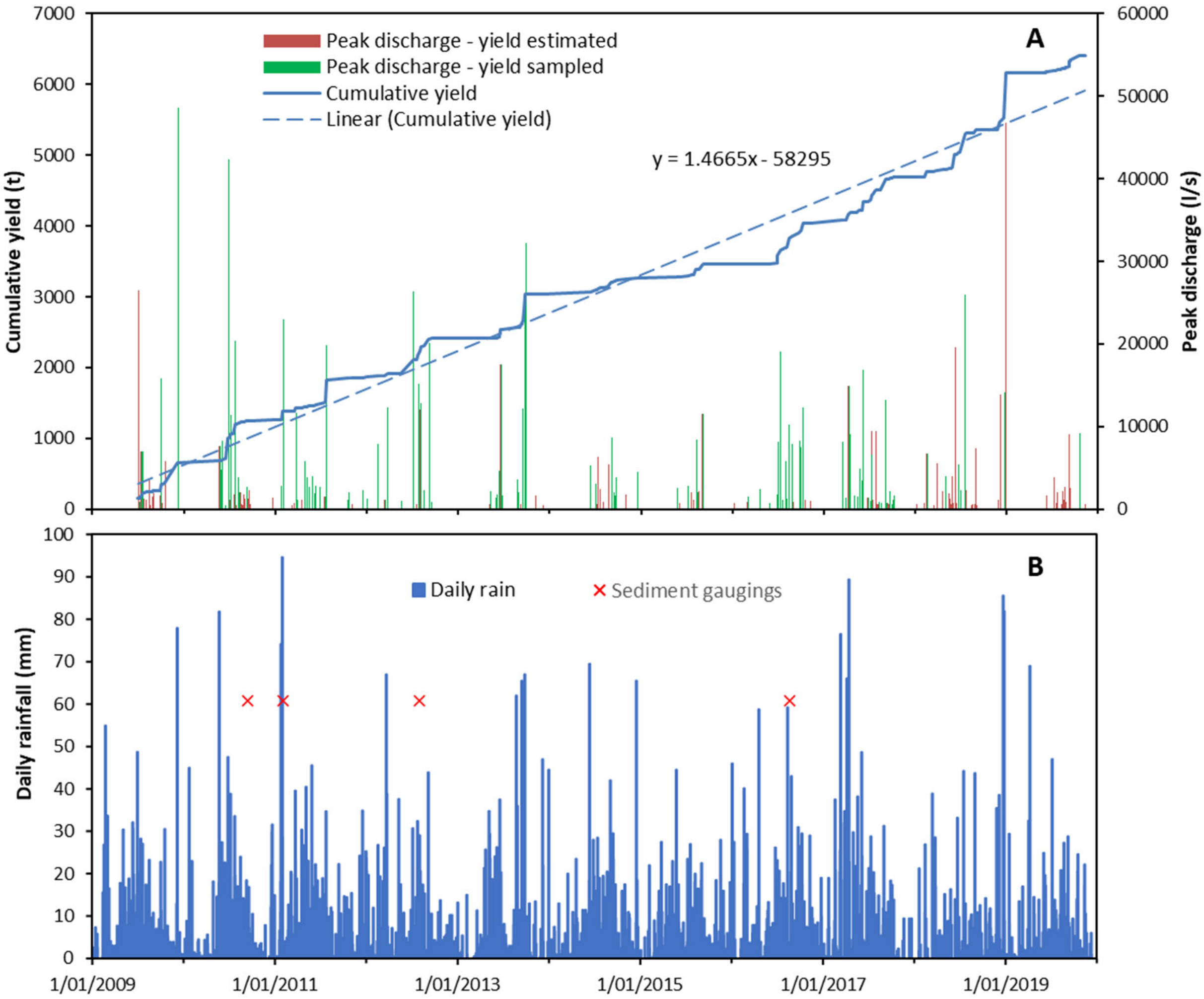



**Figure 4-14: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Orewa River at Kowhai Ave, 29/6/2009-31/12/2019.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red. xs mark gaugings of cross-section mean SSC.

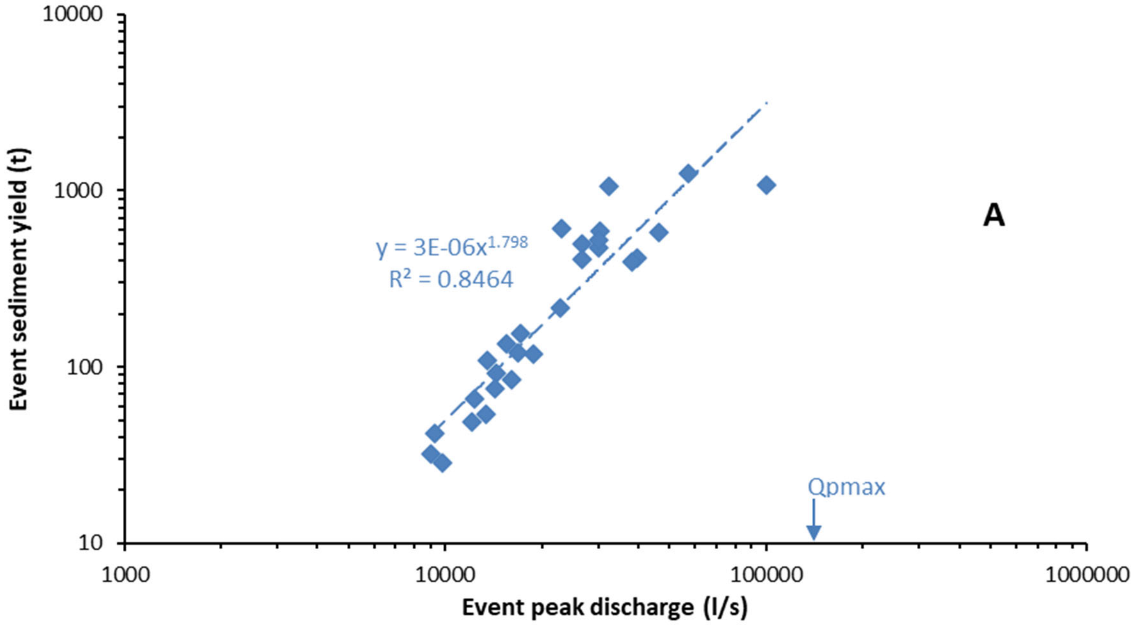
### 4.2.8 Kaipara River

The 163 km$^2$ Kaipara River catchment, monitored at the Waimauku site, is formed in Waitematā Formation bedrock and has dominantly Ultic, Allophanic, and Granular catchment soils, predominantly rolling slopes, and predominantly pasture land cover (Table 2-2). Its primary monitoring purpose is as a validation site.

The sediment record at Kaipara River spans from 12 March 2012 to 18 December 2019, although for the purpose of this study the record has been "padded-back" to 1 January 2012 and "padded-out" to 31 December 2019 using the event rating, enabling a record of eight years. Event sediment yields were determined for 139 events over this period.

Five suspended sediment gaugings were done between March 2012 and September 2015 (Figure 4-16B), covering a discharge range of 23,900-86,600 l/s, for the purpose of establishing a relation between $C_m/C_p$ and discharge (Appendix E, Table-1). Four of these data-points had $C_m/C_p$ ratios clustered around 1.0, indicating good mixing, but the fourth had a low $C_m/C_p$ ratio (0.47) despite it being measured at the highest discharge when mixing is expected to be optimal and $C_m/C_p = 1$. The cause and significance of this anomalous datapoint are unclear. It might be real and reflect a transient chance difference between depth-integrated and auto-sampled SSC due to turbulence. Alternatively, it might stem from technical issues during the sampling operation, such as the auto-sampler stirring-up additional sediment from the bed during its purge and sampling cycle. Including it in a $C_m/C_p$ adjustment function would induce a significant reduction in the derived yields. We therefore adopted a conservative approach, discarding this point and assuming $C_m/C_p = 1$ for all discharges, hence no $C_m/C_p$ adjustment was applied. We recommend further sediment gaugings at Kaipara, particularly at higher discharges, to verify this assumption.

The event yield rating, developed from 27 well-sampled single-peak events (Figure 4-15A), was $S = 3.19 \times 10^{-6} Q_p^{1.798}$. The highest peak discharge at which the rating was applied 124,000 l/s) exceeds the highest peak discharge used to derive the rating (100,300 l/s), hence the rating had to be extrapolated for that unsampled event but not by much. The residuals ratio from the rating relation (i.e. observed/predicted) showed a significant (at the 5% significance level) monotonic time trend (Figure 4-15B), defined by the function obs/pred = 82387 exp($-2.67 \times 10^{-4}$D), where D is the Excel date (days since 1 January 1900), the coefficient 82387 includes a log-bias correction factor of 1.07, and the exponential coefficient indicates a 9.4% per year reduction in event yields at a given peak discharge. The event yield rating was multiplied by this time-trend function to correct for drift in the rating.



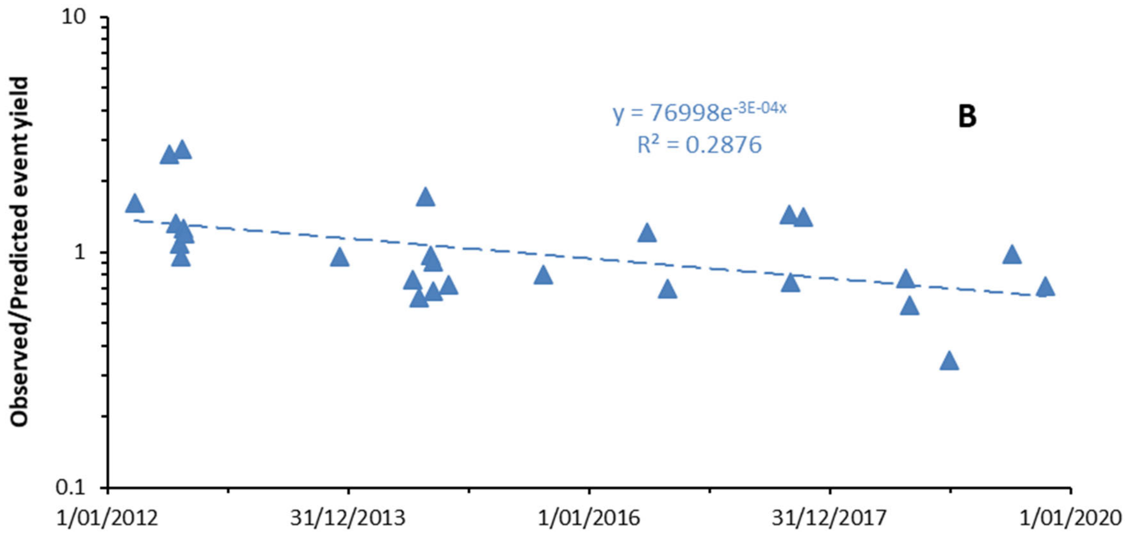




**Figure 4-15: Rating between event sediment yield and event peak discharge for Kaipara River at Waimauku, 2012-2019.**
Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. A: rating. B: Observed/Predicted event yield vs. time. Time-trend is significant at 5% level.

As summarised in Table 4-2, the total sediment yield from storm events over the monitoring period was 39,537 t, equating to a specific sediment yield of 30.4 t/km$^2$/y.

Of the total yield, 69% was captured by sampled events; the remainder from unsampled events was predicted using the time-adjusted event rating and resulted in a ± 5.5% uncertainty in the total yield over all events.

The largest event (in terms of peak discharge) across the entire record, which occurred as a multi-peak event over 24-28/09/2013 when the peak discharge was 124,000 l/s

(Figure 4-16A), was unsampled. The rating-estimated yield for this event was 4,590 t (equating to 93% of the mean annual yield and 50% of the 2013 yield). Most other large events had well sampled yields.

The time-cumulative yield plot (Figure 4-16A) shows its steepest "jump" around the 24-28/09/2013 event. The cumulative specific yield trend, derived from this plot, was 30.6 t/km$^2$/y, which is very close to the specific yield of 30.4 t/km$^2$/y.

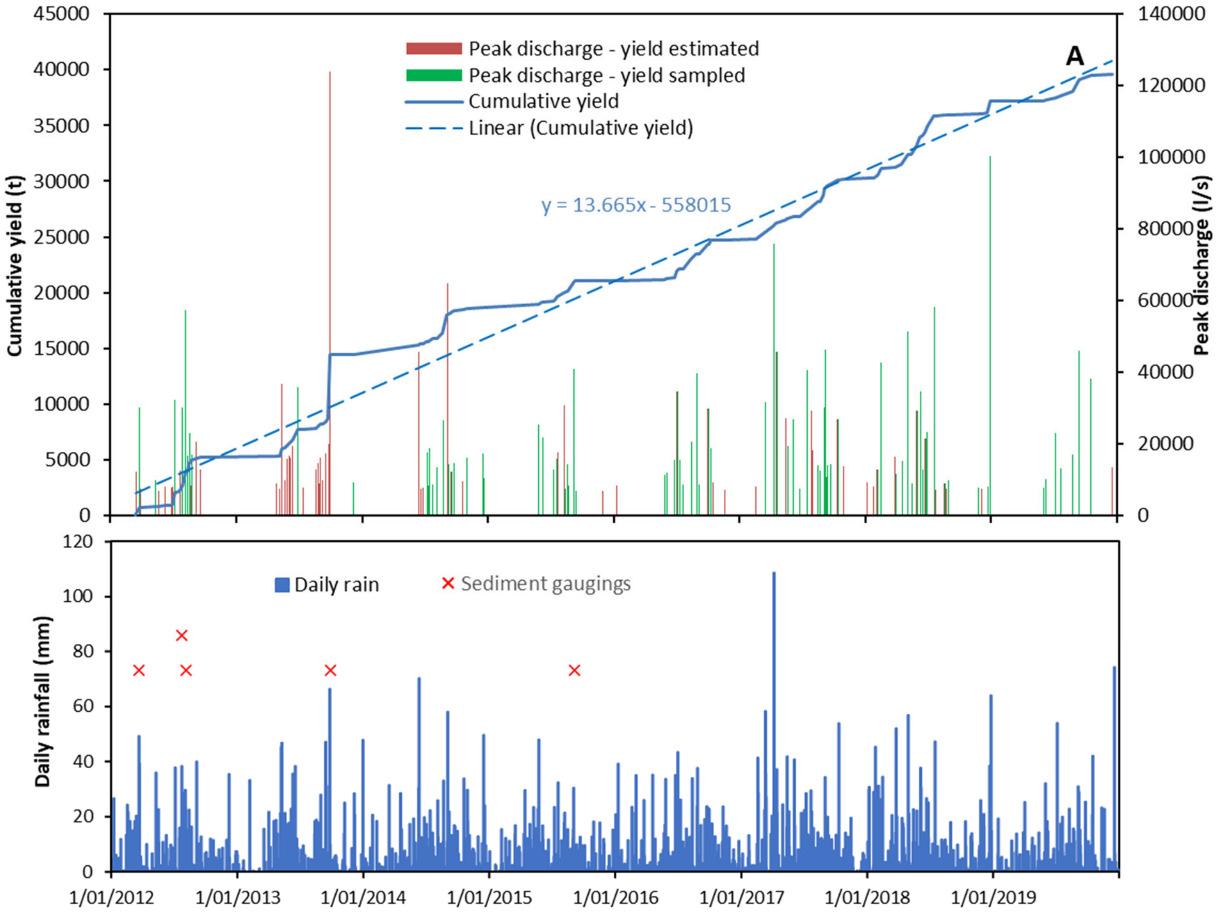



**Figure 4-16: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Kaipara River at Waimauku, 1/1/2012-31/12/2019.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red. xs mark gaugings of cross-section mean SSC.

## 4.3 Calibration catchments

### 4.3.1 Kaukapakapa River

The 62 km$^2$ Kaukapakapa catchment, monitored at the Taylors site, is formed in mudstone bedrock and has dominantly Ultic and Allophanic catchment soils, predominantly rolling slopes, and predominantly pasture land cover (Table 2-2). Its primary monitoring purpose is as a calibration site.

The sediment record at Kaukapakapa River spans from 21 May 2010 to 18 December 2019, although for the purpose of this study the record has been "padded-out" to 31 December 2019 using the event rating, enabling a record of 9.6 years. Event sediment yields were determined for 190 events over this period.

Five suspended sediment gaugings were done between March 2012 and June 2016 (Figure 4-18B), covering a discharge range of 15,100-59,300 l/s, for the purpose of establishing a relation between $C_m/C_p$ and discharge (Appendix E, Table 1). No statistically significant relation was found (at the 5% significance level), but since all $C_m/C_p$ values were less than 1 we chose to apply the linear-regression-derived relation $C_m/C_p = 6.45 \times 10^{-3} Q$, where Q is discharge in $m^3/s$ and $C_p/C_m$ equals 1 (indicating perfect mixing) at 85,900 l/s, which aligns with the maximum sampled discharge at the site.

The event yield rating, developed from 16 well-sampled single-peak events (Figure 4-17A), was $S = 4.45 \times 10^{-6}\ Q_p^{1.666}$, where the coefficient $4.45 \times 10^{-6}$ incorporates a log bias correction factor of 1.1. The highest peak discharge at which the rating was applied 116,300 l/s) exceeds the highest peak discharge used to derive the rating (84,500 l/s), hence the rating had to be extrapolated for that unsampled event, causing reduced confidence in the estimated event yield. The residuals ratio from the rating relation (i.e. observed/predicted) showed no significant (at the 5% significance level) time trend (Figure 4-17B).

As summarised in Table 4-3, the total sediment yield from storm events over the monitoring period was 17,019 t, equating to a specific sediment yield of 28.6 $t/km^2/y$.

Of the total yield, 73% was captured by sampled events; the remainder from unsampled events was predicted using the time-adjusted event rating and resulted in a ± 5.0% uncertainty in the total yield over all events.

The two largest events (in terms of peak discharge) across the entire record occurred over 24-29/12/2013 and 23-27/12/2018, when the peak discharges were 116,300 l/s and 113,100 l/s respectively (Figure 4-17A), were unsampled. The rating-estimated yield for these events were 1,219 t and 1,163 t, respectively (equating to 69% and 66%, respectively, of the mean annual yield, and 50% and 38%, respectively, of the 2013 and 2018 annual yields). Most other events had well sampled yields (Figure 4-18A).

The time-cumulative yield plot (Figure 4-18A) shows steep "jumps" around these two unsampled events, but also associated with well-sampled events (e.g. event of 15-17

July 2018, which was the third largest event on the record). The cumulative specific yield trend, derived from this plot, was 26.2 t/km$^2$/y, which is close to the specific yield of 28.6 t/km$^2$/y.

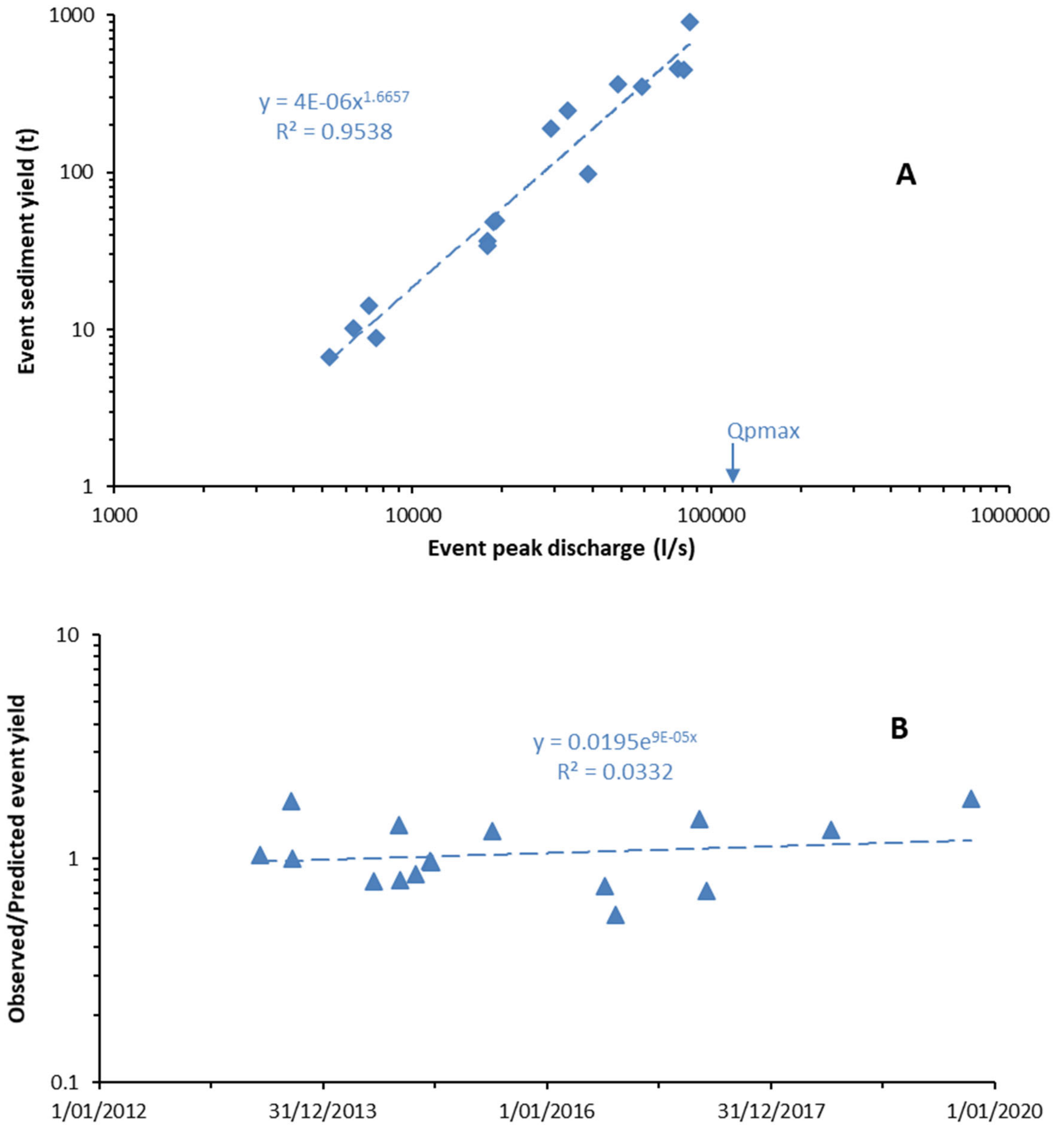



**Figure 4-17: Rating between event sediment yield and event peak discharge for Kaukapakapa River at Taylors, 2010-2019.**
Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. A: rating. B: Observed/Predicted event yield vs. time. Time-trend is not significant at 5% level.

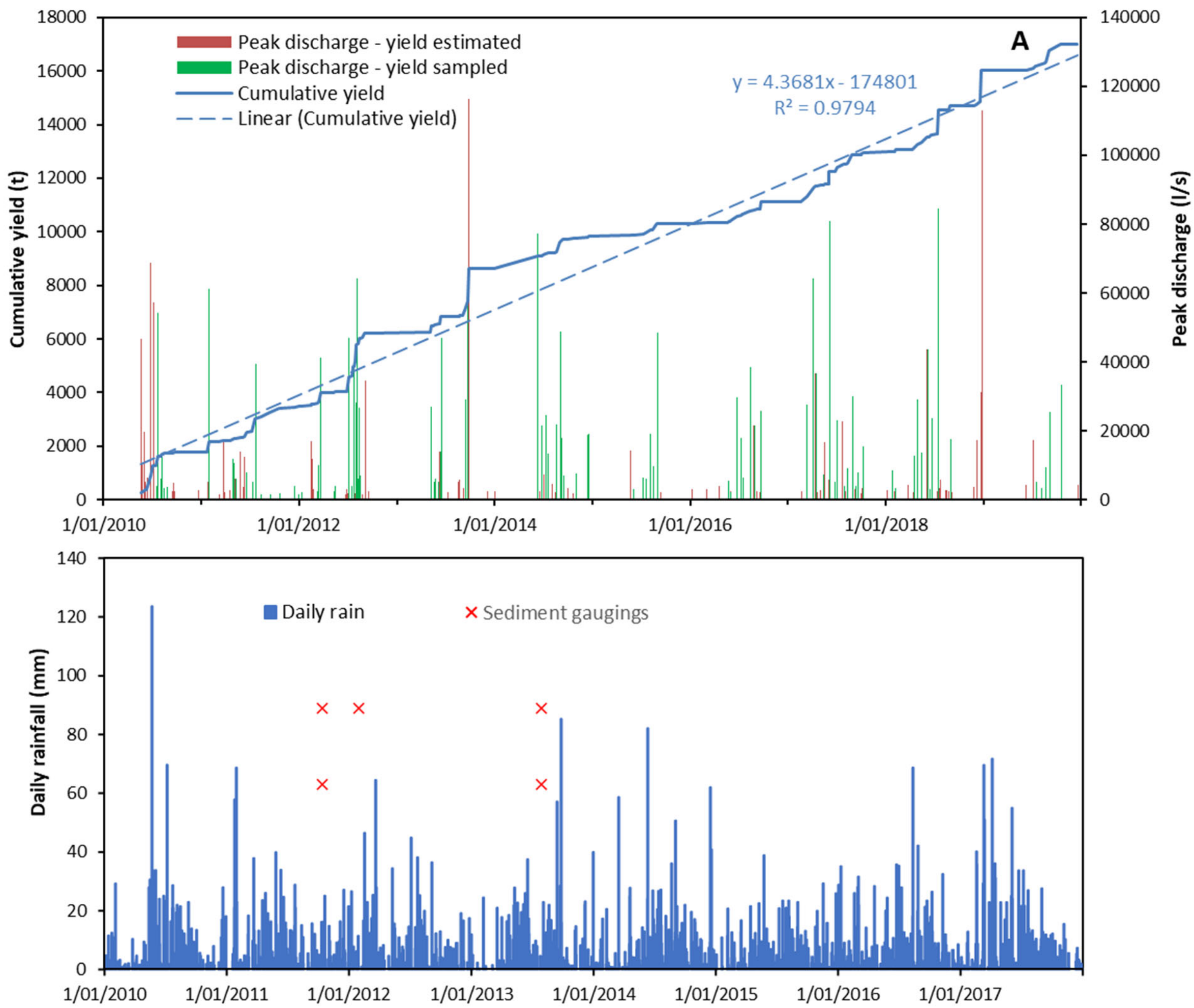



**Figure 4-18: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Kaukapakapa River at Taylors, 21/5/2010-31/12/2019.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red. xs mark gaugings of cross-section mean SSC.

**Table 4-3: Sediment yield summary for the Kaukapakapa River (calibration) catchment.**

| Description (units) | Value |
|---|---|
| Catchment area ($km^2$) | 61.9 |
| Start date | 21/05/2010 |
| End date | 31/12/2019 |
| **Duration (y)** | **9.61** |
| Maximum unsampled discharge (l/s) | 116312 |
| Maximum sampled peak discharge on rating (l/s) | 84526 |
| Total sediment yield across all events (t) | 17019 |
| Total sediment yield across sampled events (t) | 12431 |
| Total sediment yield predicted using rating (t) | 4589 |
| Standard error of regression (%) | 42% |
| Error on predicted sediment yield (t) | 873 |
| **Error on total sediment yield (%)** | **5%** |
| **Proportion of total sediment yield sampled (%)** | **73%** |
| **Yield (t/y)** | **1771** |
| **Specific yield (t/$km^2$/y)** | **28.6** |
| Cumulative yield trend (t/d) | 4.43 |
| Cumulative specific yield trend (t/$km^2$/y) | 26.2 |
| **Time trend on event yields (%/y)** | **NS** |

## 4.4 Compliance catchments

### 4.4.1 Weiti Stream

The 1.7 km$^2$ Weiti Stream catchment, monitored at the Weiti Forest site, is formed in mudstone bedrock and has dominantly Ultic soils, predominantly strongly rolling slopes, and predominantly exotic forest cover (Table 2-2). Its primary monitoring purpose is as a compliance site (to monitor the effects of plantation forestry harvest cycles). Forest harvesting occurred from December 2012 to December 2013.

Sediment data collection at Weiti Stream began on 15 April 2008 and continued through until 6 December 2016 when the site was discontinued. The data collection continued through the harvesting period (December 2012-February 2014). With "padding-out" until 31 December 2016, this provides 8.6 years of record. Event sediment yields were determined for 188 events over this period.

Sediment yield results from Weiti up to 2012 were reported by Hoyle (2013) and reproduced by Curran-Cournane et al. (2013)[9].

No suspended sediment gaugings have been done at Weiti, so we have assumed $C_m/C_p$ = 1 for all discharges.

The event yield rating, developed from 44 well-sampled single-peak events (Figure 4-19A), was $S = 1.97\text{x}10^{-3}\ Q_p^{1.169}$, where the coefficient $1.97\text{x}10^{-3}$ incorporates a log bias correction factor of 1.09. The highest peak discharge at which this rating was applied (1,734 l/s) is less than the highest peak discharge used to derive the rating (3,214 l/s), hence no rating extrapolation was required.

The residuals ratios from the rating relation (i.e. observed/predicted) showed no significant (at the 5% significance level) time trend over the monitoring period, with the data from before, during, and after forest harvesting following the same trend (Figure 4-19B).

As summarised in Table 4-4, the total sediment yield from storm events over the 8.6-year monitoring period was 519 t, equating to a specific sediment yield of 35.3 t/km$^2$/y.

[9] The present Weiti yield results prior to July 2011 differ from those previously reported by Curran-Cournane et al. (2013) as sourced from Hoyle (2013). Hoyle's event yields prior to July 2011 contained a systematic error associated with the adjustment of TSS to SSC. The present analysis uses the updated TSS-SSC relation given here in Appendix C for those events, which is also based on a larger dataset of comparative SSC vs TSS measurements than was used by Hoyle (2013). Samples collected at Weiti from July 2011 were analysed by the SSC method and so required no correction.

Of the total yield, 75% was captured by sampled events, the remainder from unsampled events was predicted using the event rating and resulted in a ± 2.2% uncertainty in the total yield over all events.

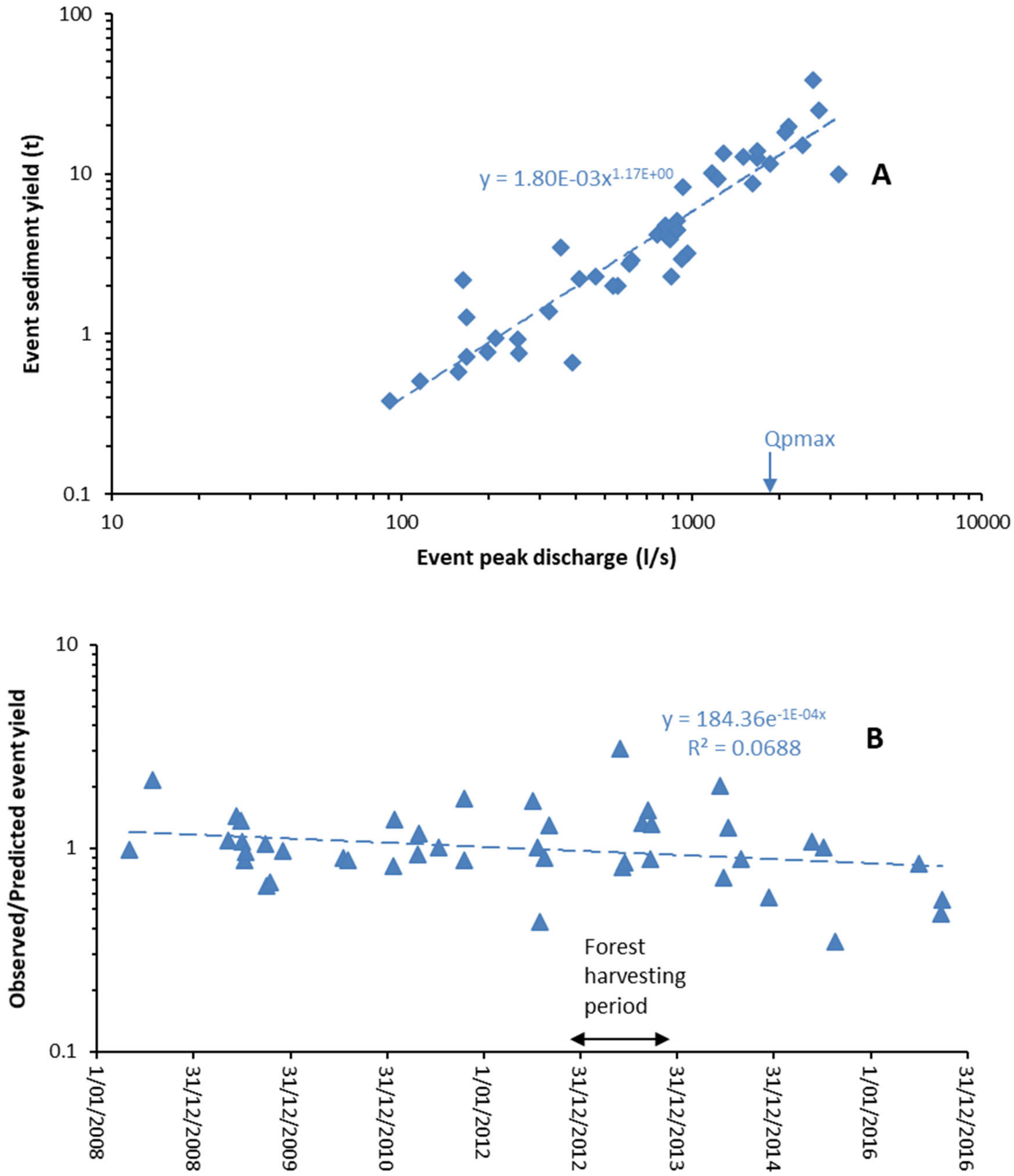



**Figure 4-19: Rating between event sediment yield and event peak discharge for Weiti Stream at Weiti Forest, 2008-2016.**

A: rating. Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. B: Observed/Predicted event yield vs. time. Forest harvesting occurred from December 2012 through December 2013. Time-trend is not significant at 5% level.

The largest event (in terms of peak discharge) occurred over 29/7/2012-1/8/2012 with a peak discharge of 3,214 l/s (Figure 4-20A) and a well sampled yield of 9.92 t (equating to 17% of the mean annual yield and 13% of the 2012 yield).

The cumulative specific yield trend, derived from the time-cumulative yield plot (Figure 4-20A), was 35.1 t/km$^2$/y, which is very close to the specific yield of 35.3 t/km$^2$/y.

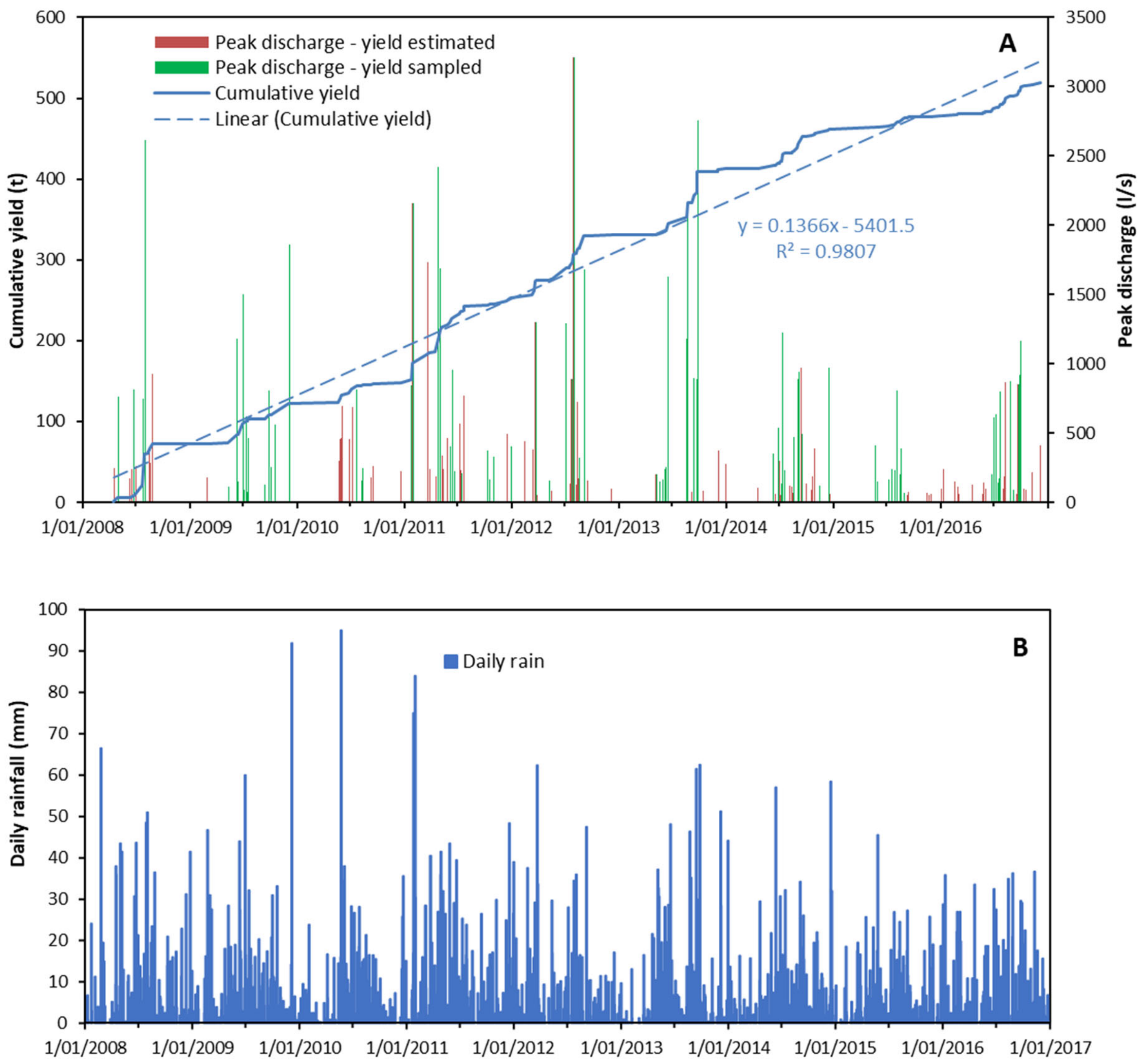



**Figure 4-20: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Weiti Stream at Weiti Forest, 15/4/2008-31/12/2016.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red.

**Table 4-4: Sediment yield summary for the Weiti Stream (compliance) catchment.**

| Description (units) | Value |
|---|---|
| Catchment area ($km^2$) | 1.7 |
| Start date | 14/04/2008 |
| End date | 06/12/2016 |
| **Duration (y)** | **8.6** |
| Maximum unsampled discharge (l/s) | 1734 |
| Maximum sampled peak discharge on rating (l/s) | 3214 |
| Total sediment yield across all events (t) | 519 |
| Total sediment yield across sampled events (t) | 387 |
| Total sediment yield predicted using rating (t) | 132 |
| Standard error of regression (%) | 52.0% |
| Error on predicted sediment yield (t) | 11 |
| **Error on total sediment (%)** | **2.2%** |
| **Proportion of total sediment yield sampled (%)** | **74.6%** |
| **Yield (t/y)** | **60.0** |
| **Specific yield ($t/km^2/y$)** | **35.3** |
| Cumulative yield trend (t/d) | 0.163 |
| Cumulative specific yield trend ($t/km^2/y$) | 35.1 |
| **Time trend on event yields (%/y)** | **NS** |

## 4.5 Upper Henderson catchments

Three sites were installed in January 2016 for the purpose of evaluating how a proposed catchment management programme for the Upper Henderson catchment would affect the sediment yield delivered to the Central Waitematā Harbour (Alley 2016), however, monitoring ceased at the end of 2018.

Among these three catchments, the greatest yield of sediment delivered to the Waitematā Harbour, and the greatest yield relative to catchment area (specific yield), was from the Oratia Stream catchment. All three catchments were well sampled, resulting in low levels of uncertainty, and the sediment yields were well determined. Further details on each catchment are outlined below (Table 4-5).

It is noted that the relatively high sediment yields observed among these three catchments are likely attributable to the three-year monitoring period assessed that coincided with the two "dirtiest" or "wet" years recorded within the past decade in the Auckland region. This is further discussed in Sections 5.1 and 5.2.

**Table 4-5: Sediment yield summary for the Upper Henderson catchments.**

| | **Values for each catchment** | | |
|---|---|---|---|
| **Description (units)** | **Opanuku Stream** | **Oratia Stream** | **Swanson Stream** |
| Catchment area ($km^2$) | 15.83 | 16.75 | 22.60 |
| Start date | 01/01/2016 | 01/01/2016 | 01/01/2016 |
| End date | 31/12/2018 | 31/12/2018 | 31/12/2018 |
| **Duration (y)** | 3 | 3 | 3 |
| Maximum unsampled discharge (l/s) | 23511 | 17657 | 84306 |
| Maximum sampled peak discharge on rating (l/s) | **67760** | **53082** | **83379** |
| Total sediment yield across all events (t) | 4286 | 9183 | 7262 |
| Total sediment yield across sampled events (t) | 3557 | 8275 | 5838 |
| Total sediment yield predicted using rating (t) | 729 | 908 | 1424 |
| Standard error of regression (%) | 38.0% | 19.8% | 16.6% |
| Error on predicted sediment yield (t) | 70 | 48 | 117 |
| **Error on total sediment (%)** | **1.6%** | **0.53%** | **1.6%** |
| **Proportion of total sediment yield sampled (%)** | 83.0% | 90.1% | 80.4% |
| **Yield (t/y)** | **1429** | **3061** | **2421** |
| **Specific yield ($t/km^2/y$)** | **90.3** | **183** | **107** |
| Cumulative yield trend (t/d) | 4.337 | 9.40 | 7.45 |
| Cumulative specific yield trend ($t/km^2/y$) | **100.1** | **205** | **120** |
| **Trend on event yields (%/y)** | **No result** | **No result** | **No result** |

### 4.5.1 Opanuku Stream

The 15.8 $km^2$ Opanuku Stream catchment, monitored at the Candia Road site, is formed in mainly volcanic sandstone bedrock and has dominantly Granular and Brown soils, predominantly moderately steep and steep slopes, and predominantly indigenous forest cover (Table 2-2). Opanuku is a long-term baseline river water quality monitoring site, monitoring the effects of upper catchment rural land use change since 1986.

The sediment record at Opanuku Stream spans from 2 January 2016 to 26 December 2018, enabling a record of three years. Event sediment yields were determined for 85 events over this period.

Four suspended sediment gaugings were done between August 2016 and June 2018 (Figure 4-22B), covering a discharge range of 1,200-5,780 l/s, for the purpose of establishing a relation between $C_m/C_p$ and discharge (Appendix E, Table 1). One of these gaugings had an unusually high $C_m/C_p$ ratio (3.3) and was dismissed as an outlier, likely due to the depth-integrating sampler "scuffing" the streambed and over-catching. The other three had $C_m/C_p$ ratios ranging between 0.61 and 1.35, averaging 1.07, and with no trend with discharge. Given the few reliable points, we assumed $C_m/C_p = 1$ for all discharges, hence no $C_m/C_p$ adjustment was applied.

The event yield rating, developed from 16 well-sampled single-peak events (Figure 4-21A), was $S = 2.19 \times 10^{-5} Q_p^{1.511}$, where the coefficient $2.19 \times 10^{-5}$ incorporates a log bias correction factor of 1.05. The highest peak discharge at which the rating was applied (23,510 l/s) is substantially less than the highest peak discharge used to derive the rating (67,760 l/s), hence there was no rating extrapolation required. The residuals ratio from the rating relation (i.e. observed/predicted) showed no significant (at the 5% significance level) monotonic time trend (Figure 4-21B).

As summarised in Table 4-5, the total sediment yield from storm events over the monitoring period was 4,286 t, equating to a specific sediment yield of 90.3 t/$km^2$/y.

Of the total yield, 83% was captured by sampled events, the remainder from unsampled events was predicted using the time-adjusted event rating and resulted in a ± 1.6% uncertainty in the total yield over all events.

The largest event (in terms of peak discharge) across the entire record, which occurred on 13/4/2017 when the peak discharge was 63,760 l/s (Figure 4-22A), was well sampled. The measured yield for this event was 413 t (equating to 29% of the mean annual yield and 21% of the 2017 yield). Most other large events also had well sampled yields.

The time-cumulative yield plot (Figure 4-22A) shows the largest "jump" associated with the mainly well sampled events of March-April 2017. The cumulative specific yield trend, derived from this plot, was 100.1 t/km$^2$/y, which is 11% larger than the specific yield of 90.3 t/km$^2$/y.

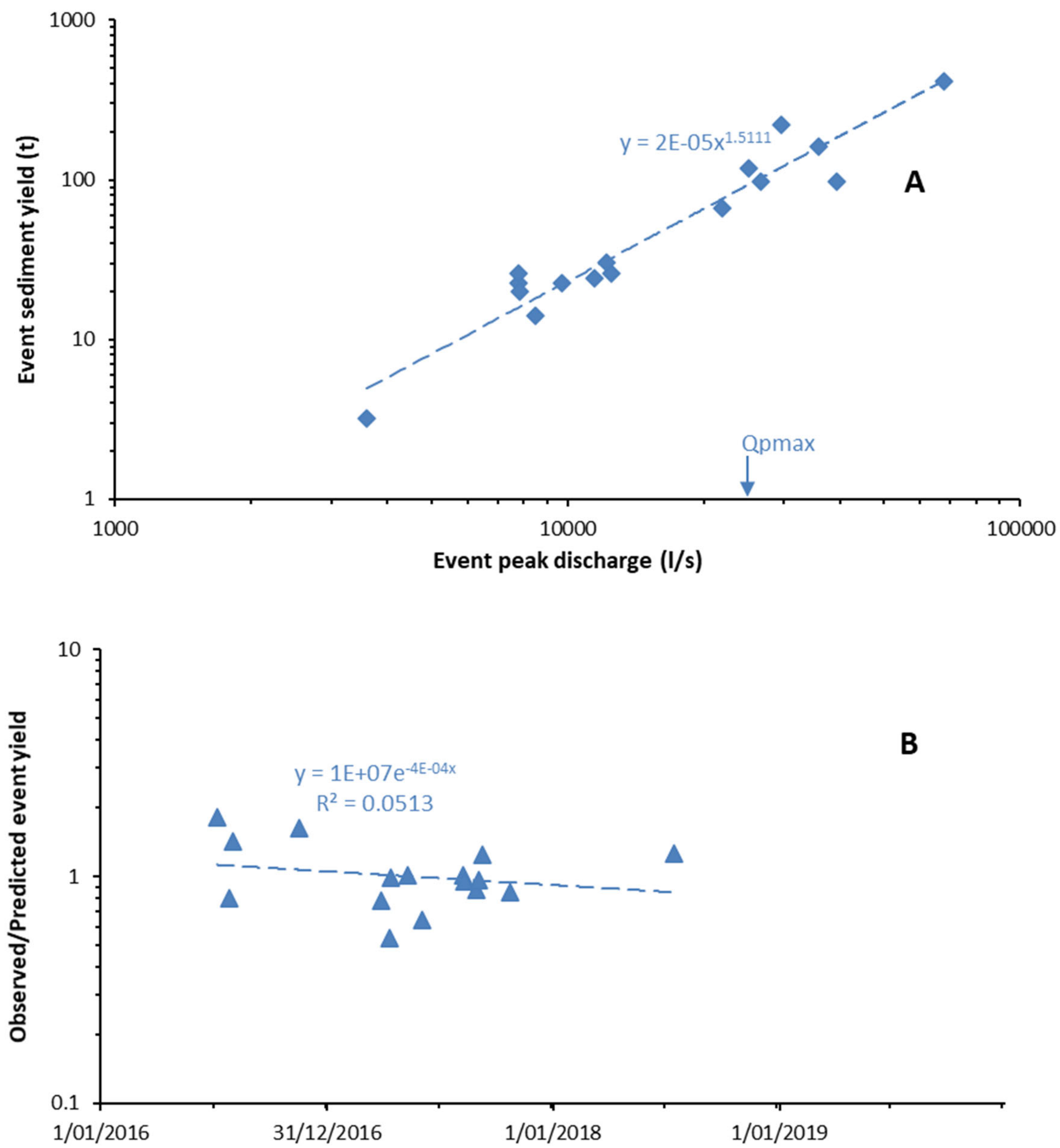



**Figure 4-21: Rating between event sediment yield and event peak discharge for Opanuku Stream at Candia Road, 2016-2018.**
Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. A: rating. B: Observed/Predicted event yield vs. time. Time-trend is not significant at 5% level.

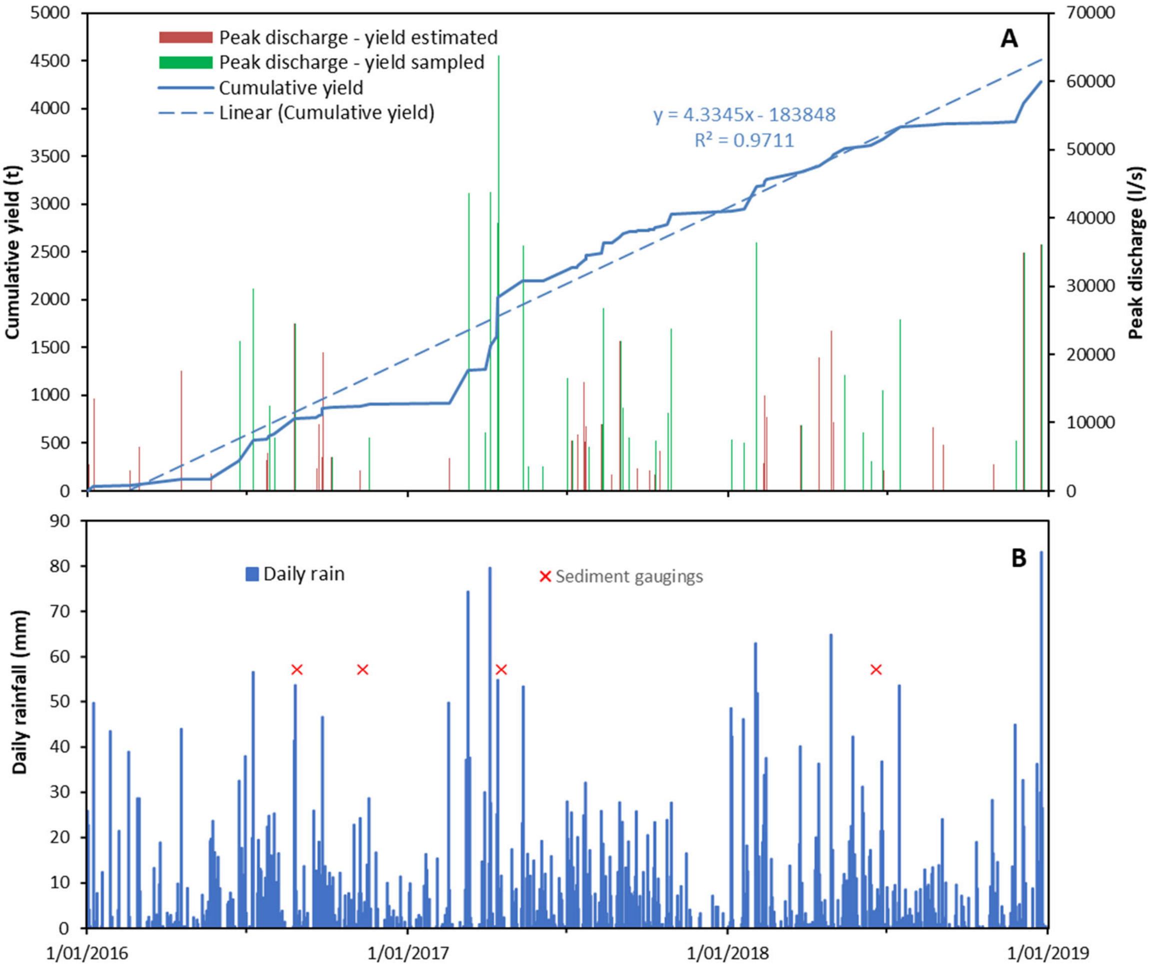



**Figure 4-22: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Opanuku Stream at Candia Road, 1/1/2016-31/12/2018.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red. xs mark gaugings of cross-section mean SSC.

### 4.5.2 Oratia Stream

The 16.8 km$^2$ Oratia Stream catchment, monitored at the Parrs Cross site, is formed in mainly volcanic sandstone or turbidite (alternating sandstone/mudstone strata) bedrock and has dominantly Granular soils, predominantly rolling and strongly rolling slopes, and predominantly indigenous forest cover (Table 2-2).

The sediment record at Oratia Stream spans from 21 January 2016 to 26 December 2018, enabling a record of three years after minor "padding" back to 1 January 2016. Event sediment yields were determined for 68 events over this period.

Three suspended sediment gaugings were done between June 2016 and June 2018 (Figure 4-24B), covering a relatively narrow discharge range of 4,389-5,175 l/s, for the purpose of establishing a relation between $C_m/C_p$ and discharge. These had $C_m/C_p$ ratios ranging between 0.88 and 1.15, averaging 0.96, and with no trend with discharge. Given the few points, we assumed $C_m/C_p = 1$ for all discharges, hence no $C_m/C_p$ adjustment was applied.

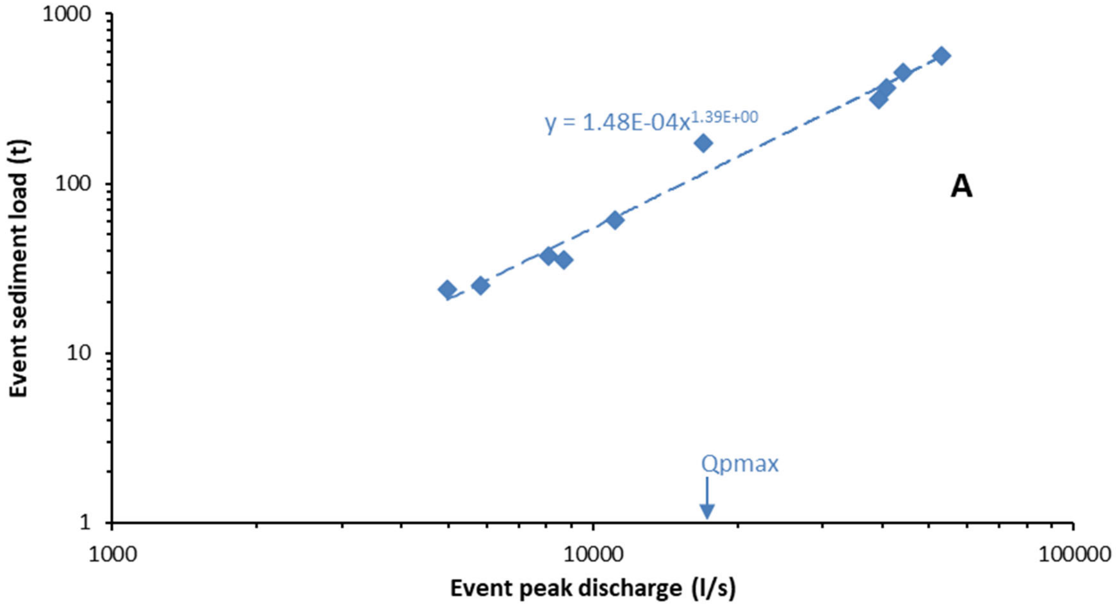
The event yield rating, developed from 10 well-sampled single-peak events (Figure 4-23A), was $S = 1.51 \times 10^{-4} Q_p^{1.392}$, where the coefficient $1.51 \times 10^{-4}$ incorporates a log bias correction factor of 1.02. The highest peak discharge at which the rating was applied (17,657 l/s) is substantially less than the highest peak discharge used to derive the rating (53,082 l/s), hence there was no rating extrapolation required. The residuals ratio from the rating relation (i.e. observed/predicted) showed no significant (at the 5% significance level) monotonic time trend (Figure 4-23B).

As summarised in Table 4-5, the total sediment yield from storm events over the monitoring period was 9,183 t, equating to a high (compared to the other sites) specific sediment yield of 183 t/km$^2$/y.

Of the total yield, 90% was captured by sampled events, the remainder from unsampled events was predicted using the time-adjusted event rating and resulted in a ± 0.5% uncertainty in the total yield over all events. Thus, we consider the sediment yield at Oratia to be well determined.

The largest events (in terms of peak discharge) across the entire record occurred in quick succession over 4-6/4/2017 and 12-13/4/2017, with peak discharges of 54,716 l/s and 53,080 l/s, respectively (Figure 4-24A), and with well sampled yields of 571 t and 340 t, respectively (their combined yield equating to 30% of the mean annual yield and 24% of the 2017 yield). Most other large events also had well sampled yields.

The time-cumulative yield plot (Figure 4-24A) shows the largest “jump” associated with the well sampled events of March-April 2017. The cumulative specific yield trend, derived from this plot, was 205 t/km$^2$/y, which is 12% larger than the specific yield of 183 t/km$^2$/year derived by dividing the total specific yield by the record period.



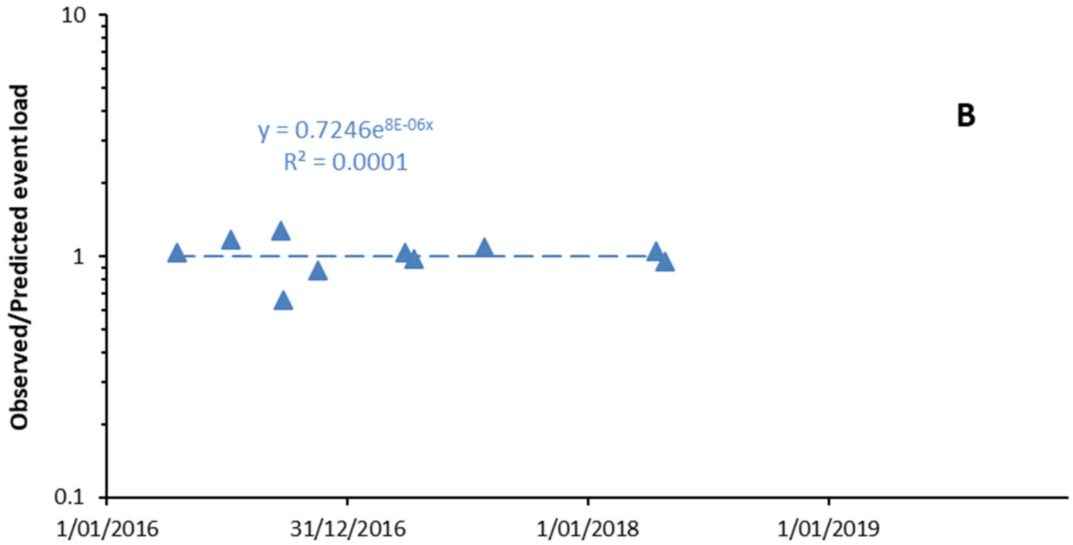




**Figure 4-23: Rating between event sediment yield and event peak discharge for Oratia at Parrs Cross, 2016-2018.**

Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. A: rating. B: Observed/Predicted event yield vs. time. Time-trend is not significant at 5% level.

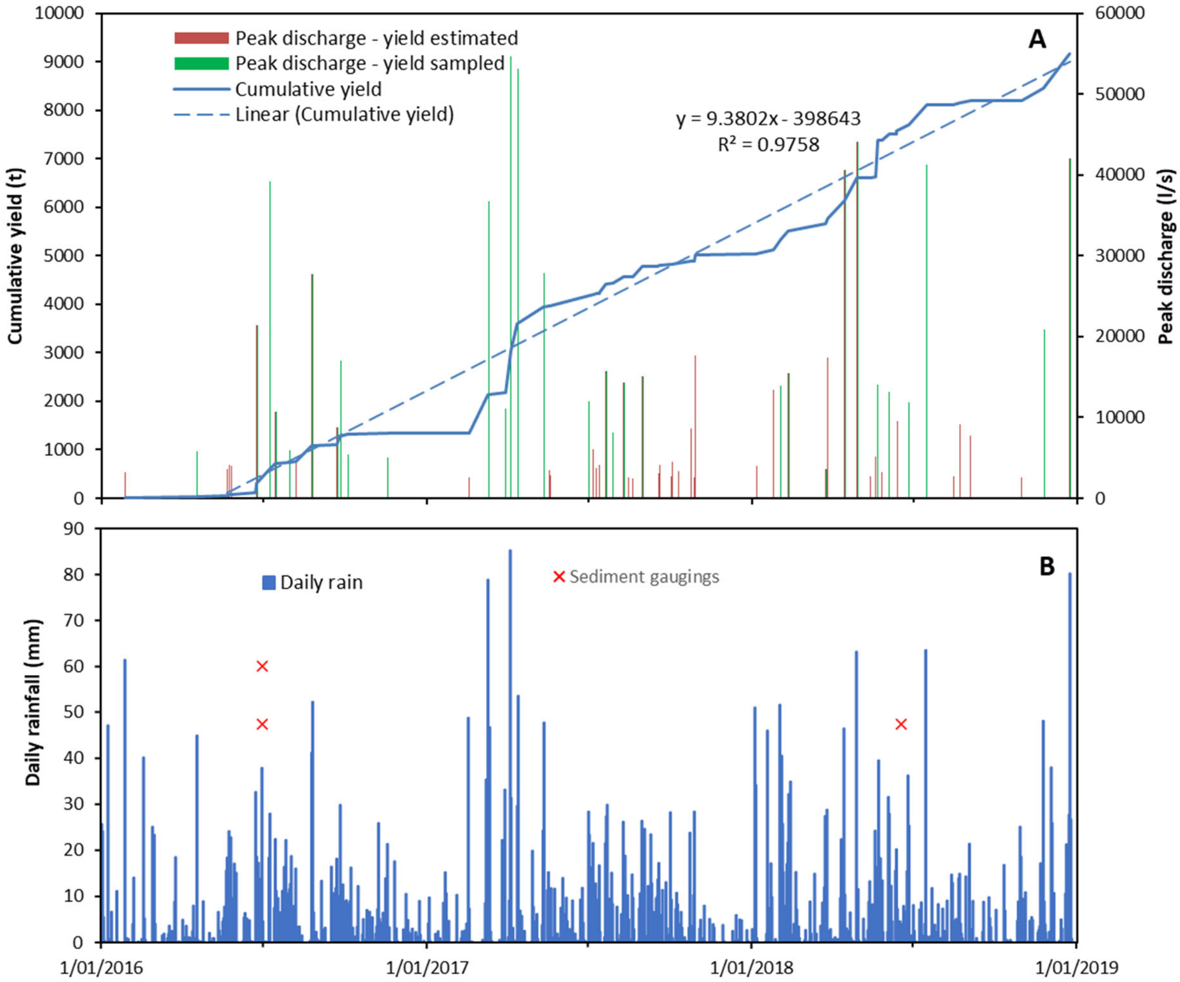



**Figure 4-24: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Oratia Stream at Parrs Cross, 1/1/2016-31/12/2018.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red. xs mark gaugings of cross-section mean SSC.

### 4.5.3 Swanson Stream

The 22.6 km$^2$ Swanson Stream catchment, monitored at the Woodside Reserve site, drains into Henderson Creek. It is formed in mainly volcanic sandstone and turbidite (alternating sandstone/mudstone strata) bedrock and has a mixture of Granular, Ultic, and Allophanic soils, predominantly rolling and strongly rolling slopes, and largely either indigenous or exotic vegetation cover (Table 2-2).

The sediment observation period at Swanson Stream spans from 1 January 2016 through 31 December 2018, providing a three-year record. Event sediment yields were determined for 102 events over this period.

Eight suspended sediment gaugings were done between June 2016 and June 2018 (Figure 4-26B), covering a discharge range of 2,020-22,000 l/s, for the purpose of establishing a relation between $C_m/C_p$ and discharge. These had $C_m/C_p$ ratios ranging between 0.35 and 1.44, averaging 1.00, and with no trend with discharge at the 5% significance level. On this basis we assumed $C_m/C_p = 1$ for all discharges, hence no $C_m/C_p$ adjustment was applied.

The event yield rating, developed from 14 well-sampled single-peak events (Figure 4-25A), was defined by a two-part function: $S = 9.45 \times 10^{-11} Q_p^{3.04}$ for $Q_p$ < 5,480 l/s, and $S = -4.59 \times 10^{-8} Q_p^2 + 0.0108 Q_p - 38.4$ for $Q_p$ > 5,480 l/s. This two-part function provided the best fit to the overall dataset, which was curved across logS-log$Q_p$ space. The highest peak discharge at which the rating was applied (84,306 l/s) is almost the same as the highest peak discharge used to derive the rating (83,379 l/s), hence there was minimal rating extrapolation required. The residuals ratio from the rating relation (i.e., observed/predicted) showed no significant (at the 5% significance level) monotonic time trend (Figure 4-25B).

As summarised in Table 4-5, the total sediment yield from storm events over the monitoring period was 7,262 t, equating to a specific sediment yield of 107 t/km$^2$/y.

Of the total yield, 80 per cent was captured by sampled events, the remainder from unsampled events was predicted using the time-adjusted event rating and resulted in a ±1.6% uncertainty in the total yield over all events. Thus, we consider the sediment yield at Swanson to be well determined.

As at the Opanuku Stream site, the largest events (in terms of peak discharge) across the three-year record occurred in quick succession over 4-6/4/2017 and 12-13/4/2017, with peak discharges of 66,315 l/s and 83,379 l/s, respectively (Figure 4-26A), and with well sampled yields of 632 t and 657 t, respectively (their combined yield equating to 53% of the mean annual yield and 41% of the 2017 yield). Most other large events also had well sampled yields.

The time-cumulative yield plot (Figure 4-26A) shows the largest “jump” associated with these well sampled events of April 2017. The cumulative specific yield trend, derived from this plot, was 120 t/km$^2$/y, which is 12 per cent larger than the specific yield of 107 t/km$^2$/y.

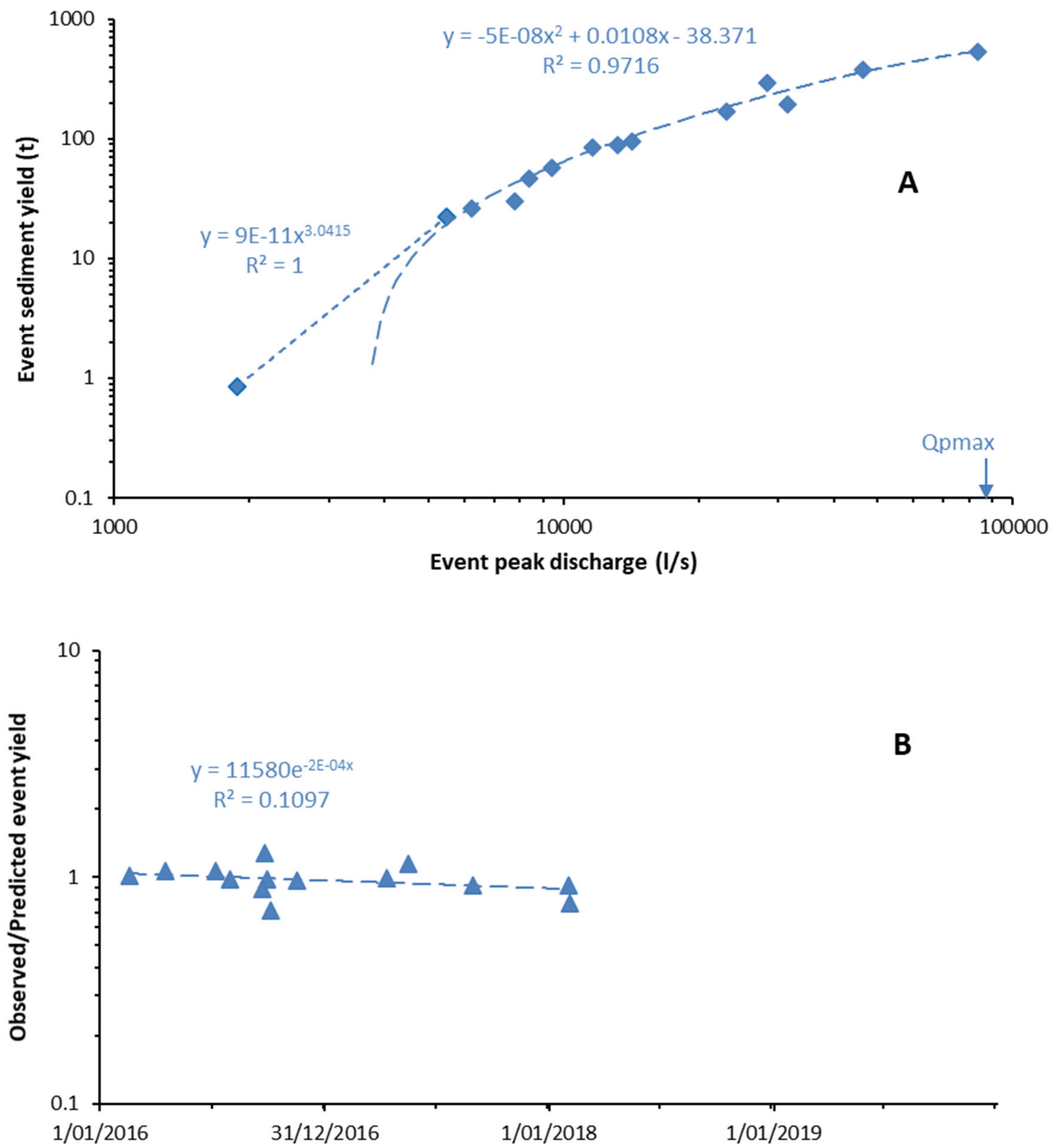



**Figure 4-25: Rating between event sediment yield and event peak discharge for Swanson Stream at Woodside Reserve, 2016-2018.**
A: rating. Rating represented by two functions meeting at a peak discharge of 5480 l/s. Qpmax indicates maximum unsampled peak discharge during sediment monitoring period. B: Observed/Predicted event yield vs. time. Time-trend is not significant at 5% level.

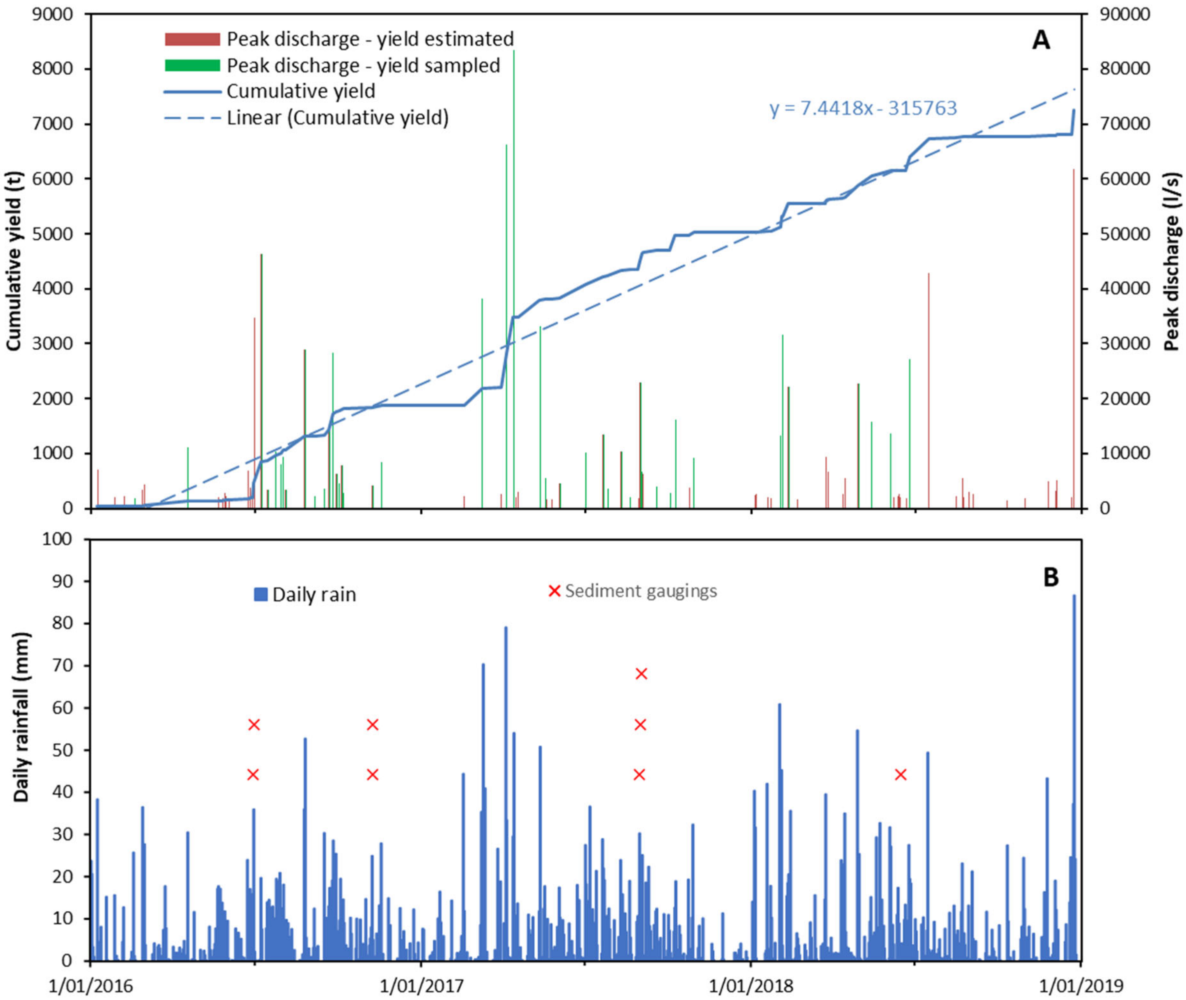



**Figure 4-26: Cumulative event sediment yield and event peak discharge (A), and daily rainfall (B) for Swanson Stream at Woodside Reserve, 1/1/2016-31/12/2018.**
Sampled events have peak discharges plotted in green; unsampled events, with rating-estimated yields, have peak discharges plotted in red. xs mark gaugings of cross-section mean SSC.

# 5.0 Discussion of rural catchment sediment yields

## 5.1 Annual variability in sediment yield

Table 5-1 and Figure 5-1 show the annual specific sediment yields for the study catchments for all full calendar years of record, along with summary statistics quantifying the annual variability.

As observed in previous studies for the Auckland region (e.g. Hicks et al. 2009a), this study shows wide annual variability in sediment yield. At individual sites, the annual yields ranged over factors of 1.7 to 42.6 and the coefficient-of-variation of annual yields ranged between 27% and 137%.

Annual sediment yields correlate reasonably well across the region (i.e. higher or lower than average yielding years typically coincide across the region, Figure 5-1). For example, 2016, 2017 and 2018 had higher than average yields everywhere, while 2015 had low yields everywhere. The majority of catchments (West Hoe, Te Muri, Vaughan, Swanson, Opanuku, Mangemangeroa, Wairoa) had their peak annual yields in 2017, but three (Orewa, Kaukapakapa, Oratia) had their peak yields in 2018, while Hōteo peaked in 2016 and Kaipara in 2013. These patterns are consistent with the same weather events typically affecting the whole region, although with some spatio-temporal variation in their relative intensities.

This large inter-annual variability, overlain on monitoring periods of varying length and phase (i.e. varying start and end dates), creates a large sampling error on estimating the long-term mean annual yield. This error is only partly quantified by the standard error on the mean yield which ranged between 16% (Swanson) and 46% (Wairoa). For example, while Swanson, Opanuku and Oratia showed relatively low standard errors of their means (16-28%), their records were limited to the three high-yielding years 2016, 2017 and 2018. Thus, these recorded mean yields are almost certainly greater than their true long-term mean yields.

This large sampling error associated with annual variability means that mean annual yield estimates among catchments with short and different record periods should be compared with caution (i.e. a large sampling error confounds analysis of spatial yield variation among sites and its causes.).

A way to avoid this is to compare sites only for a common reference period. The reference period chosen for this study was 2012-2019, which provided the optimal combination of number of sites (eight) and years of overlapping record (eight). Hōteo, Kaipara, Kaukapakapa, Mangemangeroa, Orewa, Vaughan, Wairoa, and West Hoe all had mean annual yields determined through this reference period. As shown in Table

5-1, the all-of-record mean annual specific yields for these sites generally matched their 2012-2019 mean annual specific yields except for Hōteo (all-of-record mean was 81.5 t/km$^2$ compared with the 2012-2019 mean of 71.2 t/km$^2$).

Comparison of the 2012-2019 and 2016-2018 mean yields for these eight sites (Table 5-1) shows that their 2016-2018 means were all larger, by up to a factor of 2.1 (Wairoa) and by an average factor of 1.6. This provides an indication of how much the short-term 2016-2018 mean yields from Swanson, Opanuku and Oratia (which are biased by sampling three high-yield years in a row) may be overestimating their true longer-term mean yields by. Similarly, the realtively high (172.2 t/km$^2$/y) mean yield estimated over 2014-2019 at Te Muri is strongly influenced by the high yields over 2016-2018.

The large annual variability also masks any underlying time trend, as demonstrated by the high P-values[10] (0.23-0.94) in regression relations between annual yield and year (Table 5-1). The implications of this to the value of long-term monitoring for trend detection are discussed in Section 5.3.

[10] The P-value is the probability that the slope of the trend line is not different from zero. Typically, a slope with a P-value < 0.05 is regarded as significantly different from zero.

**Table 5-1: Annual specific sediment yields (t/km$^2$) and statistics for full calendar years, all sites.**

Sites arranged by primary monitoring purpose (Ref = Reference, Val = Validation, Cal = Calibration, Com = Compliance, UH = Upper Henderson Catchment Management), and by catchment slope. Annual mean yields are based on complete years so do not always align exactly with mean annual yields over full record period (see Tables 4-2 to 4-5).

| Year | West Hoe (Ref) | Te Muri (Val) | Hōteo (Val) | Wairoa (Val) | Mange-mange-roa (Val) | Vaughan (Val) | Orewa (Val) | Kaipara (Val) | Kaukap-akapa (Cal) | Weiti (Com) | Opanuku (UH) | Oratia (UH) | Swanson (UH) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2009 | | | | | | | | | | 29.5 | | | |
| 2010 | | | | | | | 61.7 | | | 15.3 | | | |
| 2011 | | | 164.5 | 76.5 | | | 62.4 | | 27.8 | 61.5 | | | |
| 2012 | 23.9 | | 45.1 | 27.4 | 169.1 | 45.5 | 56.4 | 32.9 | 44.0 | 45.9 | | | |
| 2013 | 27.1 | | 53.8 | 12.1 | 82.0 | 31.1 | 65.1 | 61.2 | 39.2 | 48.2 | | | |
| 2014 | 5.1 | 96.1 | 37.0 | 35.9 | 43.9 | 15.5 | 23.0 | 27.6 | 19.6 | 28.8 | | | |
| 2015 | 2.4 | 19.3 | 4.3 | 34.1 | 31.3 | 7.4 | 19.9 | 15.0 | 7.6 | 9.2 | | | |
| 2016 | 14.1 | 232.7 | 181.4 | 35.9 | 54.1 | 65.2 | 60.7 | 22.7 | 13.1 | 24.5 | 57.3 | 80.0 | 83.3 |
| 2017 | 39.6 | 362.0 | 145.6 | 338.5 | 295.6 | 100.4 | 66.5 | 34.0 | 29.7 | | 125.4 | 220.2 | 139.4 |
| 2018 | 35.8 | 241.4 | 86.9 | 88.4 | 260.2 | 63.7 | 152.2 | 43.0 | 49.7 | | 88.1 | 248.1 | 98.7 |
| 2019 | 3.6 | 82.7 | 15.3 | 22.4 | 21.3 | 6.6 | 24.0 | 14.9 | 15.8 | | | | |
| Years of record | 8 | 6 | 9 | 9 | 8 | 8 | 10 | 8 | 9 | 8 | 3 | 3 | 3 |
| Mean (t/km$^2$) | 18.9 | 172.4 | 81.5 | 74.6 | 119.7 | 41.9 | 59.2 | 31.4 | 27.4 | 32.9 | 90.3 | 182.7 | 107.1 |
| Std dev (t/km$^2$) | 14.8 | 127.8 | 66.5 | 102.1 | 108.3 | 33.2 | 37.8 | 15.4 | 14.6 | 17.7 | 34.1 | 90.1 | 29.0 |
| Coefficient of variation (%) | 78% | 74% | 82% | 137% | 90% | 79% | 64% | 49% | 53% | 54% | 38% | 49% | 27% |
| Std error on mean (t/km$^2$) | 5.2 | 52.2 | 22.2 | 34.0 | 38.3 | 11.7 | 12.0 | 5.5 | 4.9 | 6.3 | 19.7 | 52.0 | 16.7 |
| % error on mean | 28% | 30% | 27% | 46% | 32% | 28% | 20% | 17% | 18% | 19% | 22% | 28% | 16% |
| Minimum (t/km$^2$) | 2.4 | 19.3 | 4.3 | 12.1 | 21.3 | 6.6 | 19.9 | 14.9 | 7.6 | 9.2 | 57.3 | 80.0 | 83.3 |
| Maximum (t/km$^2$) | 39.6 | 362.0 | 181.4 | 338.5 | 295.6 | 100.4 | 152.2 | 61.2 | 49.7 | 61.5 | 125.4 | 248.1 | 139.4 |
| Range factor | 16.7 | 18.7 | 42.6 | 27.9 | 13.9 | 15.3 | 7.6 | 4.1 | 6.5 | 6.7 | 2.2 | 3.1 | 1.7 |
| 2016-18 average (t/km$^2$) | 29.9 | 278.7 | 138.0 | 154.3 | 203.3 | 76.5 | 93.2 | 33.2 | 30.8 | | 90.3 | 182.7 | 107.1 |
| 2012-19 average (t/km$^2$) | 18.9 | | 71.2 | 74.3 | 119.7 | 41.9 | 58.5 | 31.4 | 27.3 | | | | |
| Ratio 2016-18/2012-19 averages | 1.6 | | 1.9 | 2.1 | 1.7 | 1.8 | 1.6 | 1.1 | 1.1 | | | | |
| P-value on annual yield time trend over all monitored years | 0.94 | 0.56 | 0.8 | 0.47 | 0.69 | 0.67 | 0.66 | 0.38 | 0.65 | 0.85 | Too few data | Too few data | Too few data |

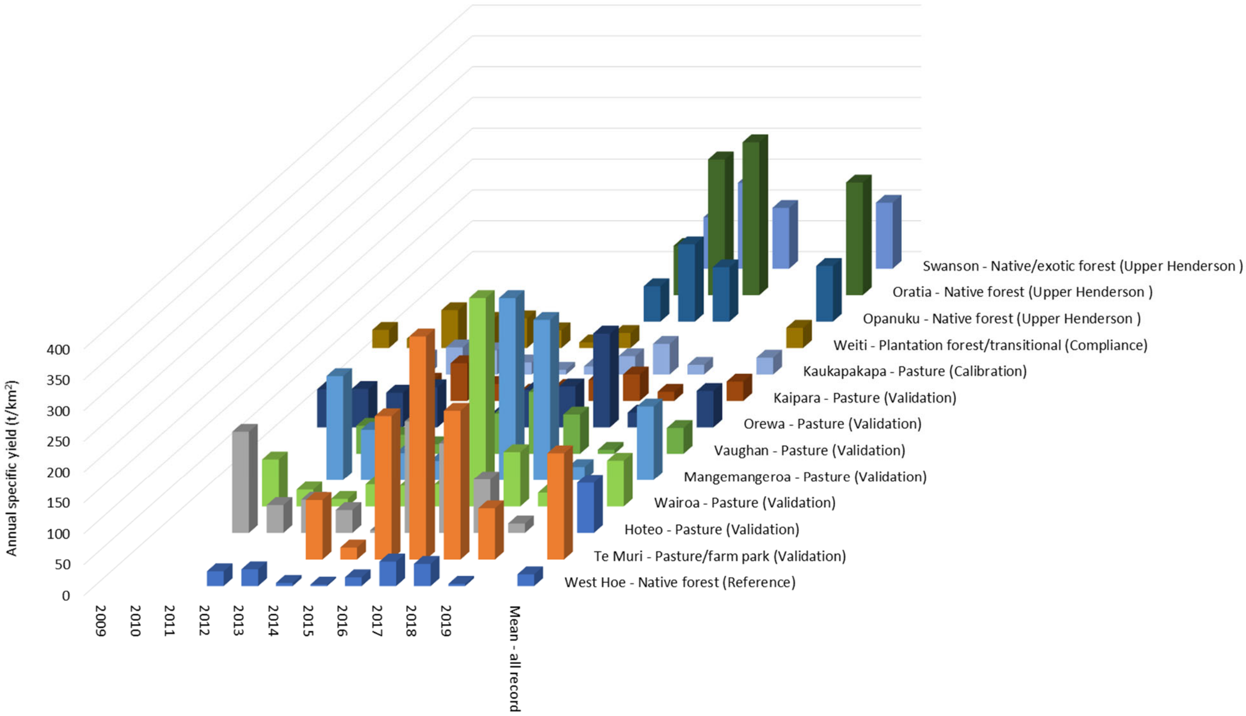



**Figure 5-1: Annual specific yields and mean annual specific yields for all catchments**. Sites ordered first by primary monitoring purpose then by catchment slope. Relatively high mean annual specific yields at Te Muri, Swanson, Opanuku and Oratia reflect the dominance of high yields over 2016-2018 for their shorter monitoring periods.

## 5.2 Factors influencing spatial variation in specific sediment yield

Spatial variation in mean annual specific yield across all 13 study sites is demonstrated in Figure 5-2, with specific yields averaged over the full periods of record and classified on an arbitrary scale[11] of *low* (< 50 t/km$^2$/y), *medium* (50-100 t/km$^2$/y), *high* (100-150 t/km$^2$/y), and *very high* (>150 t/km$^2$/y). Oratia, Te Muri, Mangemangeroa, and Swanson fall into the *high* and *very high* groups, while Weiti, West Hoe, Kaukapakapa, Kaipara, and Vaughan are in the *low* group. As discussed above, however, annual variability superimposed on different observation periods can induce significant variation in derived yields, confounding the influence of catchment characteristics.

[11] Note that these group descriptors (*low*, *medium, high, very high*) are relative to the range of specific yield observed across the Auckland region. All the Auckland specific yields would rate relatively low on a national basis, where specific yields as high as 32,000 t/km$^2$/y have been measured at East Cape and in South Westland (Hicks et al. 2011).

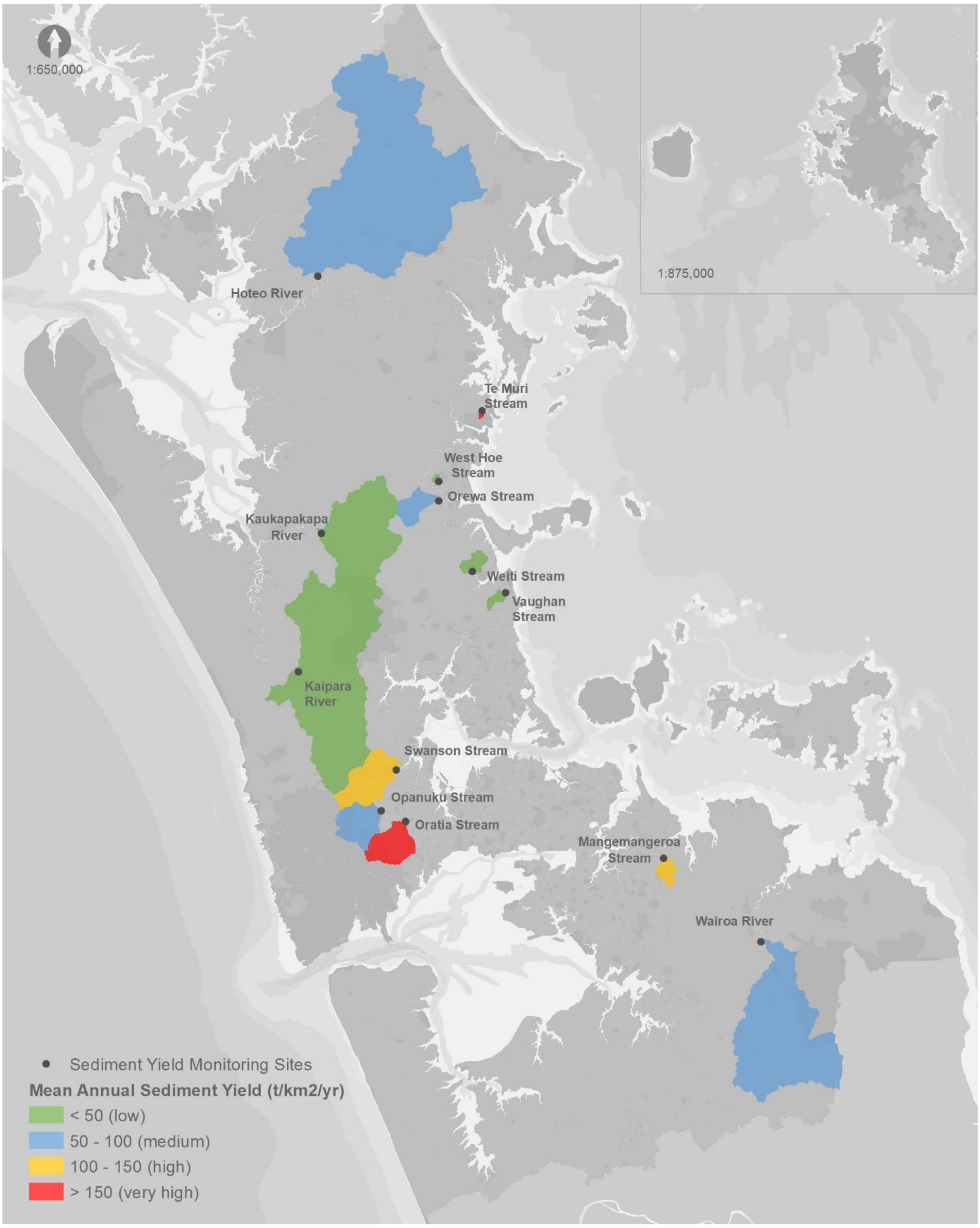



**Figure 5-2: Study catchments classified by mean annual specific sediment yield.** Based on averaging over full monitoring period. Yield classes are arbitrary.

Across the eight sites with data spanning the 2012-2019 reference period, the mean annual specific yield ranges between 19 t/km$^2$/y at West Hoe up to 120 t/km$^2$/y at

Mangemangeroa (Figure 5-3). The spatial variation can be explained in terms of predominant land cover and terrain steepness (which is associated with catchment geology). The lowest specific yield is at West Hoe by virtue of its indigenous forest cover, despite it having moderately steep slopes. The pasture catchments on rolling terrain (Kaukapakapa, Kaipara, Vaughan, Orewa) have specific yields ranging from 27 to 59 t/km$^2$/y, while the pasture catchments on moderately steep to steep terrain (Hōteo, Wairoa, Mangemangeroa) have specific yields ranging from 71 to 120 t/km$^2$/y.

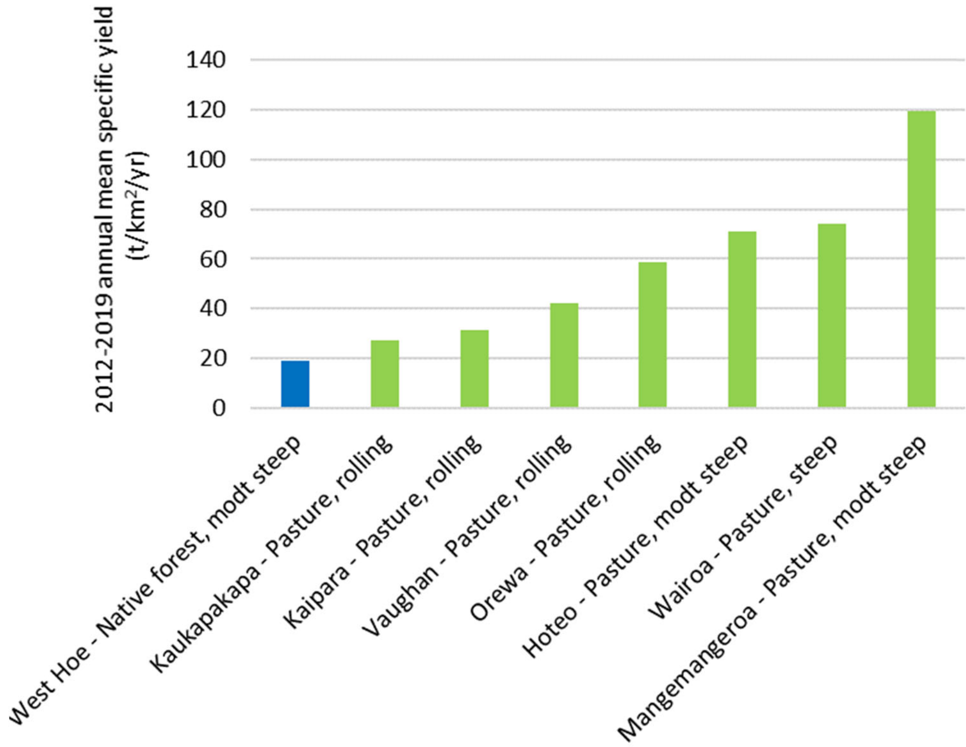



**Figure 5-3: Mean annual specific yields over 2012-2019 at the eight sites with overlapping sediment records.**
Blue indicates indigenous forest land cover; green indicates pasture.

As discussed above, the unexpectedly high mean specific yields from the three largely-forested Henderson Stream tributaries (Swanson, Oratia, Opanuku), and from the pasture covered Te Muri catchment, stem in part from their sediment yield totals being dominated by the high-yielding 2016-2018 years, with inter-annual variability confounding the land cover signature.

The influence of rainfall is apparent on Figure 5-4, which shows a general association between specific yield and rainfall (averaged over the same period as the sediment yield), with the exception of Te Muri and Mangemangeroa, which both plot well above this trend. The Mangemangeroa specific yield appears to be high because of its moderately steep slopes and pasture land cover, with gully erosion observed in its headwaters. It is not clear what is influencing the relatively high specific yield at Te Muri. It may be influenced by the small catchment area (0.3 $km^2$), which means that yields could be strongly influenced by one to several erosion features. It could also be a function of the extrapolated discharge rating. These sites have only been gauged up to certain levels and the discharge rating was extrapolated to higher levels based on theoretical calculations. This uncertainty could be driving the higher yields.

The exotic forested Weiti catchment lies within the general trend on Figure 5-4, and has a specific yield averaged over 2008-16 (35.3 $t/km^2/y$) that is almost twice that of the indigenous forested West Hoe averaged over 2012-2019 (19 $t/km^2/y$).

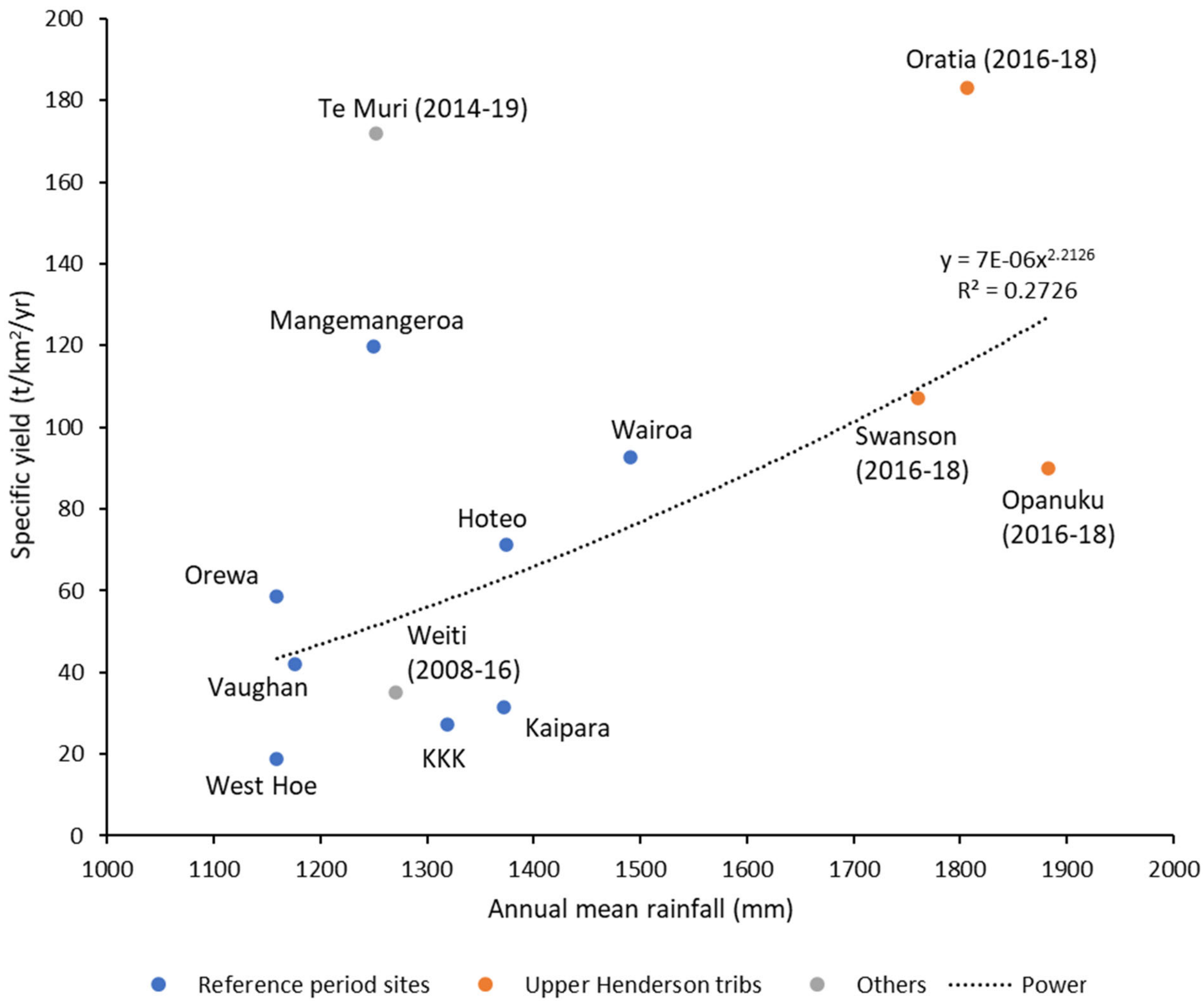



**Figure 5-4: Specific yield vs mean annual rainfall at the 13 study sites.**
Reference period sites were averaged over 2012-19. The averaging period for the remaining sites is included in the site label (e.g. 2016-18 for Opanuku). Yield and rainfall averaged over same period. Power-function trendline fitted to all data points.

Previous studies of factors controlling specific sediment yield across the Auckland, Northland and Waikato regions have shown that specific yield increases with increasing catchment rainfall and slope, land cover changing from forest to pasture, and lithology changing to more erodible, softer rock types (Hoyle et al. 2015; Haddadchi and Hicks 2016).

## 5.3 Yield statistics resilient to interannual variability

Sediment yield targets may be required to service sediment-related objectives of the NPS-FM and other regional policy instruments. However, an issue raised by Curran-Cournane et al. (2013) was that there may be too much interannual variability in catchment sediment yields to reliably resolve smaller-scale reductions in sediment yield attributable to catchment management interventions. Indeed, Hughes et al. (2012) considered interannual variability to be a possible reason why their monitoring detected no trend in yields from a Waikato catchment experiencing extensive land use interventions. This interannual variability issue is confirmed by the present study, which raises the dilemma of how best to measure progress in sediment yield reduction. It also has implications for formulating future yield targets.

In regard to target formulation, comparing the annual sediment yield in any future year with an arbitrarily-chosen target yield is fraught because of the nature of interannual variability imposed by hydrological variability. In other words, the difference will be more a matter of chance rather than any underlying change in catchment erodibility. For example, if 2017, which was an observed high-yielding year across the Auckland region, was chosen as a reference year and used to set a future yield target, then there is a low probability that yields in some future reference year will be measured exceeding this, even if catchment erodibility increases. Conversely, if a low-yielding year (e.g. 2015) was chosen as a reference year, then there will be a high probability that yields in some future reference year will exceed this, even if catchment erodibility decreases.

There are two possible solutions to this dilemma. The first is to use running means of the annual yield, which dampen the interannual variability. The other is to monitor change in response relationships such as the event yield rating, which effectively normalises hydrological variability. Both approaches were considered by Curran-Cournane et al. (2013), but at that stage the typical durations of sediment yield records were too short to form any conclusion.

The running-mean approach is implicit in studies that have sought to quantify the economic cost of catchment management to meet targeted sediment yields using models that predict mean annual sediment yield (e.g. SedNetNZ model, Green and

Daigneault 2018). However, while model-based predictions of mean annual sediment yield can be made with precision, monitoring target achievement in real catchments is another matter.

With the running-mean approach, a t-test for a difference in sample means could be used to check target compliance. For example, if the target yield at time 2 was set to be X% of the n-year running-mean Y1 at a reference time 1, then the test would be if Y2 < X.Y1, where Y2 is the n-year running-mean at time 2. The t-statistic would be $t = (X.Y1 – Y2)/(S1^2/n + S2^2 /n)^{0.5}$, where S1 and S2 are the running standard deviations of annual yields at times 1 and 2, respectively.

A key requirement with this approach is that the standard error of the running-mean must be well inside the targeted reduction in sediment yield. In general, if S is the standard deviation of annual yields (assumed time-independent), Y is the running-mean yield, and $E_Y$ is the standard error on Y (equal to $100S/Y/n^{0.5}$ as a % of Y), then the standard error in the difference between two running means is $2^{0.5}E_Y$. If the significance level is set at 5% (so any difference needs to consider two standard errors), then the targeted % reduction in yield must exceed $2^{1.5} E_Y$ to be detected. The problem with the Auckland sediment yields is that their large annual variability requires a long averaging window to detect even substantial changes in yield.

This is illustrated with the annual specific yield results from the Vaughan Stream catchment (Figure 5-5), which offers the longest record of any site (2004-2019). As the years of record accumulate since 2004, the mean annual specific yield steadies somewhat but still ranges between 44 and 50 t/km$^2$/y, while its standard error converges on ± 8 t/km$^2$/y (Figure 5-5A). The five-year running-mean specific yield (Figure 5-5B) varies with time over a broader range and has a standard error that averages ± 13 t/km$^2$/y (29% of the mean), thus a 95% confidence interval about the running-mean would span the range 20-72 t/km$^2$/y. By comparison, the 10-year running-mean specific yield (Figure 5-5B) varies less but still has a standard error that averages ± 9 t/km$^2$/y (20% of the mean), so its 95% confidence interval would span 28-64 t/km$^2$/y.

Thus, monitoring running-mean yields across the Auckland region will only reliably detect large relative yield changes and, even then, will require a decade-scale averaging window.

A variation on the running-mean approach is trend analysis of annual yields. For example, a trend-line fitted to annual yields between, say, 2012 and 2040 could be evaluated with respect to a target reduction rate (e.g., 0.53 %/y, totalling 15% over the intervening 28 years). Unfortunately, this approach also remains vulnerable to the high annual variability. For example, none of the study sites showed any statistically significant time trends in annual yields (as indicated by high P-values, Table 5-1).

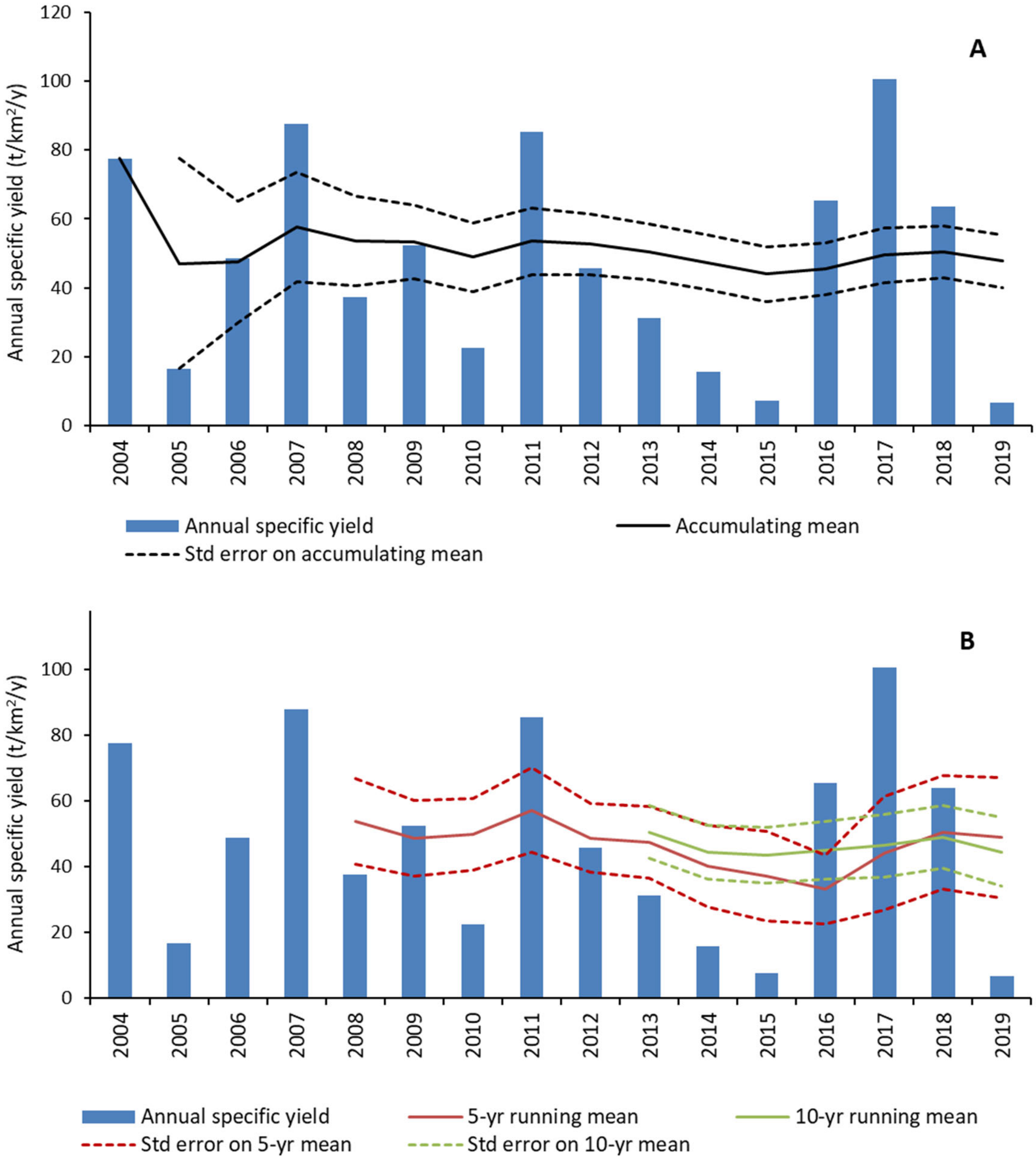



**Figure 5-5: Annual specific yields, mean annual yield, and standard error on mean annual yield at Vaughan Stream at Lower Weir site.**
A: Accumulating mean and its standard error. B: 5-year and 10-year running means and their standard errors. Running means are “backward-looking”, e.g. 5-year running mean at 2008 is the average of 2004-2008.

With the event rating approach, a temporal change in sediment yield during runoff events is assumed to manifest as a factorial change in the coefficient of the event yield rating (representing a vertical shift in the rating when plotted on log-log axes, as in Figure 4-15A of the Kaipara site, for example). This means, effectively, that event yields all change by the same factor, irrespective of event peak discharge. Thus, keeping a running-track of how observed event yields diverge from the yields predicted from a reference rating provides a measure of yield change compared to some planning target. As with the running-mean approach, this can be done using a t-test comparing the means of rating curve residuals (i.e. observed/predicted event yields) averaged on an annual or biannual basis. For example, with the Kaipara rating residuals time-plot (Figure 4-15B), a t-test shows the mean residual from sampled events over 2018-19 to be significantly less (at 5% significance level) by a factor of 2.2 than the mean residual of events sampled during 2012-13.

Monitoring change in the event yield rating appears to offer no better precision in yield change detection compared with the running-mean approach. However, it provides finer temporal resolution because the variability of data occurs between events, not between years. An underlying assumption with the event rating approach is that there is no significant change in catchment runoff response to rainstorms, so no change in event peak flows for a given rainstorm.

An important difference between the two approaches is that while the running-mean approach addresses the future absolute yield (whether driven by catchment management, climate change, or both), the event rating approach effectively only monitors changes in the availability of sediment. Thus, the event rating will monitor the efficacy of catchment management but be relatively insensitive to any underlying climate trend associated with global climate change. Pearce et al. (2020) predict that future climate change will result in more frequent extreme rainfall and runoff events, at least across the southern part of the Auckland region. They also predict an associated increase in landslides and slips on hillslopes and sheet erosion in horticultural areas. Therefore, detecting changes in sediment yield driven by these anticipated future changes in event frequency will still require a trend-analysis on annual yields.

Thus, while the event yield approach is recommended for monitoring future change in catchment erodibility and sediment availability associated with erosion mitigation works and policies, the running-mean approach (or variants thereof) remains necessary for monitoring actual sediment delivery under a changing climate.

## 5.4 Changes in event yield rating over time

Time-trends in the event yield rating data were correlated with land cover changes over the monitoring period[12].

GIS layers of land cover across the Auckland region are available for five epochs: 1996, 2001, 2008, 2012 and 2018 (LCDB 5.0). Only land cover changes between 2012 and 2018 are considered here because this period aligns best with the available sediment load records.

Figure 2-2 shows that land cover change exceeding 1% of catchment area between 2012 and 2018 occurred only in three of the study catchments:

- 6% of the Vaughan catchment was urbanised, mainly at the expense of rural pasture.
- 4.6% of the Mangemangeroa catchment was converted to rural pasture, mainly from exotic forest.
- 7.8% of the Orewa catchment was urbanised, mainly from rural pasture.

Using event yield rating data truncated to the same 2012-2018 time frame:

- The Vaughan Stream event yield rating data (Figure 4-11) showed a significant time-trend for event yields to increase by (15.6% per year) over the 2012-2018 period (although there was no significant trend when the full 2012-2019 event dataset is analysed; Table 4-2). This suggests that urbanisation in the Vaughan catchment has had a transient impact on elevating sediment yield[13].
- The Mangemangeroa River event yield rating data (Figure 4-9) showed a significant time-trend for event yields to decrease (by 5.7% per year) over the 2012-2018 period (which contained all the events used in the Mangemangeroa rating). This is the opposite of the change often experienced with conversion of exotic forest to pasture (e.g. Fahey et al. 2003), but the proportion of the catchment's land cover that was changed was small, so chance remains a valid explanation. Figure 4-9B shows most of this decline occurred from 2012 through 2015, which aligns with the suggestion of Curran-Cournane et al. (2013) that there might have been a "tailing-off" of sediment availability following the large event in July 2012. However, there is no indication that the even larger events that occurred in Mangemangeroa Stream in 2017 and 2018

[12] No correlation of land cover change with short-term mean-annual yields was sought, due to the large sampling errors in the short-term yields, discussed above.

[13] The absence of an overall time-trend in the Vaughan Stream event sediment yield aligns with previous work (e.g. Vanmaercke et al. 2012).

caused “jumps” in the event yield rating (Figure 4-10, Figure 4-9B). Thus, the cause and persistence of this apparent Mangemangeroa trend remain unclear and will likely only be resolved through further monitoring.

- The Orewa River event yield data (Figure 4-13B) showed a significant time-trend for event yields to increase (by 11.9% per year) over the 2012-2018 period – which is consistent with associated urban development earthworks.

The conclusion is that both catchments that underwent urbanisation of 6-8% by area over 2012-2018 (Vaughan, Orewa) experienced temporal shifts in their event rating relations that signalled event yields increasing by about 12-16% per year over the same epoch. In contrast, the Mangemangeroa catchment, with about 5% of its area converted from exotic forest to pasture, showed event yields reducing by about 6% per year.

Kaipara and Wairoa also showed time trends in their event yield rating data (Table 4-2) despite experiencing no significant land cover change from 2012-2018 (Figure 2-2).

In the Kaipara case, the -9.4% per year event yield reduction trend was identified over 2012-2019. We are unable to make any comment on how this relates to catchment management initiatives. Other New Zealand studies have typically struggled to identify unequivocable evidence of the effect of catchment management works on sediment yield reduction (e.g. Hughes et al. 2012, Hughes 2016).

The Wairoa trend for a +13.1% per year event yield increase is opposite to what might be expected. We suspect this may be an artefact of the signature of the extreme runoff event that occurred 4-9 March 2017, which delivered almost three times the mean annual yield over a few days. The Wairoa event yield residuals were higher on average from this date onwards (Figure 4-7B). Such extreme events tend to activate sediment sources/erosion sites that persist for several years (e.g. Basher et al. 2011), elevating event yields and masking the impact of erosion mitigation efforts in the years following the event. By contrast, no such extreme events confounded the trend at the Kaipara (e.g. compare Figures 4-8A and 4-16A).

## 5.5 Supporting sediment yield models

Key findings of previous reporting using data from this programme were that the national empirical sediment models at the time (as assessed against the CLUES model by Semadeni-Davies et al. 2015) performed poorly across the Auckland region.

This emphasised the importance of this monitoring programme in delivering data to calibrate a regional sediment yield model which was subsequently developed through the Waikato-Auckland-Northland Sediment Yield (WANSY) model programme (WANSY, Hoyle et al. 2015; WANSY2, Haddadchi and Hicks 2016). The WANSY2 model was then assessed against other existing empirical yield models available at the time (namely NZeeM, CLUES, WRENZ) and the semi-empirical SedNetNZ model. All WANSY model variations proved substantially more accurate (2-3 × better in regard to root-mean-square error of yield) than the other empirical models, which were developed using national datasets that had limited northern North Island data and tended to over-predict yields (Haddadchi and Hicks 2016). The WANSY2-C model variation was also superior to the SedNetNZ model developed for the Auckland region (Haddadchi and Hicks 2016).

More recently, Auckland Council has moved towards a dynamic process-based continuous simulation model for sediment (known as the Freshwater Management Tool, FWMT) using the LSPC (Loading Simulation Programme – C++) modelling software. This type of modelling ensures that catchment scale processes which determine the final load of sediment reaching the receiving environment are accounted for. The lack of such process-based modelling has been identified as a drawback of previous national level empirical sediment modelling, however, lack of data to support this approach at a national level was also identified (McDowell et al. 2020).

# 6.0 Conclusions and recommendations

The main conclusions are as follows:

1. On average over the 13 sites analysed, 71% of their sediment yields during runoff events were well measured by flow-proportional auto-sampling. This is a reasonable achievement given the challenges of continuously monitoring stream suspended sediment load.
2. Specific suspended sediment yields across the 13 sites ranged from 19 t/km$^2$/y at the native-forested West Hoe reference site to 183 t/km$^2$/y at Oratia, which was also largely under native forest. This regional spread reflects variation in sampling timeframes associated with high annual variability in yields (ranging year by year over factors up to 42); short and variously-overlapping monitoring periods; and differences in catchment physical characteristics. In particular, the mean yields from the three Henderson sites (Oratia, Opanuku and Swanson) were higher than most other sites mainly because these three were only sampled during 2016-2018, when yields across the region were higher than average due to elevated rainfall.
3. Higher or lower than average yielding years typically coincide across the region, with 2016-2018 having higher than average yields everywhere, while 2015 had low yields everywhere. These patterns are consistent with the same weather events and climate cycles typically affecting the whole region although with some spatio-temporal variation in their relative intensities.
4. Analysis of yields over eight years of overlapping record (2012-2019) at eight sites showed that the spatial variation in their specific yields can be explained reasonably well in terms of land cover and terrain steepness. The lowest specific yield (18.9 t/km$^2$/y) was at West Hoe by virtue of its indigenous forest cover, despite it having moderately steep slopes. The pasture catchments on rolling terrain (Kaukapakapa, Kaipara, Vaughan, Orewa) had yields ranging from 27 to 59 t/km$^2$/y. The pasture catchments on moderately steep to steep terrain (Hōteo, Wairoa, Mangemangeroa) had yields ranging from 71 to 120 t/km$^2$/y.
5. No time-trends in annual yields were observed at any of the 13 sites, but this is not surprising given the high annual variability and relatively short monitoring periods. However, four sites showed statistically significant time-trends in their event yield rating relationships over their full monitoring periods, with Wairoa and Orewa showing increasing event yields for given sized floods while Kaipara and Mangemangeroa showed decreasing event yields. It is likely that the trend for increasing event yields observed at the Wairoa is an artefact of the extreme

event that occurred in March 2017. This event delivered almost three times the mean annual sediment yield and likely activated erosion sites that persisted through 2019, masking the effects of erosion mitigation efforts there.

6. All three catchments that experienced more than 1% by area land cover change between 2012 and 2018 also showed significant time trends in their event yield ratings over the same epoch. Vaughan and Orewa, with 6-8% of their areas urbanised from pasture over 2012-2018, showed event yields increasing by about 12-16% per year, while Mangemangeroa, with about 5% of its area converted from exotic forest to pasture, showed event yields reducing by about 6% per year.
7. Monitoring the effects of plantation forestry harvest on sediment yield in the Weiti Stream catchment found that there was no significant effect on sediment yield associated with harvesting that occurred in 2012-2013 in this catchment.
8. The large variability in annual sediment yields observed across the Auckland region limits the temporal resolution and precision of any scheme to monitor progress on sediment yield reduction. Averaging windows over a period of 10 years are required to detect changes of 40% or greater.
9. Monitoring change in the event yield rating appears to offer no better precision in yield change detection, but it provides finer temporal resolution because the variability of data occurs between events, not between years. However, the event rating approach effectively only monitors changes in catchment erodibility and sediment availability, not actual sediment delivery.
10. Concurrent auto-samples and manual gaugings of the cross-section average SSC indicated that at seven sites the auto-samples appeared to be representative of the cross-section average suspended load. However, this was not the case at two sites, while four sites lacked any concurrent manual gaugings. Moreover, there was sometimes wide scatter observed in the relationship between auto-sampled and gauged SSC, and the generally small number of manual gaugings meant that this relationship was not checked over the full range of sampled water discharge.

The main recommendations are:

1. While the event yield rating approach is recommended for monitoring future change in catchment erodibility and sediment availability associated with erosion mitigation works and policies, the running-mean approach for annual yields (or variants thereof) remains necessary for monitoring actual sediment delivery under a changing climate.

2. Continued long-term sediment monitoring (10+ years) is therefore recommended, particularly in the context of managing sediment as outlined in the NPS-FM requirements against a background of changing climate and large interannual variability in sediment yields.
3. Further manual suspended sediment gaugings should be programmed at all sediment sites to improve knowledge of how well the auto-sampled SSC represents the full sediment load over the stream cross-section. Priority should be given to those sites presently without any gaugings and to higher discharges.

# 7.0 Acknowledgements

Auckland Council's environmental specialists in the Research and Evaluation Unit (RIMU) are thanked for undertaking the event-based sediment and river discharge monitoring for this programme. We acknowledge Rhian Ingley for her valuable internal peer review comments and Grant Lawrence for his geospatial expertise. We would also like to sincerely acknowledge Dr Fiona Curran-Cournane's previous contributions in developing and reporting on this programme. We also thank the external peer reviewers, Justin Wyatt and Matt Norris from Waikato Regional Council and Dr Andrew Hughes from NIWA, who improved the quality of this report.

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# Appendix A Catchment summary information

**Table A-1: "Broad-state of the environment" LCDB land cover classes and aggregation scheme.**

| LCDB Land Cover Classes within catchments upstream of river water quality monitoring sites | Aggregated Land Cover Classes | Broad Level Dominant Land Cover |
|---|---|---|
| Broadleaved Indigenous Hardwoods | Native forest | Native |
| Indigenous Forest | Native forest | Native |
| Manuka and/or Kanuka | Native forest | Native |
| Deciduous Hardwoods | Exotic forest | Exotic |
| Exotic Forest | Exotic forest | Exotic |
| Forest – Harvested | Exotic forest | Exotic |
| Orchard, Vineyard or Other Perennial Crop | Horticulture | Rural |
| Short-rotation Cropland | Horticulture | Rural |
| Gorse and/or Broom | Rural | Rural |
| High Producing Exotic Grassland | Rural | Rural |
| Low Producing Grassland | Rural | Rural |
| Built-up Area (settlement) | Urban | Urban |
| Transport Infrastructure | Urban – Infrastructure | Urban |
| Urban Parkland/Open Space | Urban Parkland | Urban |
| Sand or Gravel | Other | NA |
| Surface Mine or Dump | Other | NA |
| Lake or Pond | Water | NA |
| Mangrove | Water | NA |
| Flaxland | Wetland | NA |
| Herbaceous Freshwater Vegetation | Wetland | NA |

**Table A-2: Slope type definitions**. Adapted from Lynn et al. (2009).

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

# Appendix B Example sampled hydrograph

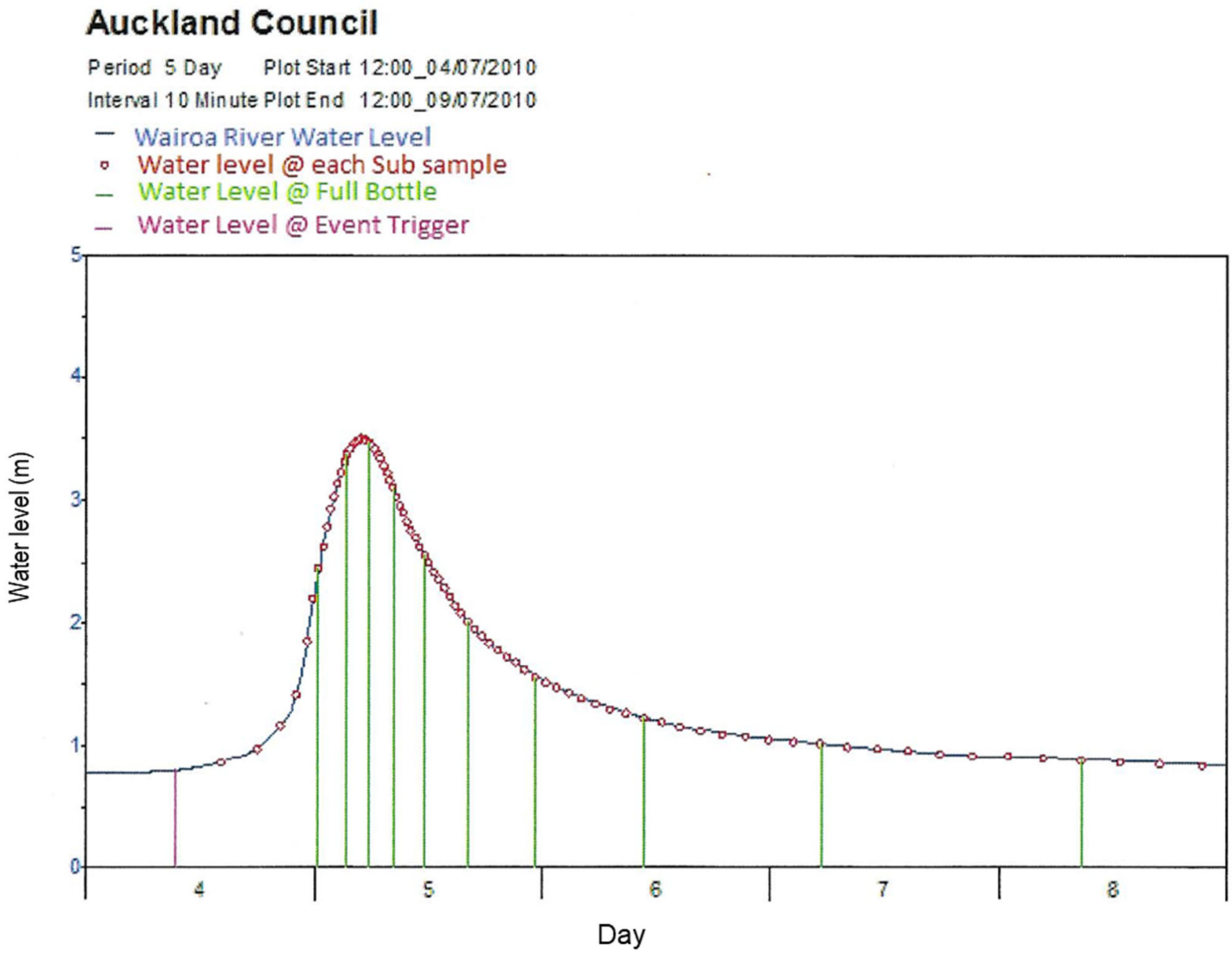


**Figure B-1: Schematic example of hydrograph illustrating flow-proportional sampling.** Sampling is activated on Day 4 when the water level exceeds 0.8 m. Sub-samples are collected after a fixed water volume passes the site, so the time between sub-samples reduces as the water level rises and increases as the water level falls. Eight sub-samples are composited in each sample bottle (green bars mark the time when each bottle is filled).

# Appendix C TSS-SSC conversion

Since July 2011-July 2012 (depending on the site), all samples were analysed for suspended sediment concentration (SSC) with the ASTM D 3977-97 method (ASTM 2007), while TSS results from before then (2540 D method, APHA 2005) have been converted to ASTM SSC equivalent results, by applying relations developed from duplicate sub-samples taken from the same bottle and then analysed using both procedures. The TSS method can induce bias in load estimates that is of similar order to sediment yield change planning targets. Correction functions were developed for Orewa, Wairoa, Weiti, Kaukapakapa and Kaipara. At Vaughan and Hōteo, it was assumed that TSS and SSC have a 1:1 relationship (Table C-1) because no duplicate sub-sample comparison was possible for these sites. This is justified because both catchments have dominantly Ultic soils and so should render a largely mud-grade suspended load.

The standard errors of the estimate in the SSC-TSS relations, ranging from 15 to 64 mg/l, indicate the extent of "erratic" behaviour of the TSS method. Being random, this order of erratic results produced by the TSS method will have minimal effect on the sediment yield accumulation over multi-year time scales but can contribute significant error to instantaneous and event yields.

The relation coefficients for Weiti (1.04) and Wairoa (1.06) are significantly different from 1 at the 5% significance level, so indicate bias in the TSS method at these two sites. This bias means that uncorrected TSS results will underestimate the sediment yield by 4% at Weiti and by 6% at Wairoa. The relation coefficients at the other three sites are not significantly different from 1.0, so there is not bias at these sites.

**Table C-1: Laboratory procedures and adjustment relations to convert TSS-measured suspended sediment concentrations to SSC.** n is number of paired analyses comparing TSS and SSC used to compile correction relations. P-value indicates the probability that the coefficient of the SSC-TSS relation does not differ from 1.

| **Stream** | **Lab procedure** | **SSC-TSS relation** | **n** | **Std error of estimate (mg/l)** | **P-value (for slope = 1)** |
|---|---|---|---|---|---|
| Hōteo | All TSS | Assumed 1:1 | | | |
| Kaipara | SSC from mid-2012 | SSC = 1.01 TSS | 40 | 12 | 0.38 |
| Kaukapakapa | SSC from mid-2012 | SSC = 1.02 TSS | 31 | 32 | 0.30 |
| Mangemangeroa | All SSC | NA | | | |
| Opanuku | All SSC | NA | | | |
| Oratia | All SSC | NA | | | |
| Orewa | SSC from mid-2012 | SSC = 0.999 TSS | 20 | 15 | 0.82 |
| Swanson | All SSC | NA | | | |
| Te Muri | All SSC | NA | | | |
| Vaughan | All TSS | Assumed 1:1 | | | |
| Wairoa | SSC from mid-2012 | SSC = 1.06 TSS | 58 | 19 | $10^{-4}$ |
| Weiti | SSC from mid-2011 | SSC = 1.04 TSS | 216 | 64 | $10^{-5}$ |
| West Hoe | All SSC | NA | | | |

# Appendix D Data quality checks

Data quality checks for this study involved reviewing the river flow records and the sediment data, which were compiled into several “running” worksheets within site-specific “master” Excel files.

The flow records were checked for gaps, particularly to identify periods of missing flow record that contained significant runoff events. When such gaps were identified, RIMU staff provided “infill” runoff event peak discharges that were estimated from flow records from nearby sites.

The sediment data Excel spreadsheets contain three “running” worksheets. The “Modsyn” worksheet contains the “raw” results of auto-sampled SSC and the streamflow volume associated with each sample, which are combined to produce a record of the sediment mass load passing the site, from which load totals for discrete runoff events are calculated and an assessment is made as to whether the event has been adequately sampled for the purpose of determining the event yield. This is an expert assessment, made by inspecting the distribution of samples collected across the event hydrograph (e.g. Appendix B). Events were deemed inadequately sampled if a significant portion of the event lacked samples. Example cases include no or few samples collected on the event rising stage; sampling truncated within the event, or no samples collected at all during the event, due to all the auto-sampler bottles being filled, auto-sampler malfunction, or auto-sampler absence.

Adjustments to correct for use of the TSS-method for SSC analysis and to correct the point-sampled SSC to the stream cross-section-averaged SSC are made within the Modsyn worksheets. For this study, the Modsyn worksheets were: (i) scanned and corrected for erratic data (e.g. incorrect decimal point, excessively high flow volume or SSC); (ii) point-SSC to cross-section-averaged relationships were applied where available and needed; and (iii) suitability of events for determining event sediment yield and for developing the event yield rating was checked.

The “Event rating” worksheets are used to fit a rating relationship between event yields and event peak discharge (see Section 3.6.2), which is then used to estimate the sediment yield of events not well sampled. The checks of the event-rating worksheets involved checking that rating-suitable events had been identified appropriately from the Modsyn worksheet.

The “Event list” worksheets list all runoff events and their peak discharges over the sediment monitoring period, assign each event a sediment yield either extracted from the Modsyn worksheet (if the event has been deemed adequately sampled) or estimated from the event yield rating (if not adequately sampled), then accumulate the total yield over time. These worksheets were checked to ensure that the correct event yield rating was used and to identify if any significant events were missed because of missing flow records.

# Appendix E Auto-sampled vs cross-section mean SSC

Differences in $C_m/C_p$ can occur due to non-uniformity in SSC over the stream cross-section associated with turbulence gradients and the particle size mixture of the suspended load. While a mud-dominated load tends to be well mixed, with $C_m/C_p \sim 1$, suspended sand tends to be less well mixed, so $C_m/C_p$ can vary from 1 with a significant proportion of sand in the suspended load. Typically, as discharge increases, turbulence and mixing also increase, so $C_m/C_p$ tends towards 1.

$C_m/C_p$ ratios have been measured at a range of high flows at nine of the study sites (Table E-1). For these, $C_m$ was measured using depth-integrating samplers at multiple verticals (i.e. cross-channel stations) using protocols detailed in NEMS (2020), with concurrent auto-samples being triggered manually.

The general approach was to relate $C_m/C_p$ to discharge (rather than simply relating $C_m$ to $C_p$) because of the expectation that mixing should depend on turbulence intensity which is discharge dependent.

Care is needed in deriving this function to avoid unrealistic extrapolations that may corrupt the derived sediment yield. When fitting $C_m/C_p$ vs Q relations to data collected from a limited range of storm discharges, it is important to be wary of curve extrapolation – particularly when using exponential, power, or polynomial functions. The Orewa data provides a good example (see below). With only a few (e.g. 3-5) datapoints defining the $C_m/C_p$ vs discharge relation, there is the chance that a single erratic datapoint could influence a false trend that induces large errors in the sediment yield. At several sites unrealistically large and small values of $C_m/C_p$ were returned from gaugings, possibly relating to either the auto-sampler or the depth-integrating sampler intercepting sandy bedload (which was observed on several occasions). For this reason, we followed a conservative approach and rejected using such erratic points, particularly where the rest of the $C_m/C_p$ data clustered close to 1 and/or where field observations rendered the datapoints suspect.

Mostly (Table E-1), there was no significant relationship between $C_m/C_p$ and discharge, nor was $C_m/C_p$ significantly different from 1, so no corrective action was required. Significant relationships (at 5% significance level) were only observed at Kaukapakapa and Orewa, and these were applied in the Modsyn worksheets to convert $C_p$ to $C_m$. No $C_m/C_p$ ratio data are available for Te Muri, Vaughan, Weiti and West Hoe, so it was simply assumed that $C_m/C_p = 1$ for these sites. This is a reasonable assumption given that (i) this relationship was observed at seven of the nine study sites with $C_m/C_p$ data, and (ii) these four catchments have predominantly Ultic soils (Table 2-2), which have a high clay content and may be expected to render a fine-grained, well-mixed suspended load.

**Table E-1: Relations used for converting auto-sampled SSC ($C_p$) to cross-section mean SSC ($C_m$).** Relations typically developed as Cm/Cp vs discharge (Q) and tested at 5% significance level.

| Stream | No. SSC gaugings | $C_m/C_p$ relation applied | Comment |
|---|---|---|---|
| Hōteo | 7 | 1:1 | After 3 outliers removed, no significant relation between $C_m/C_p$ and discharge and $C_m/C_p$ not significantly different from 1 |
| Kaipara | 5 | 1:1 | After 1 outlier removed, no significant relation between $C_m/C_p$ and discharge and $C_m/C_p$ not significantly different from 1 |
| Kaukapakapa | 5 | $C_m/C_p$ = 0.00645Q for Q < 85,900 l/s; $C_m/C_p$ =1 for Q > 85,900 l/s | All $C_m/C_p$ values less than 1 but trending towards 1 as discharge increases |
| Mangemangeroa | 3 | 1:1 | Few points, and $C_m/C_p$ not significantly different from 1 |
| Opanuku | 3 | 1:1 | Few points, and $C_m/C_p$ not significantly different from 1 |
| Oratia | 3 | 1:1 | Few points, and $C_m/C_p$ not significantly different from 1 |
| Orewa | 4 | $C_m/C_p$ = 0.0562Q + 0.587 for Q < 7,350 l/s; $C_m/C_p$ = 1 for Q > 7,350 l/s | Significant trend for $C_m/C_p$ to increase with discharge |
| Swanson | 8 | 1:1 | No significant relation between $C_m/C_p$ and discharge, and $C_m/C_p$ not significantly different from 1 |
| Te Muri | 0 | 1:1 | Assumed 1:1 relation |
| Vaughan | 0 | 1:1 | Assumed 1:1 relation |

| Stream | No. SSC gaugings | $C_m/C_p$ relation applied | Comment |
|---|---|---|---|
| Wairoa | 7 | 1:1 | Weak trend for $C_m/C_p$ to decrease with increasing discharge but no trend with discharge, and $C_m/C_p$ not significantly different from 1, when exclude highest discharge point. Sensitivity test indicated minimal impact if long-term load determined using $C_m/C_p$ vs Q relation, so simply assumed 1:1 relation. |
| Weiti | 0 | 1:1 | Assumed 1:1 relation |
| West Hoe | 0 | 1:1 | Assumed 1:1 relation |

It is recommended that further concurrent gaugings are programmed at all sites, with priority given to those sites presently without any gaugings. This is because:

- four sites lack any concurrent manual gaugings
- there is sometimes wide scatter in the observed relationships between auto-sampled and gauged SSC
- the generally small number of manual gaugings at any site means that this relationship was not always checked over the full range of sampled water discharge.

## Orewa extrapolation example

At Orewa, four $C_m/C_p$ datapoints were obtained, spanning a discharge range from 1,470 to 9,088 l/s (Figure E-1). Both linear and exponential functions provide apparently excellent fits to these sediment gaugings' $C_m/C_p$ data ($r^2$ = 0.97-0.98). However, 50% of the auto-sampled sediment yield over the monitoring period (as listed in the Modsyn worksheet) was associated with discharges greater than the maximum discharge for these sediment gaugings (9088 l/s), and the linear and exponential curves had to be extrapolated to discharges up to 48,000 l/s, where the predicted $C_m/C_p$ ratios were 3.2 and 13.1, respectively. These ratios are unrealistically high and either curve, if it had been used, would have induced a large overestimate of the Orewa sediment yield. For example, using the linear curve to correct the Orewa auto-sampled SSC data provides a sampled yield total of 6445 t over the monitoring period, and using the exponential curve provides a sampled yield total of 9660 t. In comparison, with no correction applied the yield would be 5497 t, while 'flattening' the linear relation at $C_m/C_p$ = 1 for discharges exceeding 7350 l/s (which was the approach used) gives a sampled yield of 4701 t.

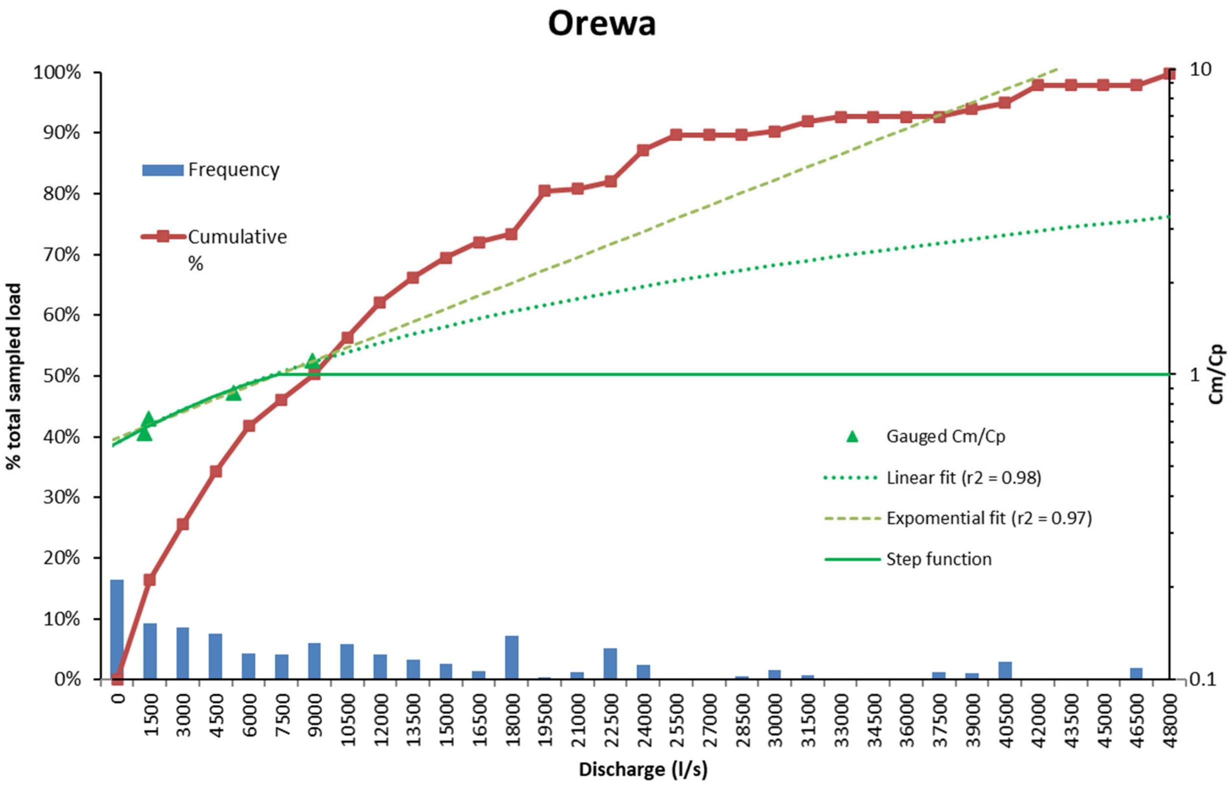


**Figure E-1: $C_m/C_p$ vs discharge relation from sediment gaugings, and frequency and cumulative distributions of auto-sampled load over record period at Orewa.**
Dotted green lines show extrapolated curves fitted with linear and exponential functions. Solid green line shows step-function, with Cm/Cp forced to equal 1 at discharges exceeding 7350 l/s.

**Find out more:** phone 09 301 0101, email rimu@aucklandcouncil.govt.nz or visit aucklandcouncil.govt.nz and knowledgeauckland.org.nz

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