Analysis of sediment yields for the Auckland region (2009–2024)

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Abbreviations

BCF	bias correction factor
CCC	Lin's concordance correlation coefficient (dimensionless)
MALF	seven-day mean annual low flow
NEMS	The National Environmental Monitoring Standards
LOWESS	Locally Weighted Scatterplot Smoothing
R^2	coefficient of determination (dimensionless)
S	event suspended sediment load (tonnes per event)
SRC	sediment rating curve
SSY	specific suspended sediment yield ($t/km^2/yr$)
SY	annual suspended sediment load (tonnes)
SSC	suspended sediment concentration (mg/L)
TSS	total suspended solids (mg/L)
Q	water discharge (L/s)
Q_{peak}	event peak water discharge (L/s)

Summary

Auckland Council (Environmental Evaluation and Monitoring Unit) contracted Manaaki Whenua – Landcare Research (MWLR) to analyse data from their event-based sediment monitoring network. The work builds on previous analyses of sediment yields from the network by Curran-Cournane et al. in 2013[1] and by Hicks et al. in 2021.[2]

The objectives of this study are listed below.

1 Produce long-term specific sediment yield estimates for 11 catchments, comparing specific time periods between 2012 and 2024 and provide related analysis and discussion.

2 Analyse annual, inter-annual, and spatial variability in sediment yields among the monitored catchments.

3 Discuss significant event years including flood or drought years, with specific commentary on the 2023 storm events.

4 Provide commentary of how climate change may influence yields in future.

5 Discuss the feasibility of using monitoring data for identifying current sediment loads and differentiating between natural and anthropogenic components to assist in setting limits for sediment management.

6 Compare load estimates derived from event-based sediment monitoring with estimates derived from discrete river water quality monitoring.

This report compares specific sediment yield estimates for 11 catchments, comparing yields for: the full record for each of the eleven sites, from the start of monitoring to June 2024; July 2012 to June 2024 for 8 sites (longest overlapping period); and July 2020 to June 2024 for all 11 sites (longest overlapping period for new sites). Estimates derived from event-based sediment monitoring are compared with estimates derived from discrete river water quality monitoring at 6 sites where both data sets are available. A list of common abbreviations is provided on p. iv.

The coefficient of determination (R^2) values for all event-based sediment rating curves (SRCs) exceeded 0.8, and the value of the concordance correlation coefficient (CCC) was above 0.9, indicating a strong model fit. Sediment rating residuals at four sites (Mangemangeroa River, Te Muri-o-Tarariki Stream, (hereafter 'Te Muri Stream') Wairoa River and Kōurawhero Stream (referred to in this report as the 'Kōurawhero River') experienced significant temporal changes and required a time-trend adjustment of the sediment load estimates. Continued monitoring is required to identify future drift in the ratings.

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[1] Curran-Cournane F, Holwerda N, Mitchell F 2013. Quantifying catchment sediment yields in Auckland. Auckland: Auckland Council

[2] Hicks DM, Holwerda N, Grant CM 2021. Rural catchment sediment yields from the Auckland region: state of the environment reporting. Auckland: Auckland Council.

Compared to event SRCs, SRCs developed from discrete water quality sampling data at six sites had lower model quality, with an average R^2 of 0.6 and a CCC of 0.68. At all sites except West Hoe Stream, manual adjustment of the rating extrapolation was required to obtain reasonable SSC estimates. Overall, sediment yields estimated using the discrete SRCs were on average 1.66 times higher than those estimated with the event SRC for the same hydrological years with variation across the sites. This overestimation is partly due to limited sample availability from discrete water quality monitoring.

Mean annual suspended sediment yields (SY) ranged from 12.5 to 26,203 t/yr across the monitoring sites from event-based rating curve estimates. Mean annual specific sediment yields (SSY) for the full records range from 23.5 to 221 t/km^2/yr, with the lowest at the native forested West Hoe Stream, and highest at Mahurangi River. These sites also had the greatest difference in mean specific sediment yields for the July 2020 to June 2024 period. For the eight sites with data available for July 2012 to June 2024, estimated mean specific sediment yields range from 23.5–107 at West Hoe Stream to Mangemangeroa River, respectively. The hill country catchments of the Mahurangi River, Te Muri Stream, and Mangemangeroa River sites fall into the regionally 'high' and 'very high' categories, while the mixed terrain and land cover catchments of the Hōteo River, Kōurawhero River, Ōrewa Stream, Kaipara River, and Wairoa River sites are classified as 'medium'. The remaining sites, Kaukapakapa River, West Hoe Stream, and Lower Vaughan Stream, which are primarily lowland or forested hill country catchments, are in the 'low' category. However we note that the arbitrary class definitions are relative to the Auckland region only.

Comparisons of sediment yields estimated from event-based and discrete monitoring programmes highlight the challenges of capturing data across the range of events experienced in these catchments. During the reporting period of 2009–2019 (as covered by the previous reporting of Hicks et al. 2021 (see footnote 2) an average of 70% of the total sediment yield had been sampled, while only 43% of the total yield had been sampled on average during the 2009–2024 period (i.e. the full record presented in the current report). This has contributed to greater uncertainty in total yield estimates, compounded by 2023 containing the largest river flows in most site records relating to large storm events. Continuous monitoring methods, such as turbidity sensors, offer the potential to continuously monitor sediment loads and reduce the uncertainty in long-term sediment yield estimates produced by rating curve methods, provided they are adequately maintained and calibrated.

Changes in catchment hydrology, land cover, and land use through time can lead to changes in the relationship between discharge and sediment yield, requiring adjustment of sediment rating curves. Analysis of the long-term sediment data in the present report identified statistically significant shifts in the SRCs at the Kaipara River, Kaukapakapa River, Mangemangeroa River, Te Muri Stream, and Wairoa River sites. At the Ōrewa and Kōurawhero sites, shifts could be seen, but statistical tests indicated the shifts were not significant. Continuation of monitoring will enable future shifts in sediment ratings to be identified, which may occur at any of the monitoring sites due to future changes in hydrology, land cover, and land use.

The impact of future climate change on erosion and sediment loads is expected to vary spatially across the Auckland region, driven by divergent trajectories for surface erosion, riverbank erosion, and shallow landslides. The net effect on sediment loads will reflect the relative contribution of these processes to catchment loads. Neverman et al. (2023)[3] estimated climate change may increase sediment loads delivered to the coast by between 14% and 75% by late century.

Data from the sediment monitoring programmes is used in combination with other methods, including sediment fingerprinting and sediment budget modelling, to estimate the contribution of erosion sources to sediment loads to support catchment and regional planning efforts.

[3] Neverman AJ, Donovan M, Smith HG, Ausseil A-G, Zammit C 2023. Climate change impacts on erosion and suspended sediment loads in New Zealand. Geomorphology 427:108607. https://doi.org/10.1016/j.geomorph.2023.108607.

1 Introduction

Streams, estuaries, and harbours provide extensive ecological, cultural, and recreational value across Auckland. Excess fine sediment, driven by accelerated erosion, causes a cascade of impacts to terrestrial, freshwater, and coastal environments. Excess sediment alters habitats, impairs biota, and decreases optical clarity in freshwater and coastal receiving environments which act as sinks for sediments and associated contaminants (Levin et al. 2001; Woods & Kennedy 2011). Excess sedimentation is the primary cause of ecosystem change in estuaries (Harty 2009; Saintilan et al. 2014). At least 50 % of New Zealand estuaries have sediment levels exceeding the threshold for ecological impact (Berthelsen et al. 2020). This has implications not only for biodiversity, but also for the communities who rely on these environments (Harmsworth & Awatere 2013; Harmsworth et al. 2014; Clapcott et al. 2018; Stewart-Harawira 2020). Climate change further threatens to exacerbate these issues (Neverman et al. 2023).

Concerns about sediment impacts on freshwater and coastal receiving environments have been recognised in the Auckland region and nationally, with objectives for sediment reduction set in the Auckland Plan (Auckland Council 2012) for coastal receiving environments, and the National Policy Statement for Freshwater Management (NPS-FM) 2020 for rivers and streams. The need to reduce erosion and sediment in freshwater and marine environments is further underscored in the national climate adaptation plan (Ministry for the Environment 2022), and Te Mana o te Taiao biodiversity strategy (Department of Conservation 2020). Auckland Council therefore needs an understanding of the baseline and current state of sediment-related attributes to identify where objectives are not being met. Where objectives are not met, erosion and sediment control practices and/or land management change will be required to reduce erosion and sediment.

Over the past two decades, Auckland Council has undertaken monitoring of rural stream sediment yields from storm events at a network of sites across the region (the 'Auckland Council event-based sediment monitoring network'). The aim of this programme is to provide scientifically robust and defensible information for improved catchment sediment management and state of the environment requirements. The monitoring network was designed to be regionally representative, stratified by catchment geology, climate, and land cover (Hicks et al. 2009).

A list of common abbreviations used in this report is provided on p. iv.

2 Background

Sediment yield from ten sites in the monitoring network up to 2012 were reported by Curran-Cournane et al. (2013). Hicks et al. (2021) expanded this analysis to cover the period up to 2019, and included three additional project sites from the upper Henderson catchment.

The current report extends the analysis of Hicks et al. (2021) to cover the period up to 2024, and includes estimation of sediment yields for six sites based on samples from the discrete river water quality monitoring programme. Two sites (Mahurangi River and Kōurawhero River [Kōurawhero Stream (referred to in this report as the 'Kōurawhero River']) have been added to the analysis, while Weiti Stream, Ōpanuku Stream, Oratia Stream and Swanson Stream sites were excluded as they are no longer in operation.

3 Objectives

The objectives of this study are listed below.

1 Produce long-term specific sediment yield estimates for eleven catchments, comparing the following time periods and providing related analysis and discussion.

- A full record for each site of the 11 sites, from start of monitoring to June 2024.
- July 2012 to June 2024 for 8 sites (longest overlapping period).
- July 2020 to June 2024 for all 11 sites (longest overlapping period for new sites)
- Provide any relevant analysis and discussion on the shift to reporting on a hydrological year compared to previous reports based on a calendar year.

2 Analyse annual, inter-annual, and spatial variability in sediment yields among the monitored catchments.

3 Discuss significant event years including flood or drought years, with specific commentary on the 2023 storm events.

4 Provide commentary of how climate change may influence yields going forward.

5 Discuss the feasibility of using monitoring data for identifying current sediment loads and differentiating between natural and anthropogenic components to assist in setting limits for sediment management.

6 Compare load estimates derived from event-based sediment monitoring with estimates derived from discrete river water quality monitoring.

4 Catchment descriptions

Data were provided by Auckland Council for 11 sediment monitoring sites and 12 rainfall stations (Figure 1 and Table 1). Across these, catchment areas range from 0.27 km^2 (Te Muri Stream) to 270 km^2 (Hōteo River). Lithologies varied from Tertiary mudstone to greywacke, with the Waitematā Formation (interbedded sandstone and mudstone) being dominant. Catchments range from predominantly hill country (West Hoe Stream, Te Muri-o-Tarariki Stream, [hereafter 'Te Muri Stream']), Mangemangeroa River), to mixed hill country and lowland (Wairoa River, Kaipara River, Kōurawhero River, Hōteo River, Mahurangi River, Kaukapakapa River), to predominantly lowland (Ōrewa Stream, Lower Vaughan Stream) based on mapping from the New Zealand Land Resource Inventory (Newsome et al. 2008). The dominant land use is typically pasture, with exceptions of West Hoe Stream and Te Muri Stream, where native forest occupies most of the catchment. The Te Muri Stream experienced a significant land cover change during the monitoring period, discussed in Section 6.2. Figure 2 shows some of the sites, highlighting their diversity.

The study period spans from July 2009 to June 2024, during which time some exceptional floods and droughts occurred in the region (Johnson 2021, 2023). In late January and early February 2023, the Auckland region experienced two significant weather events: the Auckland Anniversary Weekend Floods (January 2023) and Cyclone Gabrielle (February 2023). On January 27, 2023, Auckland Airport recorded 258 mm of rain and the Māngere station 265 mm in 24 hours.[4] Both the Anniversary flood and Cyclone Gabrielle were among the largest events on record for the majority of sites in the Auckland Region, in terms of water discharge and rainfall, over the last 50 years. The annual recurrence interval for the 2023 flow maxima on the Hōteo, Wairoa, and Ōrewa rivers was in the range of 18–36 years. However, on the Hōteo River, 2023 was only the second-largest annual recurrence interval, with the 2011 being the largest (Rongen &Throssell 2024).

Over the past 15 years, the Auckland region has also experienced several significant droughts, with the 2019–2020 calendar year considered one of the most extreme (Johnson 2021). Between January 1 and May 21, 2020, 126 mm of rain was recorded at NIWA's Māngere weather station, which is 31% of the normal rainfall for that period. Auckland endured over 77 consecutive days in drought or severe drought conditions during this time. Regional average rainfall records indicate rainfall during the 2020 drought was the lowest on record, at 52% below the long-term mean (Johnson 2021).

Several rivers experienced their lowest ever gauged flows during the summer of 2020. The regional average number of days below the seven-day mean annual low flow (MALF) provide an insightful way to characterise annual river flows over time (Johnson 2021). In 2020, this figure reached approximately 100 days on average across the region, representing the greatest number of days below MALF over the period of analysis from 1980 to 2020. In the 21st century, only 2010 and 2013 had more than 70 days below MALF.

[4] https://tewaihanga.govt.nz/media/oeapj3qb/the-2023-auckland-anniversary-weekend-storm.pdf

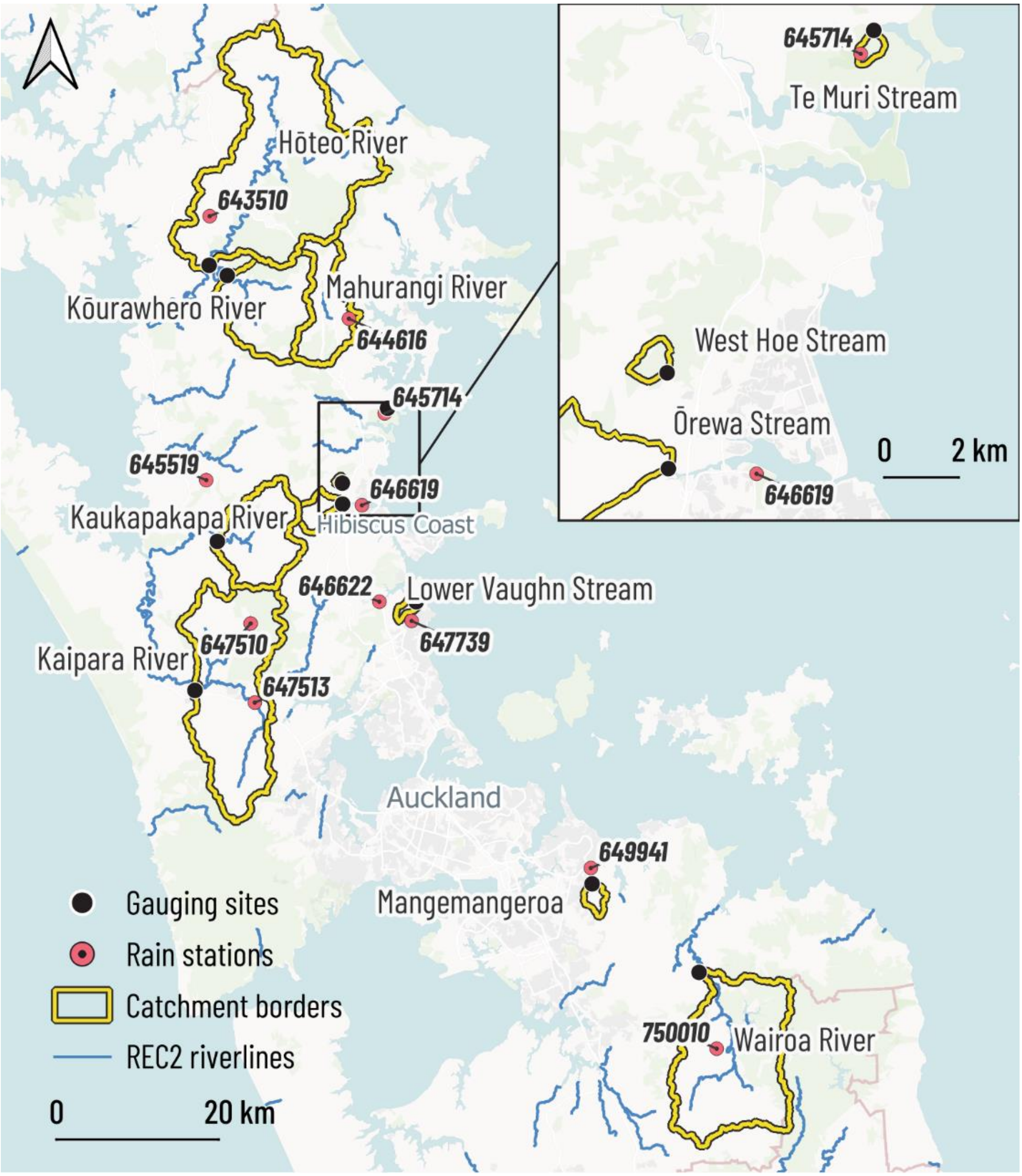

Figure 1. Location of the 11 monitoring sites, their catchments and associated rainfall stations within the Auckland region. Map data: Maptiler, OpenStreetMap contributors.

Table 1. Catchment characteristics. Only top three dominant geology and land cover classes are listed in the table.

Site name	Catchment area (km^2)	Dominant geology (based on NZL GNS 1:250K Geology (3rd edition))[a]	Dominant land cover (based on LCDB v5.0, 2018)[b]	Dominant land cover in 2023 (Auckland Council 2025)	Dominant soil order (based on NZLRI)[c]
Hōteo River	270	Waitematā (77%) Mudstone (8%) Alluvium (8%)	Rural (55%) Exotic forest (23%) Native forest (21%)	Rural (55%) Exotic forest (22%) Native forest (22%)	Ultic (75%) Recent (16%)
Kaipara River	156	Waitematā (45%) Alluvium (34%) Sand/dune (10%)	Rural (59%) Exotic forest (24%) Native forest (10%)	Rural (57%) Exotic forest (24%) Native forest (11%)	Ultic (43%) Allophanic (25%)
Kaukapakapa River	61.6	Mudstone (33%) Waitematā (25%) Alluvium (23%)	Rural (78%) Native forest (14%) Exotic forest (7%)	Rural (75%) Native forest (18%) Exotic forest (6%)	Ultic (74%) Allophanic (13%)
Lower Vaughan Stream	2.39	Waitematā (97%) Limestone (3%)	Rural (49%) Native forest (28%) Urban (18%) Exotic forest (6%)	Rural (38%) Native forest (30%) Urban (24%)	Ultic (90%)
Mangemangeroa River	4.76	Waitematā (100%)	Rural (57%) Native forest (37%)	Rural (57%) Native forest (40%) Urban (3%)	Ultic (100%)
Ōrewa Stream	9.58	Mudstone (50%) Waitematā (26%) Alluvium (23%)	Rural (73%) Native forest (14%) Urban (8%)	Rural (69%) Native forest (19%) Urban Parkland (7 %)	Ultic (89%) Gley (11%)
Te Muri Stream	0.27	Waitematā (99%) Alluvium (1%)	Rural (92%) Native forest (8%)	Native forest (70%) Rural (30%)	Ultic (100%)
Wairoa River	149	Greywacke (58%) Waitematā (33%) Alluvium (6%)	Rural (70%) Native forest (15%) Exotic forest (15%)	Rural (48%) Native forest (28%) Exotic forest (22%)	Granular (36%) Ultic (28%)
West Hoe Stream	0.53	Waitematā (100%)	Native forest (90%) Rural (8%)	Native forest (99%) Rural (1%)	Ultic (100%)
Mahurangi River	47.2	Waitematā (88%) Tauranga (11%)	Rural (49%) Native forest (18%) Exotic forest (17%)	Rural (49%) Native forest (26%) Exotic forest (21%)	Ultic (57.5%) Recent (25.8%) Brown (5.24%)

Site name	Catchment area (km^2)	Dominant geology (based on NZL GNS 1:250K Geology (3rd edition))[a]	Dominant land cover (based on LCDB v5.0, 2018)[b]	Dominant land cover in 2023 (Auckland Council 2025)	Dominant soil order (based on NZLRI)[c]
Kōurawhero River	73.4	Waitematā (66%) Tauranga (17%) Mangakahia (17%)	Rural (53%) Exotic forest (28%) Native forest (9%)	Rural (52%) Exotic forest (29%) Native forest (18%)	Ultic (79.4%) Recent (13.2%) Brown (2.51%)

[a] See: https://data.gns.cri.nz/metadata/srv/eng/catalog.search#/metadata/5F6780CB-4135-4204-A2C8-50DD74B0466F

[b] See: https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/

[c] See: https://soils.landcareresearch.co.nz/tools/nzlri-soil/nzlri-development

Figure 2. Photos of selected monitoring sites highlighting the diversity of site locations and catchment characteristics. A: Hōteo River. B: Kōurawhero River. C: Kaukapakapa River. D: Lower Vaughan Stream (D) monitoring sites, highlighting the diversity of site locations and catchment characteristics. Source: Photos provided by Auckland Council (EEMU) Hydrology team.

5 Methods

Two approaches were used to determine annual sediment yields for catchments in the Auckland region and to analyse potential changes in sediment dynamics. The first approach involved developing sediment rating curves from storm-event sampling, a method previously used to estimate sediment yields in the Auckland region (Curran-Cournane et al. 2013; Hicks et al. 2021). The second approach established a relationship between discretely sampled sediment concentration and instantaneous water discharge. This method was applicable only to six river sites (see Table 2) where Auckland Council collected discrete water quality data during the study period. Both event- and discrete-based ratings were applied across the full flow record to estimate annual and mean annual suspended sediment yields. Additional details on each approach are provided below.

Table 2. Event sediment load monitoring sites in the Auckland region analysed in the current report. Sites with overlapping discrete sampling are indicated in bold.

Site name	Site number	Rainfall site number	Sediment event sampling		Discrete water quality sampling	
			Start	End	Start	End
Hōteo River	**45703**	**643510**	**21/05/2010**	**24/06/2024**	**09/08/2023**	**06/06/2024**
Kaipara River	45311	647510	12/03/2012	18/06/2024	—	—
Kaukapakapa River	**45415**	**645519**	**21/05/2010**	**26/06/2024**	**06/01/2010**	**12/06/2024**
Lower Vaughan Stream	**7506**	**647739**	**03/07/2012**	**24/06/2024**	**04/07/2012**	**11/06/2024**
Mangemangeroa River	8304	649941	15/02/2012	25/06/2024	—	—
Ōrewa Stream	7202	646619	05/07/2009	24/06/2024	—	—
Te Muri Stream	6995	645714	23/12/2013	23/06/2024	—	—
Wairoa River	**8516**	**750010**	**21/05/2010**	**18/06/2024**	**04/06/2010**	**17/06/2024**
West Hoe Stream	**7206**	**646619**	**09/05/2012**	**23/06/2024**	**05/06/2012**	**11/06/2024**
Mahurangi River	**6863**	**64416**	**21/07/2020**	**24/06/2024**	**25/08/2020**	**12/06/2024**
Kōurawhero River	45731	643510	19/06/2020	22/06/2024	—	—

5.1 Data description

5.1.1 Water stage, water discharge and rainfall

Auckland Council monitor river water stage and discharge at each site. They provided high-frequency flow data at 2–15 minute intervals, along with daily averages. Rainfall is measured using automated 'tipping-bucket' gauges, which typically record when approximately 0.5 mm of rain has fallen (Hicks et al. 2021). Auckland Council supplied both 1-minute and daily rainfall totals.

Sediment and water discharge monitoring occur at the same site. Rainfall stations were not co-located but were usually within the monitoring site catchment (see Figure 1). Table 2 lists all site IDs.

5.1.2 Event sediment sampling

The event-based sediment monitoring programme is part of the State of the Environment (SOE) monitoring undertaken to monitor and report on the state of the region's environment to meet Resource Management Act (RMA) requirements. This type of monitoring is undertaken to provide information on changes through time. The event-based sediment monitoring programme started in 2009 and currently has 11 sites monitored during storm events (see Table 2).

Each site is equipped with an automatic sampler (hereafter auto-sampler, ISCO model 3700s with 24 sample bottles), mounted on the riverbank, and programmed to trigger at frequent intervals and/or key times during runoff events. The suspended sediment concentration (SSC, mg/L) was measured for collected samples by an ISO-accredited laboratory using ASTM D 3977-97 method. However, on several sites (Hōteo River, Wairoa River, Kaukapakapa River and Ōrewa Stream) before mid-2012 the samples were analysed for total suspended solids (TSS) using the APHA 2005 method. See Hicks et al. (2021) for more discussion on this and corrections applied.

At most sites, auto-samplers operated in a flow-proportional compositing mode, meaning the sampling rate was proportional to the stream flow rate. Each sampler bottle contained a composite of four to eight samples. At Hōteo, automated samples were collected flow-proportionally but were not composited. At West Hoe, compositing began after 1 September 2017.

Sampling was controlled by a water stage (level) logger. Sampling was activated when a stage threshold was exceeded, triggering collection once a calculated volume had passed the monitoring point. This calculation was based on the site's stage-discharge rating programmed into the logger, so higher flow rates resulted in shorter intervals between sample collections. The water stage threshold was site-specific and changed frequently so that whole events were typically well sampled (see Table 3).

Table 3. Water stage and discharge triggering thresholds for event sampling. Start date indicates the date after which the threshold has been in use.

Site (site No.)	Start date	Water stage threshold (m)	Water discharge threshold (m^3/s)
Hōteo River (45703)	22/05/2010	2	20
	07/01/2023	2	18.305
Kaipara River (45311)	12/03/2012	4	6.9
	31/08/2021	4	4.858
Kaukapakapa River (45415)	21/05/2010	1	1.9
	26/06/2012	1.3	1.9
Lower Vaughan Stream (7506)	11/01/2001	0.6	0.03
	04/05/2013	0.7	0.05
	03/05/2020	0.2	0.16
Mangemangeroa River (8304)	15/02/2012	0.37	0.11
	03/09/2012	0.45	0.226
Ōrewa Stream (7202)	29/06/2009	1.28	0.52
	25/06/2020	1.28	0.496

Site (site No.)	Start date	Water stage threshold (m)	Water discharge threshold (m^3/s)
Te Muri Stream (6995)	29/12/2013	0.28	0.018
Wairoa River (8516)	21/05/2010	0.8	2.26
	14/08/2010	1.2	5.35
	05/07/2022	1.2	6.35
West Hoe Stream (7206)	15/02/2012	0.35	0.044
	11/11/2019	0.35	0.043
Mahurangi River (6863)	27/05/2020	1.5	1.672
Kōurawhero River (45731)	19/12/2019	1	1.88
	29/07/2021	1	1.625
	27/01/2023	1	1.31
	30/10/2023	1	1.086
	05/03/2024	1	0.865

At times, auto-samplers experienced mechanical failures, or their bottle supply was exhausted before a storm event finished. Less frequently, auto-samplers were offline or absent for extended periods, typically lasting several months. As a result, some event sediment yields were only partially sampled, while others were not sampled at all. These are known challenges for the use of auto-samplers (Hicks et al. 2020).

Auckland Council provided a list of all hydrological events where the triggering water stage was exceeded, distinguishing between sampled and unsampled events. Staff classified sampled events based on their suitability for sediment rating curve development: i) single-peak well sampled events, were called 'well sampled for rating'; ii) (usually) multi-peak well-sampled events, were called 'well sampled for yield,' and used for sediment load estimation only; iii) unsampled events, or those deemed unsuitable for rating development or yield estimation, were called 'unsampled'. We verified this classification during the development of our SRCs. Sediment load during the 'unsampled' events was estimated using the event sediment rating curves and measured event peak discharge (see Section 5.3).

5.1.3 Discrete water quality sampling

For the discrete monitoring programme, samples were collected monthly, predominantly during low-flow periods[5] (see Table 4). Suspended sediment concentration was calculated as total suspended solids (TSS) following the APHA 2540 D standards. Numerous studies have found laboratory methods for measuring TSS tend to underestimate suspended sediment concentration (SSC), particularly when sand makes up more than 20% of the water-sediment mixture by mass

[5] Analysis of water quality monitoring data for the Auckland Region indicated that the distribution of flows corresponding with water quality sampling was not significantly different from the full flow distribution between 2013 and 2020, but highlights that sampling did not capture high flows at many sites, which are important for sediment transport, and tended to correspond to lower flows (Snelder & Kerr 2022). It is important to note this analysis did not capture the significant events of 2023.

(Rasmussen et al. 2009; Hicks et al. 2020). As paired SSC and TSS samples were not available for these periods to develop a bias correction factor, we followed Hicks et al. (2021) and assumed the TSS: SSC ratio was 1, except for the Kaukapakapa River ($SSC = 1.02 \times TSS$) and Wairoa ($SSC = 1.06 \times TSS$), based on previous comparisons of TSS and SSC from the Auckland region (following Hicks et al 2021). We therefore use the term 'SSC' for discrete ratings.

Table 4. Summary of instantaneous discharge during the discrete sediment sampling campaign. The descriptive statistics for instantaneous water discharge (Q, in L/s) are presented, along with the dates when the maximum and minimum Q values were recorded.

	Hōteo River	Kaukapakapa River	Lower Vaughan Stream	Wairoa River	West Hoe Stream	Mahurangi River
Number of sediment samples	10	157	106	130	129	42
Max Q	27,831 (01/11/2023)	22,931 (23/09/2021)	370 (25/08/2020)	18,464 (17/06/2024)	107 (23/09/2021)	29,014 (23/09/2021)
Min Q	679 (03/04/2024)	6.8 (09/03/2020)	1.23 (05/06/2014)	305 (01/05/2020)	1.07 (03/04/2013)	82.9 (03/02/2021)
Median Q	2,852	366	12.9	1,710	4.9	560
St. Dev. Q	8,490	2,118	52.1	2,802	14.9	4,662

5.1.4 Correction to cross-section average concentration

Auto-samplers typically collect water samples at a point near the riverbank (C_p), where SSC may differ from the discharge-weighted cross-section average SSC (C_m) which is required to calculate the total cross-section load. To tackle this issue, a conversion from C_p to C_m was developed for several sites following Hicks et al. (2021). In general, while some additional paired C_p– C_m samples were collected during the 2020–2024 period, the C_p– C_m relation did not alter. Therefore, for this report we used the conversion equations adapted after Hicks et al. (2021) as presented in Table 5. As the relationship between C_m and C_p may change in future, continued sampling to monitor changes through time may be beneficial.

Table 5. Relations used for converting auto-sampled SSC (C_p) to cross-section mean SSC (C_m). Adapted from Hicks et al. (2021).

Site	Relation	New data collected during the 2020–2024 period (count)	No. SSC gaugings (full record)
Hōteo River	$C_m/C_p = 1$	Yes (1)	8
Kaipara River	$C_m/C_p = 1$	Yes (1)	8
Kaukapakapa River	$C_m/C_p = \begin{cases} 0.00645 \times Q, & Q < 85{,}900\ l/s \\ 1, & Q \geq 85{,}900\ l/s \end{cases}$	No	5
Lower Vaughan Stream	$C_m/C_p = 1$	No	0
Mangemangeroa River	$C_m/C_p = 1$	No	3
Ōrewa Stream	$C_m/C_p = \begin{cases} 0.0562 \times Q + 0.587, & Q < 7{,}350\ l/s \\ 1, & Q \geq 7{,}350\ l/s \end{cases}$	No	4
Te Muri Stream	$C_m/C_p = 1$	Yes (2)	2
Wairoa River	$C_m/C_p = 1$	No	8
West Hoe Stream	$C_m/C_p = 1$	No	0
Mahurangi River	$C_m/C_p = 1$	Yes (2)	2
Kōurawhero River	$C_m/C_p = 1$	Yes (2)	4

5.2 Data quality checks

Quality checks of the flow record and event sediment data were undertaken to check for factors such as significant data gaps and erroneous values. Sediment data were corrected by Auckland Council staff due to fouling, sensor calibration drift, or mixing of bottles during automatic sampling. Data values may be missing from the continuous flow record because of equipment malfunctions, lightning strikes, or other factors.

To identify hydrological events which may have been missed, records of mean daily stage were used to identify days where stage could have been expected to exceed the site-specific triggering level for sediment sampling (defining the start of an event), but for which no event data were provided. Where gaps occurred in the stage record, daily rainfall totals were used to identify potential high flow events using a threshold of ≥10 mm of rainfall in 48 hours. Where such gaps were identified, Auckland Council provided 'infill' runoff event peak discharges based on relationships with neighbouring sites. In total, 15 potentially missing events were identified across all sites, with 1–2 missing events identified at the Hōteo River, Kaipara River, Kaukapakapa River, Lower Vaughan Stream, Te Muri Stream, and West Hoe Stream, and 7 potentially missing events at the Kōurawhero River. Infill data were provided for 6 of the 15 missing events. Affected sites and events are listed in Appendix 1 along with empirical equations used to infill missing events.

5.3 Development of storm-event Sediment Rating Curves

Event-based sediment rating curves (SRCs) were constructed for each site following standard procedures described in the National Environmental Monitoring Standards (NEMS) 'Measurement of Fluvial Suspended Sediment Load and its Composition' (Hicks et al 2020). Event-based SRC relate event peak discharge (Q_{peak}, L/s) to event total suspended sediment load (S, tonnes). The rating curves used in this study are of the power-law form:

$$S = a \times Q_{peak}^{b} \times BCF \times Z \quad (1)$$

where S is the predicted event sediment load in tonnes; Q_{peak} is the event peak discharge in litres per second; a and b are empirical coefficients, BCF is a bias correction factor, and Z is a correction factor for temporal trends in prediction error. NEMS (Hicks et al. 2020) recommend having a minimum of 12 data points for SRC development.

Following methods recommended in the NEMS and other studies (Warrick 2015; Helsel et al. 2020; Hicks et al. 2020), a and b were derived by applying ordinary least squares linear regression to the $\log_{10}$-transformed measured event total suspended sediment load (S_{obs}) and $\log_{10}$-transformed Q_{peak}:

$$\log_{10}(S) = b \times \log_{10}(Q_{peak}) + \log_{10}(a) \quad (2)$$

In this equation, b is the slope between the log-transformed Q_{peak} and S data, and $\log_{10}(a)$ is the "y-intercept" or "vertical offset" value of $\log_{10}(S)$ defined where $\log_{10}(Q_{peak})$ is equal to zero (i.e. where Q_{peak} is equivalent to 1 L/s). The $\log_{10}$-transformed model is retransformed to the original units to directly calculate the sediment load. The retransformation from $\log_{10}$-space introduces a negative bias in the retransformed predicted sediment load (Ferguson 1986). To correct for this retransformation bias, the NEMS recommends using Duan's (1983) nonparametric bias correction factor (BCF), referred to as the 'smearing' estimator (Helsel & Hirsch 2002; Hicks & Gomez 2016). For the $\log_{10}$-transformation used in the current report, the BCF may be estimated following Rasmussen et al. (2009):

$$BCF = \frac{\sum_{i=1}^{n} 10^{e_i}}{n} \quad (3)$$

where e_i is the residual or the difference between each measured and estimated sediment yield (in $\log_{10}$ units); n is the number of measurements.

All site-specific regression models were evaluated for normality and homoscedasticity of residuals in $\log_{10}$ space. Residuals are the difference between the measured and predicted suspended sediment load. The relationship is homoscedastic when the variance of residuals remains constant across the range of predicted values, indicating errors do not increase or decrease systematically with the magnitude of sediment load. The Shapiro–Wilk's test (1965) was used to assess whether the residuals followed a normal (Gaussian) distribution, with a p-value <0.05 indicating a significant deviation from normality. Residuals were also tested for homogeneity of variance using the Breusch-Pagan test (1979), with a p value <0.05 indicating heteroscedasticity (non-constant variance). When the normality assumption of residuals was violated, the log-transform bias correction (BCF) was not applied, as it may induce errors larger than those it is designed to correct (Hicks et al. 2000).

Following the NEMS approach (Hicks et al. 2020) and previous sediment rating approaches for these catchments (Curran-Cournane et al. 2013; Hicks et al. 2021), the SRC residuals were examined for a temporal trend (see Figure 3B) by regressing the residuals against the event start date:

$$Z = \alpha \times e^{Date \times \beta} \tag{4}$$

where Z is the residual of S_{obs} and S_{pred} (Eq. 1) in natural log-space, i.e. $\log(S_{obs}) - \log(S_{pred})$ which is equivalent to $\log\left(\frac{S_{obs}}{S_{pred}}\right)$; α and β are the regression coefficients; and $Date$ is the starting date of the event in Excel serial date format, i.e. days since 1 January, 1900.

A temporal trend was identified if β was significantly different from zero (at the 5% significance level using a two-sided t-test). In these cases, the Z value derived from Eq. 4 was used in Eq. 1. If no significant temporal trend was identified, $Z = 1$ was used in Eq. 1.

The residual plots and aforementioned statistics and metrics are included in each site-specific sediment rating curve in Appendix 2.

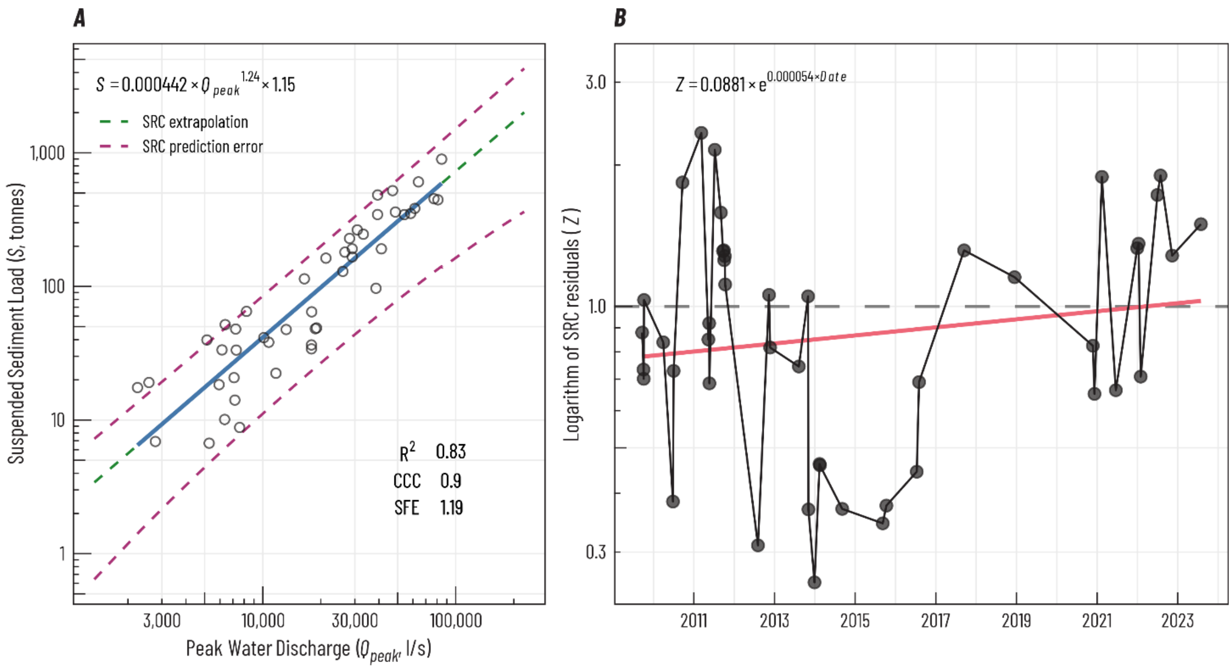

Figure 3. Example of the event sediment rating curve for the Kaukapakapa River. A: Relationship between event suspended sediment load and peak water discharge on a log$_{10}$ scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error. B: Distribution of the unadjusted model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

The coefficient of determination (R^2) and concordance correlation coefficient (CCC [Lin 1989]) were used to evaluate the effectiveness of site-specific SRCs. All metrics were estimated after applying bias correction and time-trend adjustments.

$$CCC = \frac{2\rho \times \sigma_{\text{obs}} \times \sigma_{\text{pred}}}{\sigma_{\text{obs}}^2 \times \sigma_{\text{pred}}^2 \times \left(\overline{S_{\text{obs}}} - \overline{S_{\text{pred}}}\right)^2} \tag{5}$$

where $\overline{S_{\text{obs}}}$ and $\overline{S_{\text{pred}}}$ are the average of the observed and predicted S over the entire observation period, respectively. An R^2 between 0.5 and 0.7 indicates satisfactory efficiency, with metric above 0.8 considered 'very good' (Moriasi et al. 2015). Similarly, a CCC above 0.6 is 'satisfactory', above 0.7 is 'good', and above 0.9 is 'excellent' (Moeys et al. 2012). Additionally, the standard factorial error (SFE) was estimated following the recommendations from Hicks et al. (2020). The SRC is usually considered 'unacceptable' if the SFE exceeds 2 (Hicks et al. 2011).

$$SFE = \exp\left(\sqrt{\frac{1}{n}\sum\left(log\frac{S_{obs,\,i}}{S_{pred,\,i}}\right)^2}\right) \tag{6}$$

In accordance with Hicks et al. (2021), we estimated the multiplicative prediction error by incorporating the calibration error (from the log-residuals) and additional uncertainty due to deviations of Q_{peak} from the mean Q_{peak}:

$$S_{error,\,i} = S_{pred,\,i} \times \left(\exp\left[\sigma\sqrt{1 + \frac{1}{n} + \frac{\left(\log(Q_{peak,\,i}) - \overline{Q_{peak}}\right)^2}{\sum\left(\log(Q_{peak,\,i}) - \overline{Q_{peak}}\right)^2}}\right] - 1\right) \tag{7}$$

where $S_{error,\,i}$ is the prediction error of suspended sediment load of the i-th event (tonnes); $S_{\text{pred},\,i}$ is the predicted sediment load of the i-th event (tonnes); $Q_{peak,\,i}$ is the peak water discharge of the i-th event (L/s); $\overline{Q_{peak}}$ is the mean $\log(Q_{peak})$; n is the number of observations; σ is the standard deviation of the log-residuals, i.e.: $\sigma = sd\left(\log\left(\frac{S_{obs}}{S_{pred}}\right)\right)$.

Extrapolation of the SRC above and below the sampled discharge range was required for most sites (Table 6). While it is generally acceptable to use the SRC for prediction beyond the range of the calibration data (Asselman 2000; Horowitz 2003), extrapolation may introduce additional errors, especially for higher water discharges (Gray 2018; Schmidt et al. 2023), and therefore needs to be applied with caution (Hicks & Gomez 2016). Most studies emphasise the importance of limiting predictions to within the period of observed data used to develop the SRC to ensure the S– Q_{peak} relationship remains stationary (Horowitz et al. 2015; Warrick 2015; Gray 2018; Jaeger et al. 2023). However, there is some evidence that the relationship between water discharge and suspended sediment concentration may flatten at high flows, requiring a separate SRC or the use of localised regression (i.e. LOWESS see (Farnsworth & Warrick 2007; Gray 2018)) to extrapolate beyond the range of sampled discharge even within the same time interval. Therefore, the validity of extrapolated values should be additionally evaluated. For example, Hicks et al. (2011) considered sediment yield estimates to be unacceptable if more than 50% of the estimated total sediment yield was carried by discharges exceeding the maximum gauged discharge.

Following Farnsworth and Warrick (2007) and Gray et al. (2018) an additional 10% error was added to predicted event sediment load values outside of the sampled discharge range to account for additional uncertainty introduced by extrapolation. Therefore, the combined error for unsampled high flow events was estimated as follows:

$$S_{error,\,i} = \sqrt{S_{error,\,i}^2 + \left(0.1 \times S_{pred,\,i}\right)^2} \qquad (8)$$

The S_{error} was further used for estimation of the overall uncertainty (U_j, %) of the SRC for the j-th site of interest. For the whole observation period at site j, the uncertainty was estimated as follows (Hicks et al. 2021):

$$U_j = 100 \times \frac{SY}{\sqrt{\sum_{i=1}^{n}(S_{error,\,i})}^{\,2}} \qquad (9)$$

Where SY is the total suspended sediment yield (in tonnes) at the site j estimated over the entire observation period.

Table 6. Summary statistics of peak water discharge (L/s) for the sampled and unsampled hydrological events over the event sampling campaign period.

Statistic	Used for SRC fitting	Well sampled for event yield	Unsampled
Hōteo River (site No. 45703)			
Count	47	70	141
Max	259,084 (27/01/2023)	259,084 (27/01/2023)	306,568 (28/01/2011)
Min	22,988 (28/11/2022)	20,810 (29/10/2021)	18,352 (24/06/2024)
Median	49,756	44,393	39,122
St. Dev.	49,633	44,268	43,854
Kaipara River (site No. 45311)			
Count	36	111	108
Max	100,257 (23/12/2018)	100,257 (23/12/2018)	438,674 (30/08/2021)
Min	9,065 (17/08/2018)	5,696 (12/10/2021)	4,878 (06/02/2023)
Median	17,688	15,190	10,401
St. Dev.	17,122	15,461	57,000
Kaukapakapa River (site No. 45415)			
Count	46	137	144
Max	84,527 (15/07/2018)	124,609 (28/08/2021)	216,426 (27/01/2023)
Min	2,242 (08/01/2012)	1,416 (30/12/2012)	1,521 (21/09/2010)
Median	18,321	12,638	3,104
St. Dev.	22,520	19,658	34,147
Lower Vaughan Stream (site No. 7506)			
Count	45	122	350
Max	7,610 (03/09/2012)	11,066 (24/09/2013)	18,190 (27/01/2023)
Min	260 (01/04/2019)	61.6 (30/06/2014)	50.1 (27/09/2013)
Median	920	656	150
St. Dev.	1,712	1,820	1,544
Mangemangeroa River (site No. 8304)			
Count	28	91	256
Max	11,285 (15/07/2018)	12,046 (04/04/2017)	23,279 (09/05/2023)
Min	1,025 (17/03/2023)	226 (06/06/2018)	226 (06/07/2020)
Median	2,430	1,535	473
St. Dev.	3,161	2,660	2,168
Ōrewa Stream (site No. 7202)			
Count	70	155	236
Max (Date)	77,844 (08/08/2022)	106,639 (09/05/2023)	113,466 (27/01/2023)
Min (Date)	761 (26/05/2010)	488 (06/06/2010)	442 (27/07/2010)
Median	6,031	3,565	915
St. Dev.	12,656	12,550	9,691

Statistic	Used for SRC fitting	Well sampled for event yield	Unsampled
Te Muri Stream (site No. 6995)			
Count	34	168	197
Max	2,163 (03/06/2018)	5,228 (29/08/2018)	2,320 (27/01/2023)
Min	29.7 (02/10/2022)	18.1 (04/02/2018)	18.1 (25/05/2014)
Median	176	83.3	39.9
St. Dev.	547	514	345
Wairoa River (site No. 8516)			
Count	71	128	184
Max	360,725 (08/03/2017)	360,726 (08/03/2017)	475,098 (12/02/2023)
Min	4,033 (17/08/2010)	4,064 (24/05/2010)	2,444 (20/06/2010)
Median	27,184	15,108	8,524
St. Dev.	62,066	45,749	44,257
West Hoe Stream (site No. 7206)			
Count	36	79	132
Max	2,654 (08/08/2022)	2,654 (08/08/2022)	3,637 (27/01/2023)
Min	71.3 (17/12/2022)	46.7 (26/07/2023)	43.5 (24/06/2022)
Median	586	435	93
St. Dev.	584	548	567
Mahurangi River (site No. 6863)			
Count	15	45	110
Max	103,411 (04/01/2023)	235,618 (03/05/2023)	247,258 (27/01/2023)
Min	2,362 (02/08/2020)	1,796 (28/05/2023)	1,621 (30/11/2022)
Median	18,688	12,763	4,027
St. Dev.	24,344	37,168	34,366
Kōurawhero River (site No. 45731)			
Count	29	46	56
Max	25,199 (23/09/2021)	25,199 (23/09/2021)	204,553 (27/01/2023)
Min	1,540 (26/12/2023)	1,230 (07/01/2024)	1,193 (29/01/2024)
Median	3,753	4,064	6,531
St. Dev.	6,269	5,669	40,237

Note: Dates of recorded minimum and maximum values are presented in brackets. Single-peak, well-sampled events were considered as suitable for SRC fitting, while multi-peak events were considered as suitable for event sediment load estimation. Poorly sampled and under- or over-sampled, as well as missing events were considered 'unsampled' and required additional estimation using the SRC. See Section 5.1.2 for event categorisation details. St. Dev. – standard deviation.

5.4 Development of LOWESS Rating Curves for discrete sediment sampling

In addition to the event-based sediment ratings, rating curves were developed from suspended sediment samples collected as part of discrete river water quality monitoring program at six sites (see Table 2). For each site, a rating was determined by plotting instantaneous sediment concentration against instantaneous water discharge (Q). Q was estimated from a 15-minute interval record, linearly interpolated to the timestamp of the discrete water quality sample. A sediment rating curve was fitted using a scatterplot smoothing approach, following the recommendations in the NEMS (Hicks et al. 2020). To fit the ratings for each catchment, a LOWESS (Locally Weighted Scatterplot Smoothing) approach was applied. This method constructs a 'running' linear regression fit within a moving window of discharge. The window size is controlled by the 'stiffness' factor (or span), which is adjusted to optimise the LOWESS fitting by maximising R^2 and minimising SFE (Eq. 6). Since the data were log-transformed for curve-fitting, the predicted sediment concentrations were corrected for log-transformation bias (see Eq. 3).

Because most discrete water samples were collected during low-flow periods (see Table 4), extrapolation beyond the observed discharge range was necessary, as conditions at the river site significantly differ from the sampled data (Table 7). This extrapolation followed the practices recommended in the NEMS (Hicks et al. 2020). Specifically, projections beyond the sampled discharge range were made using regression coefficients derived from the highest sampled discharge. We then assessed whether the predicted sediment concentration at the maximum recorded discharge was sensible with respect to what could be reasonably anticipated for the site or similar sites based on literature (Hicks et al. 2011, 2021) and available SSC samples. If the projected maximum sediment concentration appeared unrealistic, we estimated a more plausible maximum value from the event sampling campaign and refitted the LOWESS model.

As an additional independent validation, we compared the sediment concentrations predicted from the discrete rating curves with measured concentrations from the event-based sampling. The same set of metrics used for SRC development were applied in this validation. An example of the fitted discrete sediment rating for the Ōrewa Stream is presented in Figure 4.

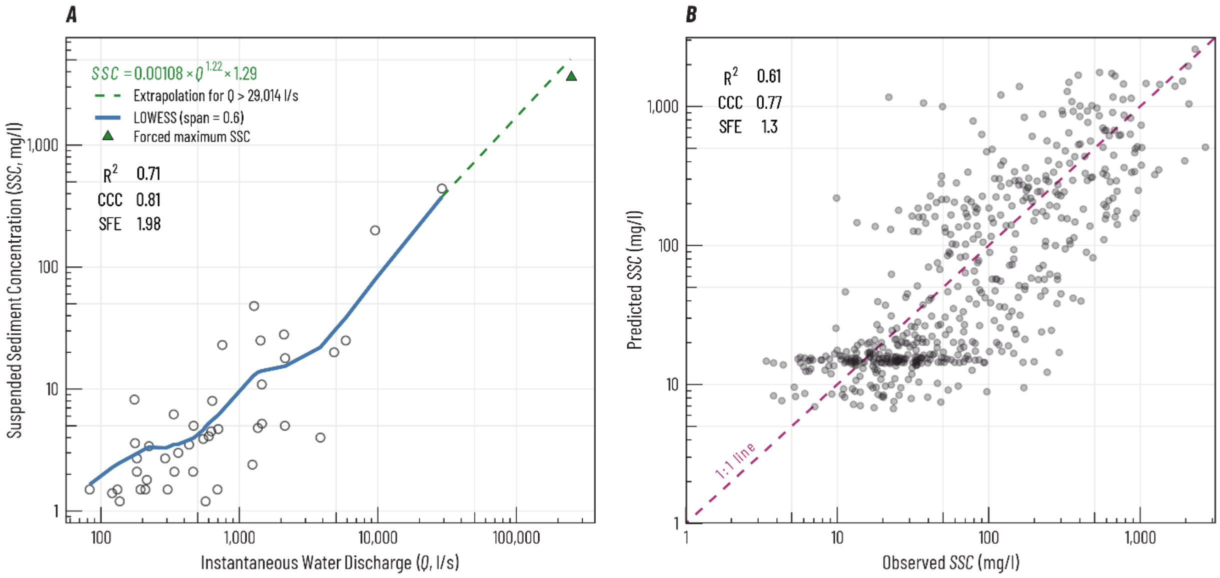

Figure 4. Example of a sediment rating curve developed from discrete sediment concentration samples from the Mahurangi River. A: Relationship between suspended sediment concentration (SSC) and instantaneous water discharge (Q) on a $\log_{10}$ scale. The blue line indicates the fitted LOWESS model, while the green dashed line represents a linear extrapolation to the maximum known water discharge at the site. B: Validation of SSC predicted from the discrete rating curve using measured suspended sediment concentration from sampled hydrological events with auto-sampler.

Table 7. Descriptive summary statistics of the instantaneous water discharge, Q, (in L/s) at selected sites used for developing discrete rating curves. St. Dev – standard deviation.

Parameter	Hōteo River (45703)	Kaukapakapa River (45415)	Lower Vaughan Stream (7506)	Wairoa River (8516)	West Hoe Stream (7206)	Mahurangi River (6863)
Period	21/05/2010–26/06/2024	21/05/2010–26/06/2024	03/07/2012–24/06/2024	21/05/2010–18/06/2024	09/05/2012–23/06/2024	21/07/2020–24/06/2024
Missing	17.3%	5.57%	13.1%	17.4%	1.19%	0.13%
Min Q	90 (09/04/2020)	4.6 (17/03/2022)	0	254 (07/04/2020)	0.3 (05/03/2013)	60.3 (26/03/2021)
Max Q	306,568 (29/01/2011)	216,259 (27/01/2023)	17,091 (27/01/2023)	474,316 (14/02/2023)	3,420 (27/01/2023)	246,625 (27/01/2023)
Mean Q	7,188	1,323	33.9	3,047	10.6	1,740
Median Q	3,111	515	8.74	1,642	4.85	626
St. Dev.	15,571	4,251	150	7,911	35.7	6,021

5.5 Suspended sediment yield estimation

Annual suspended sediment yield (SY, tonnes) was estimated for calendar years and for hydrological years. The hydrological year (also called the water year) is the period starting on 1 July and ending the following 30 June (Watson 2024).

For the event-based estimates (derivatives from Section 5.3) SY was computed as a sum of S during the period (calendar, or hydrological year):

$$SY = \sum_{i=1}^{n} S_i \,, \quad (10)$$

where S_i is the sediment load of the i-th event (tonnes); and n is the total number of hydrological events during the period. For sampled events of sufficient quality, the observed sediment load is used for S_i. For unsampled events, and sampled events of insufficient quality, the predicted using Eq. 1 sediment load was used for S_i.

SY was estimated from the discrete monitoring rating curves (Section 5.4) following the NEMS (Hicks et al. 2020):

$$SY = k \sum \Delta t \times \frac{(Q_n + Q_{n+1})(SSC_n + SSC_{n+1})}{4} \quad (11)$$

where Q_n is the instantaneous discharge at time n (L/s), SSC_n is the matching SSC generated by the discrete rating curve (mg/L), Δt (s) is the time interval between records, k is a unit conversion factor equal to 10^{-9}. Existing continuous flow records for the Hōteo, Kaukapakapa, Lower Vaughan, Wairoa, West Hoe, and Mahurangi sites were aggregated into 15-minute intervals. Missing data, if present, were filled using linear interpolation only for gaps no longer than 60 minutes (i.e. four data entries) following recommendations in the 'Processing of environmental time-series data' NEMS (Watson et al. 2024).

Long-term specific suspended sediment yields (SSY, t/km^2/yr) were calculated from both the event-based and discrete monitoring SRCs for the periods of interest were estimated from mean annual SY as follows:

$$SSY = \frac{\sum SY}{N \times A}, \quad (12)$$

where SSY is the long-term specific suspended sediment yield (t/km^2/yr); N (yr) is duration of the period of interest; and A (km^2) is the catchment area.

5.6 Stationarity of event rating curves

Over extended periods, changes in catchment land cover, land use, or climate may alter the relationship between flow and suspended sediment concentration due to changes in either catchment hydrology or sediment supply dynamics, which can cause fundamental shifts in sediment rating curve model parameters, a and b from Eq. 1 (Asselman 2000; Warrick 2015; Ahn & Steinschneider 2018; Gray 2018).

The NEMS (Hicks et al. 2020) recommends that SRCs are developed for each year to assess the stationarity of the rating. The NEMS also recommends ≥12 points are used to fit SRCs. As there are insufficient event data points to develop yearly SRCs, we use several approaches to identify potential rating shifts. Firstly, trends in the $S - Q_{peak}$ relationship and temporal trends in residuals (see Section 5.3) were examined for potential shifts and change points. Secondly, satellite imagery spanning the event records were assessed visually for substantial changes in land cover and land use, as databases such as the New Zealand Land Cover Database (LCDB) do not span the monitoring period. Where potential shifts in the $S - Q_{peak}$ relationship, land cover, or land use were identified, SRCs were developed for sub-periods of the record before and after the shifts, rounded to whole calendar years for simplicity (see Section 6.2).

Sub-period SRCs were developed using the same approach as for the full record (see Section 5.3), with the exception of normalising Q_{peak} by the geometric mean for the sub-period of the streamflow values (for Q_{peak} centering) to provide a meaningful comparison of the vertical offset between sub-periods (Warrick 2015). The bias-correction factors were applied (Duan 1983) after retransforming the data into the original units:

$$\log_{10}(S_i) = b \times \log_{10}(Q_{peak}/\overline{Q_{peak}}) + \log_{10}(\hat{a}) \quad (13)$$

$$S_i = \hat{a} \times (Q_{peak}/\overline{Q_{peak,\,i}})^b \times BCF \quad (14)$$

where S_i is the suspended sediment load for the *i*-th sub-period (tonnes); $\hat{a}$ is a vertical offset parameter (tonnes per event) equivalent to the suspended-sediment concentration of the middle of the sample distribution; $\overline{Q_{peak,\,i}}$ is the geometric mean of the Q_{peak} for the *i*-th sub-period (L/s). The geometric mean is the optimal normalisation parameter because it is the centre of mass of the $\log_{10}(Q_{peak})$ data and the least squares technique uses the mean of the $\log_{10}(Q_{peak})$ to compute the slope and offset parameters (Warrick 2015). Note that vertical offset $\hat{a}$ has meaningful units of tonnes per event, unlike a in Eq. 1.

The differences in slope (b) and vertical offset ($\hat{a}$) parameters of the sub-period rating curves in Eq. 14 were tested for significance with the *t*-statistic and analysis of covariance (ANCOVA), respectively, following recommendations from Helsel et al. (2020) and Warrick (2015). If the test's p-value was <0.05, i.e. the null hypothesis was rejected, the difference in slopes and/or vertical offsets was considered statistically significant, indicating a shift in the sediment rating and changes in the sediment–water discharge relationship.

5.7 Statistical analysis

All reported p values were two-sided, with $\alpha < 0.05$ used as a threshold for significance, calculated using a Wilcoxon rank sum test (Mann 1945), unless otherwise specified. All statistical analyses and GIS procedures were done in *R* version 4.4.2 using the 'stats', 'sf' (Pebesma 2018), 'terra' (Hijmans 2023) and 'tidymodels' (Kuhn & Wickham 2018) packages, unless otherwise specified.

The statistical significance of monotonic trends in SY were assessed using the non-parametric Mann-Kendall trend test (Mann 1945). The magnitude of the trends was calculated using Sen's slope estimator (Sen 1968). Unlike parametric statistical tests, the Mann-Kendall test does not require data to be normally distributed. Additionally, as a rank-based method, it is resistant to the influence of outliers and small numbers of unusual values (Helsel & Hirsch 2002). Sen's slopes were further converted into percentage change per year by dividing them by the geometric mean of SY. The Mann-Kendall test was conducted in *R* using the 'rkt' package (Marchetto 2012), as recommended by Helsel et al. (2020).

6 Results

6.1 Rating curves

6.1.1 Event sediment rating curves

A total of 11 event-based sediment rating curves were developed (see Table 8). On average, data from 40 sampled hydrological events were used to fit a single SRC. However, for some sites established in 2020, such as Mahurangi River, only 15 data points were available for SRC development. For all models, the R^2 exceeded 0.8, and the CCC was above 0.9, indicating a strong model fit. The standard factorial error (SFE) remained below 2 for all sites except Te Muri Stream, confirming that the developed SRCs are generally acceptable (Hicks et al. 2011). Model residuals were normally distributed at all sites except for Wairoa River, where the Shapiro-Wilk test indicated a non-normal distribution with high confidence (p-value <0.001).

Residual time trend analysis (Table 9) showed a significant negative monotonic trend in sediment yield estimation at Mangemangeroa River and Te Muri Stream, with annual average declines in yields of −3.8% and −9.7% per year, respectively, for a given peak discharge. In contrast, the Wairoa River and Kōurawhero River exhibited statistically significant positive monotonic trends, with annual increases of +7.3% and +26.9% per year, respectively, for a given peak discharge. Other sites did not have a statistically significant monotonic trend. Therefore, temporal trend adjustment (Eq. 4) was applied only at the Mangemangeroa River, Te Muri Stream, Wairoa River, and Kōurawhero River sites to correct for drift in the rating curves.

Table 8. Event suspended sediment ratings and summary statistics for computation of event-based suspended sediment yield in the Auckland region, using data collected prior to 2024. Rating curves are presented in a power form of $S = a \times Q_{peak}^{b} \times BCF$ (see Eq. 1). R^2, CCC and SFE are the metrics used to assess the model quality; n is the total number of hydrological events used for the development of the SRC. The p-values of Shapiro-Wilk's test for normality and Breusch-Pagan's test for homoscedasticity of residuals are presented. Residuals are considered normally distributed with homogeneous variances if both p-values are greater than 0.05.

Site (site No.)	Period[a]	Events used for fitting (n)	SRC equation	R^2	CCC	SFE	Normality test p-value	Homosceda-sticity test p-value	Range of values in variable measurements	Mean	Median
Hōteo River (45703)	2010–2023	47	$S = 0.0000000187 \times Q_{peak}^{2.23} \times 1.13$	0.88	0.93	1.08	0.6	0.7	S: 46.6–34,455 Q_{peak}: 22,988–259,084	2,553 67,630	669 49,756
Kaipara River (45311)	2012–2023	36	$S = 0.00000867 \times Q_{peak}^{1.7} \times 1.11$	0.81	0.89	1.09	0.28	0.22	S: 28.5–1,247 Q_{peak}: 9,065–100,257	298 24,000	145 17,688
Kaukapakapa River (45415)	2010–2024	46	$S = 0.000442 \times Q_{peak}^{1.24} \times 1.15$	0.83	0.9	1.19	0.19	0.02	S: 6.71–897 Q_{peak}: 2,242–84,527	173 26,088	64.8 18,321
Lower Vaughan Stream (7506)	2012–2024	45	$S = 0.000203 \times Q_{peak}^{1.33} \times 1.08$	0.9	0.94	1.92	0.64	0.38	S: 0.22–26.1 Q_{peak}: 260–7,610	4.79 1,671	1.82 920
Mangemangeroa River (8304)	2012–2023	28	$S = 0.000035 \times Q_{peak}^{1.69} \times 1.05$	0.96	0.98	1.13	0.91	0.46	S: 2.98–253 Q_{peak}: 1,025–11,285	55.9 3,699	22.6 2,430
Ōrewa Stream (7202)	2009–2024	70	$S = 0.0000391 \times Q_{peak}^{1.51} \times 1.14$	0.91	0.95	1.52	0.25	0.08	S: 0.514–1,611 Q_{peak}: 761–77,844	74.3 10,409	20.2 6,031
Te Muri Stream (6995)	2014–2024	34	$S = 0.000535 \times Q_{peak}^{1.4} \times 1.19$	0.89	0.94	2.54	0.1	0.87	S: 0.029–13.3 Q_{peak}: 29.7–2,163	2.65 392	0.94 176
Wairoa River (8516)	2010–2023	71	$S = 0.00000864 \times Q_{peak}^{1.65} \times 1.15$	0.91	0.95	1.12	0.05	0.66	S: 3.79–17,713 Q_{peak}: 4,033–360,725	875 45,694	140 27,184
West Hoe Stream (7206)	2012–2024	36	$S = 0.0000913 \times Q_{peak}^{1.41} \times 1.08$	0.92	0.96	2.23	0.75	0.55	S: 0.034–6.89 Q_{peak}: 71.3–2,654	1.33 729	0.72 586
Mahurangi River (6863)	2020–2024	15	$S = 0.00000455 \times Q_{peak}^{1.71} \times 1.07$	0.94	0.97	1.1	0.16	0.84	S: 2.7–1,704 Q_{peak}: 2,362–103,411	227 25,263	85 18,688
Kōurawhero River (45731)	2020–2024	29	$S = 0.0000753 \times Q_{peak}^{1.46} \times 1.08$	0.94	0.97	1.13	0.56	0.7	S: 3.63–230 Q_{peak}: 1,540–25,199	41.5 7,070	19.1 3,753

[a] In calendar years.

Table 9. Summary of the SRC residuals' time trends estimated using ordinary least square regression. Sites highlighted in bold experienced a significant temporal change (at the 5% significance level using a two-sided *t*-test) in their SRC's residuals, and their sediment yield estimates were adjusted using the equations in the current table.

Site (site No.)	SRC time-trend adjustment (Z)	R^2	Period[a]	Events used for fitting (n)	Percentage change each year	p-value
Hōteo River (45703)	$S_{obs}/S_{pred} = 0.621 \times e^{0.00000827 \times Date}$	0.0008	2010–2023	47	0.30%	0.85
Kaipara River (45311)	$S_{obs}/S_{pred} = 28.5 \times e^{-0.0000808 \times Date}$	0.06	2012–2023	36	−2.9%	0.16
Kaukapakapa River (45415)	$S_{obs}/S_{pred} = 0.0881 \times e^{0.000054 \times Date}$	0.025	2010–2024	46	1.99%	0.29
Lower Vaughan Stream (7506)	$S_{obs}/S_{pred} = 0.232 \times e^{0.0000318 \times Date}$	0.013	2012–2024	45	1.17%	0.45
Mangemangeroa River (8304)	$\boldsymbol{S_{obs}/S_{pred} = 80.7 \times e^{-0.000105 \times Date}}$	**0.17**	**2012–2023**	**28**	**−3.8%**	**0.03**
Ōrewa Stream (7202)	$S_{obs}/S_{pred} = 1.86 \times e^{-0.0000178 \times Date}$	0.004	2009–2024	70	-0.65%	0.61
Te Muri Stream (6995)	$\boldsymbol{S_{obs}/S_{pred} = 166358 \times e^{-0.000279 \times Date}}$	**0.3**	**2014–2024**	**34**	**−9.7%**	**<0.001**
Wairoa River (8516)	$\boldsymbol{S_{obs}/S_{pred} = 0.00027 \times e^{0.000192 \times Date}}$	**0.23**	**2010–2023**	**71**	**7.3%**	**<0.001**
West Hoe Stream (7206)	$S_{obs}/S_{pred} = 3.96 \times e^{-0.0000334 \times Date}$	0.01	2012–2024	36	−1.2%	0.56
Mahurangi River (6863)	$S_{obs}/S_{pred} = 19449 \times e^{-0.000222 \times Date}$	0.092	2020–2024	15	−7.8%	0.27
Kōurawhero River (45731)	$\boldsymbol{S_{obs}/S_{pred} = 0.000000000000218 \times e^{0.000652 \times Date}}$	**0.46**	**2020–2024**	**29**	**26.9%**	**<0.001**

[a] In calendar years.

6.1.2 Discrete river water quality monitoring rating curves

LOWESS rating curves were developed for six sites (see Table 10) to predict discrete sampled sediment concentration based on instantaneous water discharge. Compared to event SRCs, discrete SRCs had lower model quality, with an average R^2 of 0.6 and a CCC of 0.68. Despite having, on average, more than 95 points available for LOWESS model development, the data showed significant scatter and was primarily collected during low-flow periods (see Table 4 and Table 7). At all sites except West Hoe Stream, manual adjustment of the rating extrapolation was required to obtain reasonable SSC estimates.

Nevertheless, independent validation using measured SSC from the event sampling campaign showed 'satisfactory' results, with an average R^2 above 0.5 and a CCC of 0.68. One of the poorest results was achieved at the Hōteo River, where only 10 discrete samples were available – an insufficient number for SRC development. Independent validation indicated that the discrete SRC explained only 36% of SSC variability. In contrast, the West Hoe Stream site showed good validation results (R^2 = 0.69, CCC = 0.8), where most discrete samples were taken at water discharges below 50 L/s. However, extrapolation of the West Hoe Stream SRC up to 3,420 L/s (measured on 27/01/2023) was required.

Table 10. Discrete sediment rating curve summary fit statistics. BCF is the bias correction factor; R^2, CCC and SFE are the metrics used to assess the LOWESS model quality; and Max Q is the maximum instantaneous water discharge recorded during sampling period and used for the LOWESS model fitting.

River (site No.)	BCF	Normality test p-value	Homoscedasticity test p-value	Calibration			Validation			Max Q	Extrapolation equation
				R^2	CCC	SFE	R^2	CCC	SFE		
Hōteo River (45703)	1.07	0.48	0.0028	0.93	0.96	1.14	0.36	0.54	1.23	27,831	$SSC = 0.00181 \times Q^{1.07} \times 1.07$
Kaukapakapa River (45415)	1.17	0.02	0.55	0.65	0.78	1.57	0.36	0.54	1.3	22,931	$SSC = 0.102 \times Q^{0.72} \times 1.17$
Lower Vaughan Stream (7506)	1.72	<0.01	0.59	0.32	0.4	2.02	0.48	0.68	1.23	370	$SSC = 0.124 \times Q^{0.99} \times 1.72$
Wairoa River (8516)	1.12	0.01	0.16	0.78	0.87	1.47	0.63	0.78	1.32	18,464	$SSC = 0.0351 \times Q^{0.86} \times 1.12$
West Hoe Stream (7206)	1.24	<0.01	0.67	0.15	0.23	2.04	0.69	0.8	1.4	107	$SSC = 0.0104 \times Q^{1.55} \times 1.24$
Mahurangi River (6863)	1.29	0.69	0.22	0.71	0.81	1.98	0.61	0.77	1.3	29,014	$SSC = 0.00108 \times Q^{1.22} \times 1.29$

6.2 Stationarity of event sediment ratings

The SRC stability assessment was conducted solely on sampled hydrological events considered 'well sampled for rating' by both Auckland Council and MWLR staff. Therefore, it is important to emphasise that the analysis in this section reflects only part of the sediment yield variability. As discussed later in Section 7.1, some significant events (especially during the high-flow years of 2022 and 2023) were not measured for various reasons (see Section 5.1.2), meaning that their inclusion in the analysis may alter the conclusions we present. The current analysis should be treated with caution, as it only represents the well sampled events.

Long-term monitoring data provides an opportunity to identify shifts in sediment ratings, which can occur through time as catchment hydrology, land cover, and land use change. This section presents a site-by-site assessment of SRC stability. As insufficient data points were available to develop yearly SRCs for stationarity assessment as recommended by the NEMS (Hicks et al. 2020), we developed SRCs for periods with observable changes in the temporal trend of model residuals, or where substantial changes in land cover or land use were observed in satellite imagery (outlined in Section 5.6). While changes in ratings may coincide with periods of land cover or land use change, this does not necessarily indicate a direct causal relationship.

Our analysis revealed statistically significant vertical offset shifts (parameter $\hat{a}$ in Eq. 14) in the SRCs at the Kaukapakapa River, Mangemangeroa River, Te Muri Stream, Wairoa River, and Kaipara River sites. At the Ōrewa Stream and Kōurawhero River sites, shifts were noticeable on a visual check, but statistical tests (t-test and ANCOVA) indicated the shifts were not significant. The SRCs for other sites remained stationary over the full record. The magnitude of significant shifts at each site are outlined in individual subsections below. Continuation of sediment monitoring is necessary to identify future shifts in sediment ratings.

6.2.1 Kaukapakapa River

A statistically significant shift in sediment ratings was observed at the Kaukapakapa River when comparing the 2022–2024 sub-period to the 2010–2021 one. While the slopes of the curves remained similar (no statistically significant difference indicated by t-test), the change in the vertical offset was statistically significant (ANCOVA's p-value <0.05; see Appendix 3), indicating a change in the sediment–water discharge relationship. The 2010–2021 vertical offset (89 tonnes per event) was greater than the 2022–2024 vertical offset (55.3 tonnes per event) while the slopes of the models were very similar (Figure 5A). The mean water discharge during the second period was half that of the first period. Nevertheless, event sediment loads were greater in 2022–2024 than in 2010–2021. For example, an event with a peak water discharge of 10,000 L/s in 2010–2021 is estimated to have a sediment load of 44 tonnes per event, while the same water discharge in 2022–2024 would have an estimated export of 63.2 tonnes per event. Similarly, a peak streamflow of 30,000 L/s would have an estimated export of 180 and 294 tonnes, respectively.

From late 2022, increased sediment loads are observed relative to event rainfall totals compared to earlier events in the record dating back to 2010 (see Figure 5B). This shift in rating is noted to have occurred around the time of the Anniversary Weekend floods (January 2023). This period also corresponds with renewed activity at King's Quarry between late 2022 and early 2023, evident in observations from satellite imagery, which was previously inactive.[6] No other substantial changes in land cover or land use were observed.

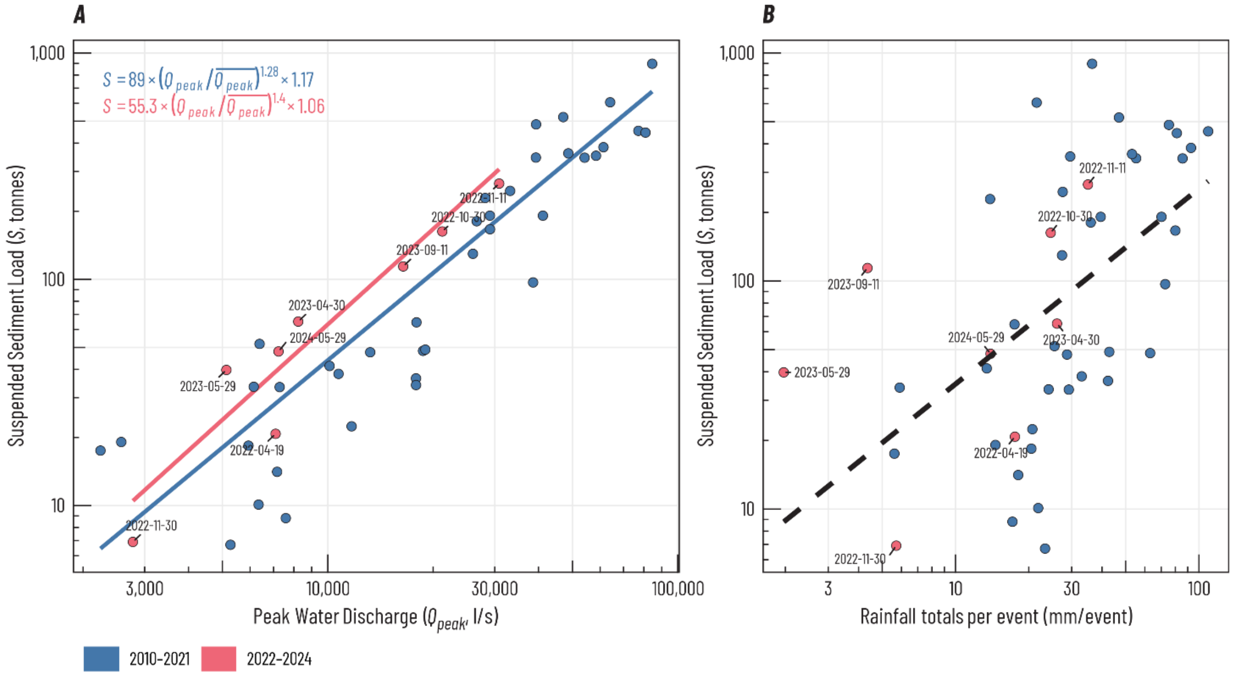

Figure 5. A: Sub-period sediment rating curves for Kaukapakapa River 2010–2021 (blue) and 2022–2024 (red) built using Eq. 14. Note that vertical offset has units of tonnes, and it is defined where the $Q_{peak}/\overline{Q_{peak}}$ is equal to 1, i.e. in the middle of the water discharge distribution. B: Relationship between rainfall totals per event (based on rainfall station No. 645519) and event suspended sediment load; the black dashed line represents a linear trend.

6.2.2 Mangemangeroa River

A 4.76 km^2 area of Mangemangeroa River catchment was harvested in early 2015, with the removal of 0.16 km^2 of exotic forest in the eastern part of the river catchment. The area subsequently underwent residential development from 2019 (see Figure 6). Partitioning of existing well-sampled events into pre-clearing (2010–2014) and post-clearing (2015–2024) groups was done to explore the possibility of an SRC shift.

[6] See: https://www.kingsquarry.co.nz/about-us/

Figure 6. Exotic forest clearing in 2015 in the Mangemangeroa River catchment (white circle), with further residential development of the cleared area in 2023. Map data: Google, Maxar Technologies.

The ANCOVA determined there was a significant difference in the vertical offset parameters of the SRC. The post-clearing vertical offset (31.9 tonnes per event; Appendix 3) was greater than the pre-clearing vertical offset (19.2 tonnes per event; Appendix 3), indicating the sediment–water discharge relationship has changed. This might be partly due to the presence of higher rainfall events observed in the second period (see Figure 7B). The mean total rainfall per event in the pre-harvest period was 28 mm, while in the post-harvest period it was 55 mm. The Wilcoxon rank-sum test indicated a statistically significant difference in rainfall between periods (p-value <0.03). The difference in sediment loads was more pronounced for small events with peak water discharge of less than 3,000 L/s. As Figure 7B shows, post-harvest events tended to have smaller sediment loads than pre-harvest for equivalent event rainfall totals.

The slopes of the SRCs differed but were not statistically significant (see Figure 7), reflecting lower yields for equivalent low flows in the 2015–2024. For comparison of the SRCs, an event with a peak water discharge of 3,000 L/s in 2010–2014 would have an estimated sediment yield of 31 tonnes, while the same water discharge in 2015–2024 would have a reduced yield of 23 tonnes. However, a peak streamflow of 10,000 L/s would have yielded similar estimates of 206 and 219 tonnes, respectively.

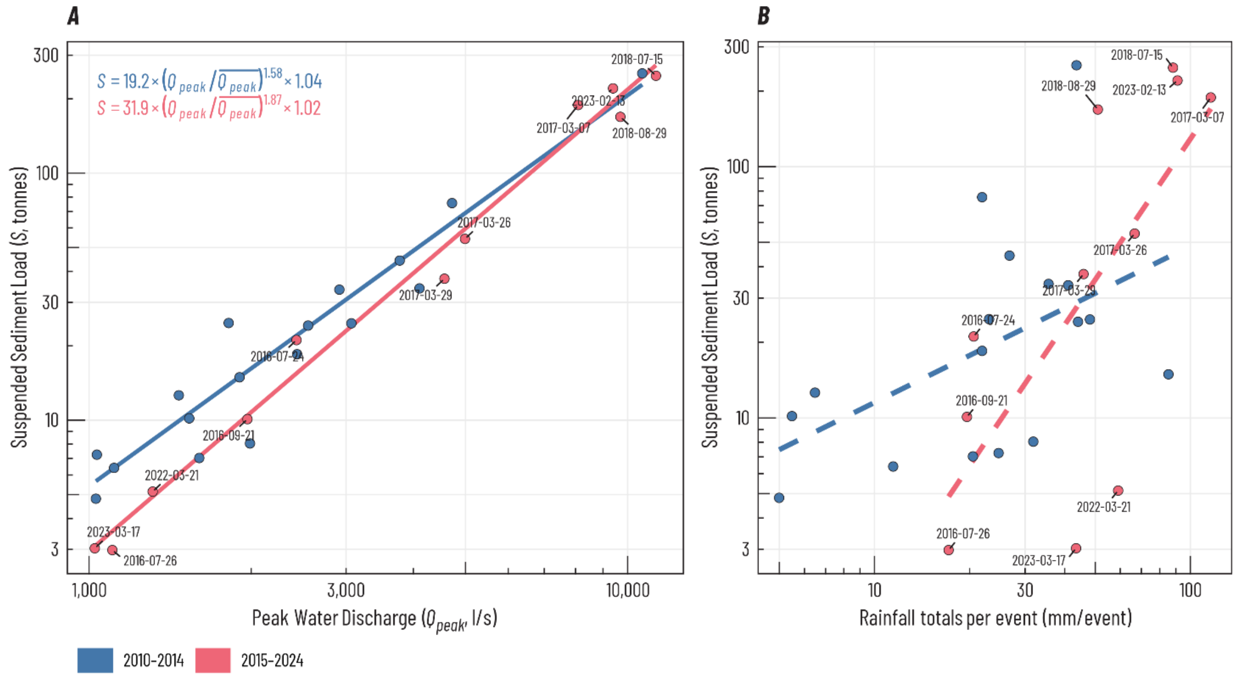

Figure 7. A: Sub-period sediment rating curves for Mangemangeroa River 2010–2014 (blue) and 2015–2024 (red) built using Eq. 14. Note that vertical offset has units of tonnes, and it is defined where the $Q_{peak}/\overline{Q_{peak}}$ is equal to 1, i.e. in the middle of the water discharge distribution. B: Relationship between rainfall totals per event (based on rainfall station No. 649941) and event suspended sediment load; each dashed line represents a linear regression. Events of the 2015–2024 period are labelled.

6.2.3 Te Muri Stream

The catchment area upstream of the Te Muri Stream site has a history of pastoral grazing and was recently reported to have very high specific sediment yields (Hicks et al. 2021). In 2016–2017, grazing was discontinued as part of an Auckland Council Regional Park catchment-wide reforestation effort to study the environmental impacts of farming on the Te Muri Stream (Waitkins & Rennie 2015). Retirement and planting of native species such as pōhutukawa, pūriri, tōtara, and kahikatea[7] began in 2020 (Figure 8), with apparent rapid influence on the SRC (see Figure 9). While in 2018 native forest occupied 8% of the territory, by 2023 native forest covered more than 70% of the basin area (see Table 1).

A statistically significant change (see Appendix 3) was observed in both the slopes and vertical offsets of the SRCs when comparing the 2010–2019 and 2020–2024 periods. A *t*-test indicated a significant difference between the regression slopes of the 2010–2019 and 2020–2024 models: during the pre-restoration period the regression slope was close to 1 and became two times steeper (1.85) after the revegetation practices, indicating a greater rate of change in sediment load for a change in discharge, noticeably for the 100–300 L/s range in Figure 9 where sampled peak discharges overlap. The vertical offset shifted from 2.34 tonnes to 0.36 tonnes following revegetation, partly reflecting the mean peak water discharge for the events decreasing from

[7] See: https://www.greenfleet.com.au/blogs/forest/te-muri

313 L/s during the pre-restoration period to 135 L/s. The difference in means is statistically significant according to the Wilcoxon rank-sum test (p-value = 0.04). The difference in offset therefore needs to be considered in relation to the change in mean discharge. As a result, the 2020–2024 SRC predicts lower suspended sediment yields compared to the 2010–2019 SRC. For example, an event with a peak water discharge of 313 L/s would be estimated to produce 2.38 tonnes of suspended sediment during the 2010–2019 period, compared to 1.85 tonnes during the 2020–2024 period—a 22% decrease. A more significant decrease is observed at lower water discharges, for example, an event with peak water discharge of 135 L/s, would produce 1.0 and 0.4 tonnes accordingly.

Additionally, while the mean rainfall sums per event also reduced by 27% from 30.2 mm per event to 21.9 mm per event, this difference was not statistically significant (p-value = 0.24). Therefore, it is possible the observed shift in SRCs is likely associated with factors other than changes in rainfall patterns, such as the afforestation efforts, which have been shown to influence the hydrological regime over similar time periods (Hughes et al. 2020).

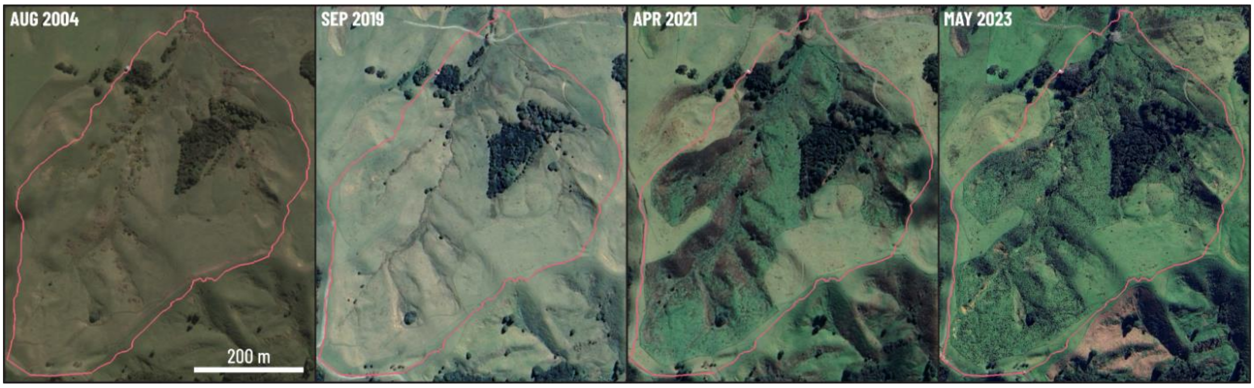

Figure 8. Revegetation of the catchment upstream of the Te Muri Stream site during the catchment-scale reforestation process to investigate the environmental impacts of farming practices on the stream. Map data: Google, Maxar Technologies or CNES/Airbus.

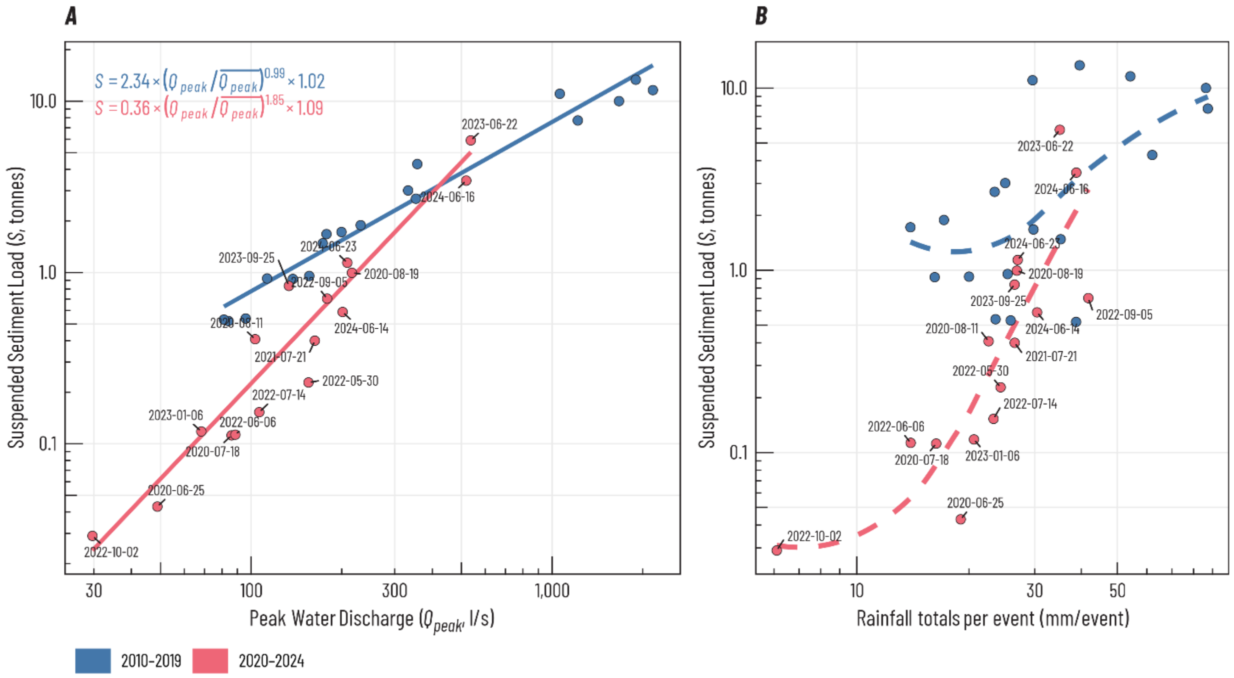

Figure 9. A: Sub-period sediment rating curves for Te Muri Stream 2010–2019 (blue) and 2020–2024 (red) site built using Eq. 14. Note that vertical offset has units of tonnes, and it is defined where the $Q_{peak}/\overline{Q_{peak}}$ is equal to 1, i.e. in the middle of the water discharge distribution. B: Relationship between total rainfall per event (based on rainfall station No. 645714) and event suspended sediment load; each dashed line represents a LOWESS regression line. Events of the 2020–2024 period are labelled.

6.2.4 Wairoa River

Figure 10 summarises sub-period SRCs and the relationship between rainfall events and event suspended sediment load. Exploratory data analysis revealed evidence that a possible SRC shift occurred around 2014–2016. A *t*-test determined there was no statistically significant difference in SRC slopes between the 2010–2014 and 2015–2024 periods (Appendix 3). However, an ANCOVA determined there was a statistically significant change in the vertical offset, from 124 during the 2010–2014 to 402 tonnes per event in 2015–2024 periods.

Apart from occasional forest harvesting in the southern part of the basin (in 2013, 2014, 2015 and 2022), we found no substantial changes in land use within the catchment during the period of interest. However, some data indicate that the average rainfall per event increased from 29.7 mm in 2014 to 47.2 mm in 2015–2024, with the five highest recorded rainfall events occurring between 2017 and 2019. A Wilcoxon rank-sum test confirmed a statistically significant difference in rainfall means (p-value = 0.02).

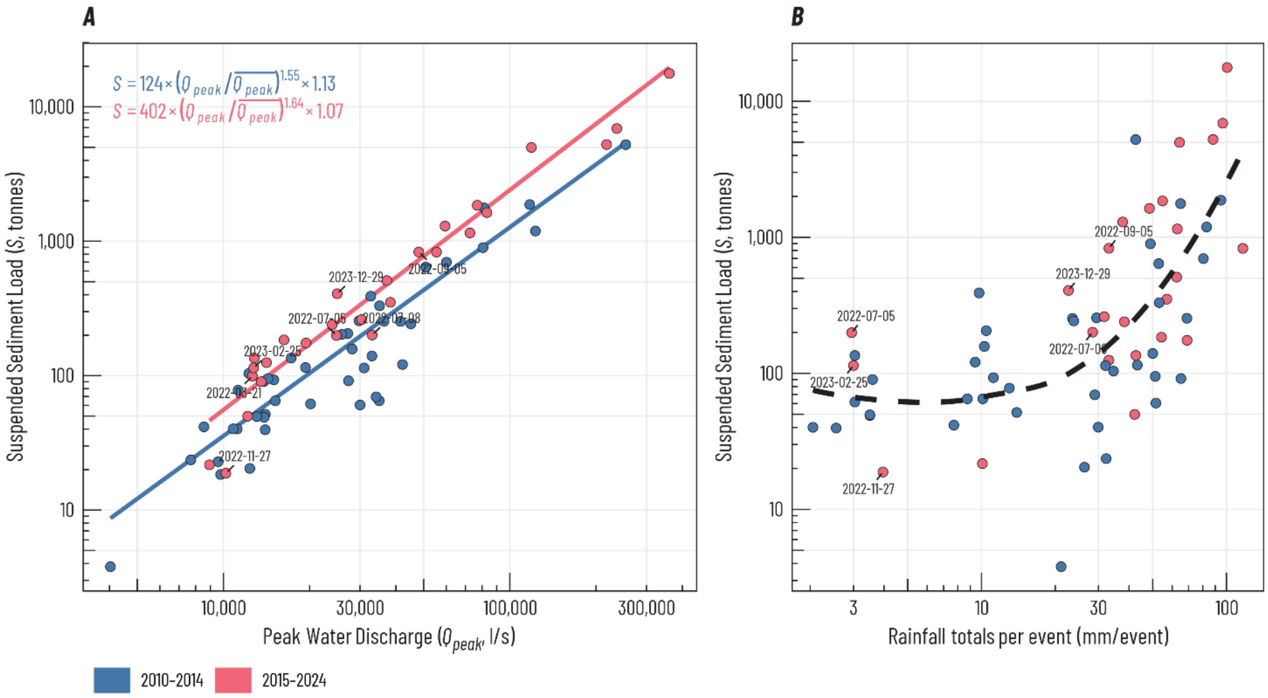

Figure 10. A: Sub-period sediment rating curves for Wairoa River site 2010–2014 (blue) and 2015–2024 (red) built using Eq. 14. Note that vertical offset has units of tonnes, and it is defined where the $Q_{peak}/\overline{Q_{peak}}$ is equal to 1, i.e. in the middle of the water discharge distribution. B: Relationship between total rainfall per event (based on rainfall station No. 750010) and event suspended sediment load; the dashed line represents a LOWESS line. Events of 2022 and 2023 calendar years are labelled.

6.2.5 Kaipara River

A statistically significant shift in the sediment rating was observed at the Kaipara River site between the periods 2012–2017 and 2018–2024 (Figure 11). The location of the break point is informed by the trend in event SRC residuals (see Appendix 2, Figure A2.3B). Differences in observed mean peak water discharges (20,879 vs. 19,629 L/s) and rainfall sums per event (32.3 mm vs. 37.7 mm) for the two periods were not statistically significant (Wilcoxon rank sum p-value >0.4 for both). A t-test confirmed a significant difference between the regression slopes of the 2012–2017 and 2018–2024 models, with the slope decreasing from 2.06 to 1.35 (see Appendix 3). An ANCOVA also indicated a significant difference in the vertical offset parameters, which reduced by 25% between 2012–2017 and 2018–2024 periods (from 206 to 149 tonnes per event). As a result, the 2018–2024 SRC predicts lower suspended sediment yields for discharges over 14,500 L/s compared to the 2012–2017 SRC. For example, an event with a peak water discharge of 50,000 L/s would be estimated to produce 1,344 tonnes of suspended sediment during the 2012–2017 period, compared to 569 tonnes during the 2018–2024 period: this represents a 2.4-fold decrease.

We did not observe any substantial changes in land cover or land use in the catchment over the period of interest that were likely to cause the observed shift in rating. The only visible change in land cover between 2012 and 2024 was the occurrence of forest harvesting in the north-eastern part of the Kaipara River basin, covering approximately 4.6% of the catchment area over 6 years. The observed shift may relate to longer-term trends in the catchment regime, such as the effect of events preceding the monitoring period, or the effect of processes not observed in the satellite imagery.

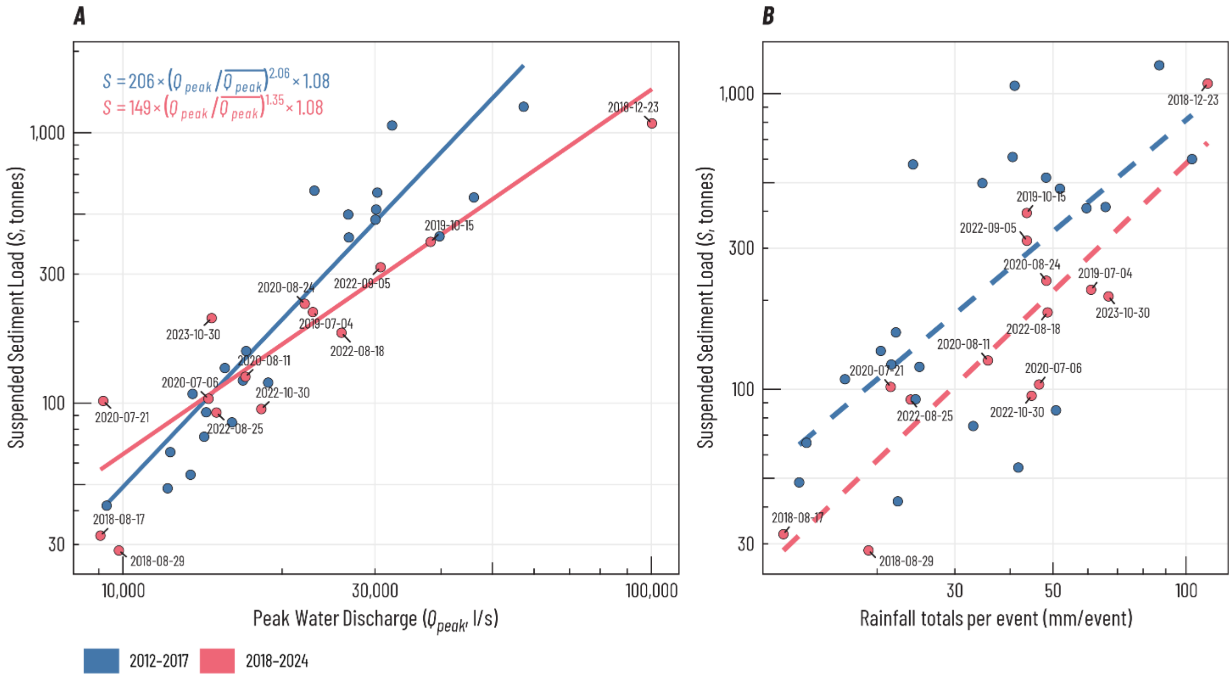

Figure 11. A: Sub-period sediment rating curves for the Kaipara River 2012–2017 (blue) and 2018–2024 (red) built using Eq. 14. Note that vertical offset has units of tonnes, and it is defined where the $Q_{peak}/\overline{Q_{peak}}$ is equal to 1, i.e. in the middle of the water discharge distribution. B: Relationship between rainfall sum per event (based on rainfall station No. 647510) and event suspended sediment load; the dashed lines represents linear regressions. Events of the 2018–2024 period are labelled.

6.2.6 Ōrewa Stream

A potential change in relationship between peak water discharge and event sediment load is observed at the Ōrewa Stream site between the 2009–2013 and 2014–2017 periods, with a second shift between the 2014-2017 and 2018-2024 periods

The 2014–2017 SRC has a vertical offset of 23 tonnes per event, exceeding the 2009–2013 and 2018–2024 values, and a lower slope of 1.27 (compared to 1.53 and 1.66 for 2009–2013 and 2018–2024, respectively). However, the differences in slope and offset among the SRCs are not statistically significant (see Appendix 3), indicating the differences are within the model uncertainties. Nevertheless, Figure 12 suggests that sediment loads were higher for equivalent discharges during the 2014–2017 interval, particularly for lower flows (below 3,000 L/s), when suspended sediment yield was 1.5 times greater for events with a similar peak water discharge than during the 2009–2013 or 2018–2024 periods. This temporary shift may contribute to overestimation of the total suspended sediment yield for the monitoring period by the long-term sediment rating curve (2009–2024) (Figure A2.9B).

Satellite imagery indicates the 2014–2017 period aligns with the construction phase of the Wainui Golf Course[8] in the headwaters of the Ōrewa catchment (see Figure 13). Subsequently, residential construction has been carried out on the eastern boundary of the golf course.

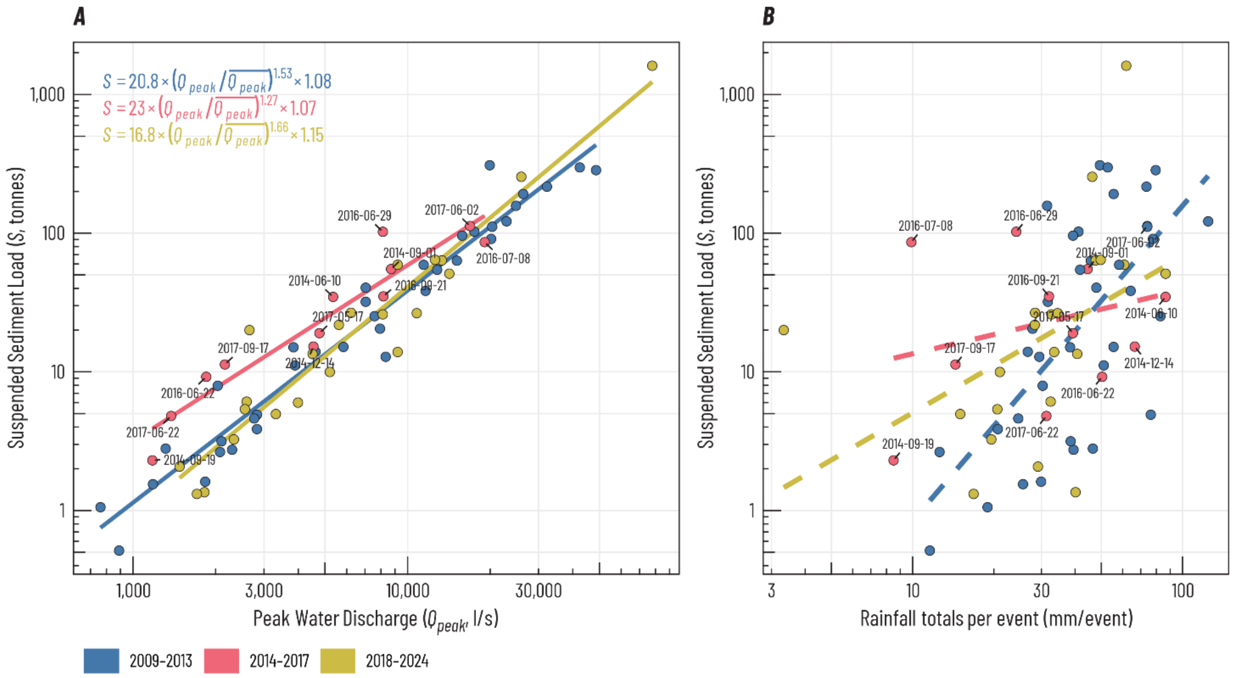

Figure 12. A: Sub-period sediment rating curves for Ōrewa Stream site 2009–2013 (blue), 2014–2017 (red) and 2018–2024 (gold) built using Eq. 14. Note that vertical offset has units of tonnes, and it is defined where the $Q_{peak}/\overline{Q_{peak}}$ is equal to 1, i.e. in the middle of the water discharge distribution. B: Relationship between rainfall sum per event (based on rainfall station No. 646619) and event suspended sediment load; each dashed line represents a linear regression line. Events of the 2014–2017 period are labelled.

[8] See: https://www.nzherald.co.nz/sport/golf/wainui-on-track-to-open-in-2016/2LEDYRZAFK756IWB4LMS7LGIEI/

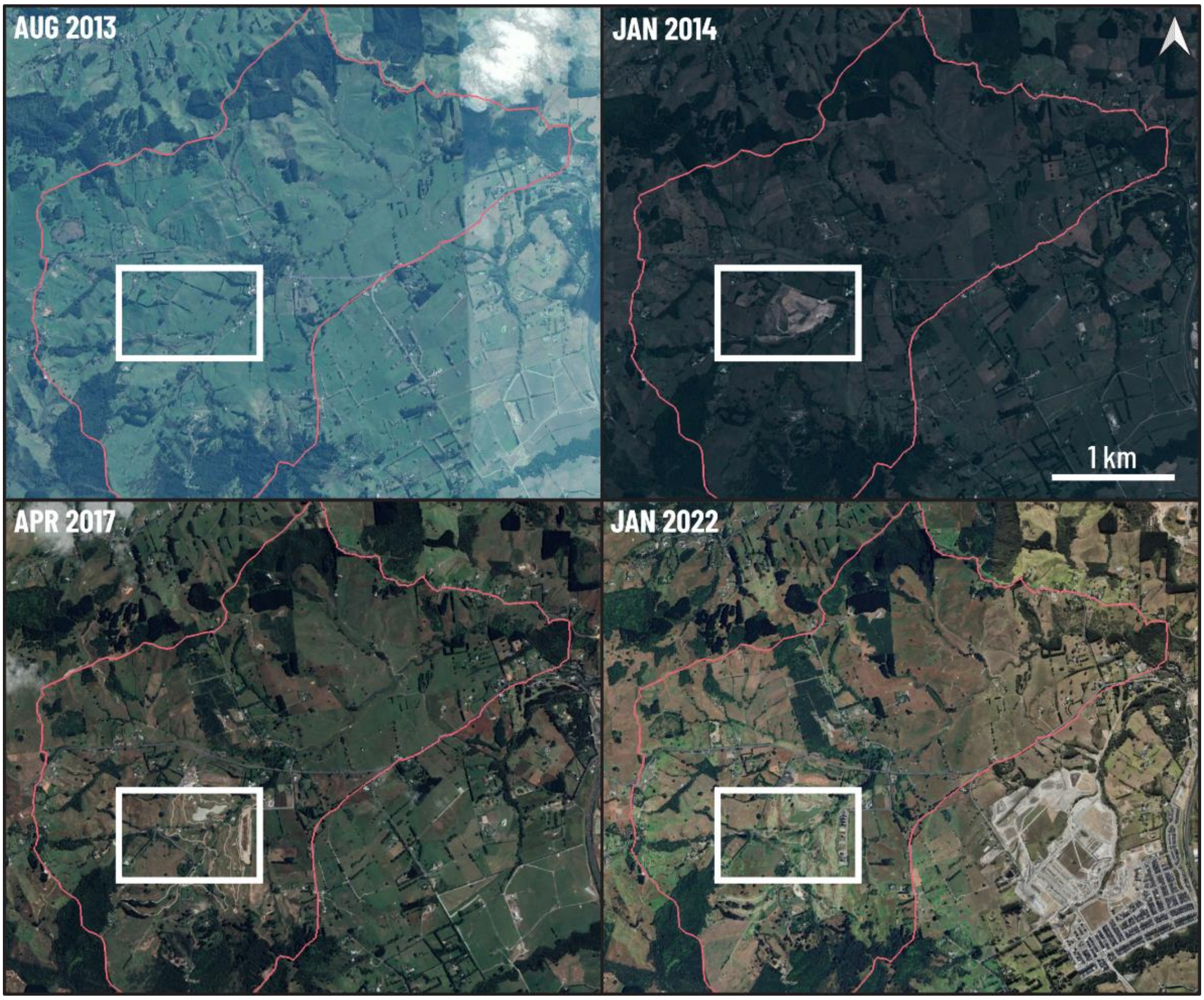

Figure 13. Construction of the golf course (white rectangles) in the Ōrewa Stream basin. Map data: Google, Maxar Technologies or CNES/Airbus.

6.2.7 Kōurawhero River

In addition to a very steep and statistically significant positive trend in SRC residuals (see Figure A2.17B), there is some visual evidence that the long-term SRC for the Kōurawhero River can be split into two time intervals: 2019–2022 and 2023–2024, as seen in Figure 14. However, both the *t*-test and ANCOVA suggest that differences between SRC slopes and vertical offsets are statistically insignificant (see Appendix 3). During the second period (2023–2024), the mean peak water discharge was 30% lower (3,854 L/s) than during the 2019–2022 period (5,797 L/s). However, this difference was not statistically significant in a Wilcoxon rank-sum test (p-value = 0.2). A shift in rating may become more apparent if the record is extended with future sampling. No substantial change in land cover was evident from satellite imagery for these periods.

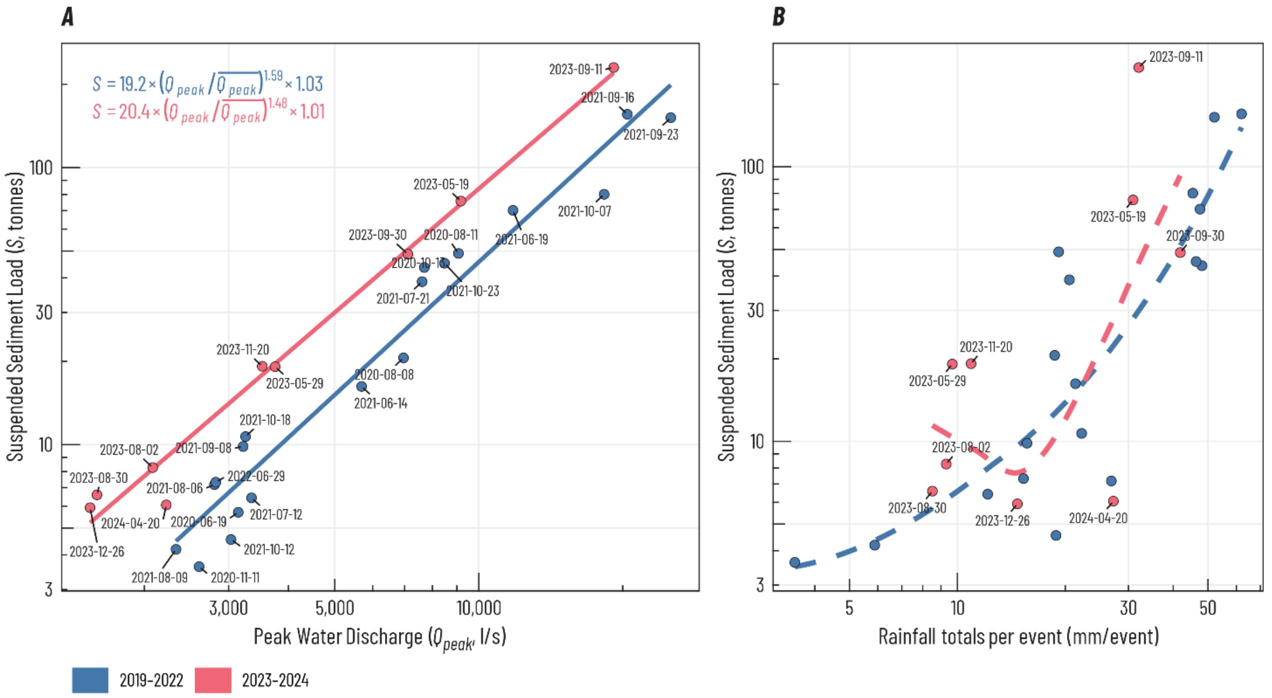

Figure 14. A: Sub-period sediment rating curves for Kōurawhero River site for 2019–2022 (blue) and 2023–2024 (red) built using Eq. 14. Note that vertical offset has units of tonnes, and it is defined where the $Q_{peak}/\overline{Q_{peak}}$ is equal to 1, i.e. in the middle of the water discharge distribution. B: Relationship between rainfall sum per event (based on rainfall station No. 643510) and event suspended sediment load; each dashed line represents a LOWESS line. Events of the 2023–2024 period are labelled.

6.2.8 Other sites

Only 15 well sampled single-peak events were available to develop the Mahurangi SRC. Given that the observation period spans only four years (2020–2024), the data were insufficient for identifying rating shifts.

The temporal distribution of the SRC residuals at the West Hoe Stream site was nearly constant (see Figures A2.13 and A2.14). Additionally, there were no significant land use changes visible from satellite imagery in the West Hoe Stream catchment, which remained undisturbed throughout the entire period from 2012 to 2024. Testing different sub-periods revealed no shift in SRC.

In contrary, the Hōteo River SRC's residuals were not distributed constantly through time (see Figures A2.1 and A2.2). Moreover, some forest clearings were visible in satellite images in the Hōteo River catchment at the start of the observation period (2011–2012), land cover remained largely stable afterward. However, no shift in SRC, nor clustering of data points were identified.

The Lower Vaughan Stream catchment is among the most urbanised areas examined in this report. Satellite image analysis shows that residential construction and development in the Long Bay suburb have been ongoing throughout the entire observation period (2012–present). However, no significant changes in the SRC were found, suggesting that any anthropogenic influence on the sediment yield was either absent or not captured during the storm event sampling campaign. This may reflect the 'Water Sensitive Design (WSD)' approach undertaken in Long Bay (an exemplary case study of integrated urban development and WSD), which includes management of sediment and water discharge (Ira 2022).

6.3 Suspended sediment yield

Figure 15 and Figure 16 together with Table 11 and Table 12 present the annual suspended sediment yields (SY) for the study catchments, covering all full calendar years of record, along with summary statistics describing annual variability. Consistent with previous studies from the Auckland region (Hicks et al. 2021), this study shows significant inter-annual variability in sediment yield.

Across all sites, the 2023 hydrological and calendar years recorded the highest average suspended sediment yields, averaging 28,246 and 26,110 t/yr, respectively. The 2023 year was one of the wettest years in the record (Rongen & Throssell 2024). However, at the smallest catchment, Te Muri Stream, the highest sediment yield was recorded in the 2017 calendar year, which across the whole region can be considered as a normal year, with an average of 20 days below MALF (Johnson 2021). The lowest sediment yield at the majority of sites (6 out of 11) was observed in the 2020 calendar year, the driest year for the last 50 years of record, with a regional average of 100 days below MALF (Johnson 2021).

The estimated annual suspended sediment yields across all sites show an overall increasing monotonic trend when aggregated by hydrological years, as at all sites apart from the Hōteo River and Lower Vaughan Stream, a positive Mann-Kendall trend was observed. On average, across those sites, yields increased by 3.1%/yr (see Table 11). Suspended sediment yield, aggregated by hydrological years, at the Hōteo River and Lower Vaughan Stream sites showed a monotonic non-significant decrease of −1%/yr and −5 %/yr, respectively. When aggregated by calendar year, yields at most rivers increased by 3.1%/yr on average, showing similar patterns to hydrological year aggregation. The exception was the Hōteo River, which showed a slightly positive non-significant trend of 1.1 %/yr, and Te Muri Stream, which showed a slightly negative trend of −0.8%/yr. However, none of the trends were statistically significant at the level of $\alpha = 0.05$, indicating that the observed changes could simply be due to random variation rather than a true monotonic trend.

The 3-year moving average revealed a peak in annual suspended sediment yield in 2019 at Te Muri Stream, Lower Vaughan Stream, and Mangemangeroa River, in contrast to the 2023 peak observed at other sites. This resulted from three consecutive hydrological years (2017–2019) with elevated SY. The lowest sediment yields were recorded during the 2020–2021 hydrological years (corresponding with significant drought periods (e.g., Johnson 2021)), showing consistency across the region. For the majority of sites, the 5-year moving average showed a relatively stable pattern with no or little change in annual sediment yields (see Figure 15). At the Kaukapakapa River, Ōrewa Stream, Wairoa River, and West Hoe Stream, the 2023 hydrological year was slightly increased compared to other 5-year windows. However, at the Kaipara River, the 5-year moving average revealed a twofold increase in sediment yield in the 2022-2023 hydrological years. At the Te Muri Stream, the 5-year moving average showed a noticeable decrease in annual totals over the full observation record.

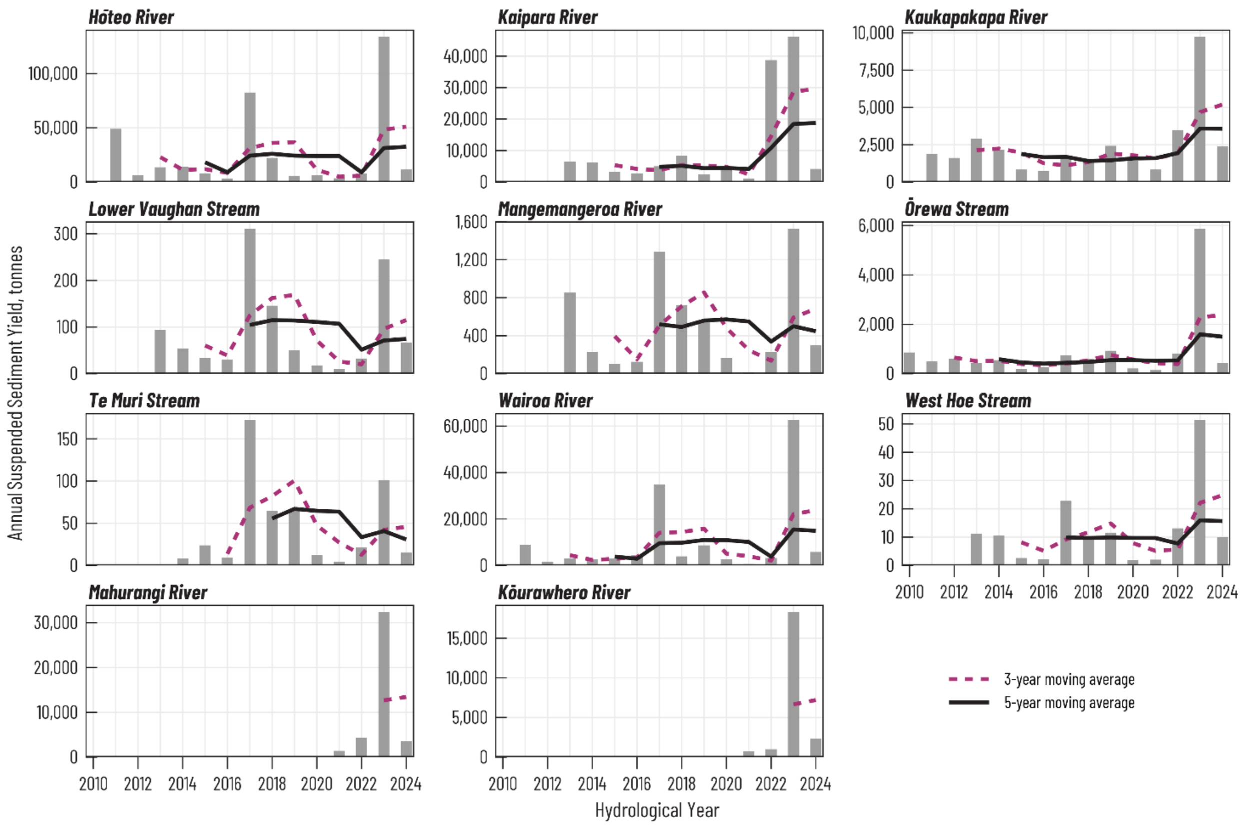

Figure 15. Inter-annual variability of suspended sediment yield estimated using event SRCs for hydrological years. The dashed and solid lines represent the 3-year and 5-year moving averages.

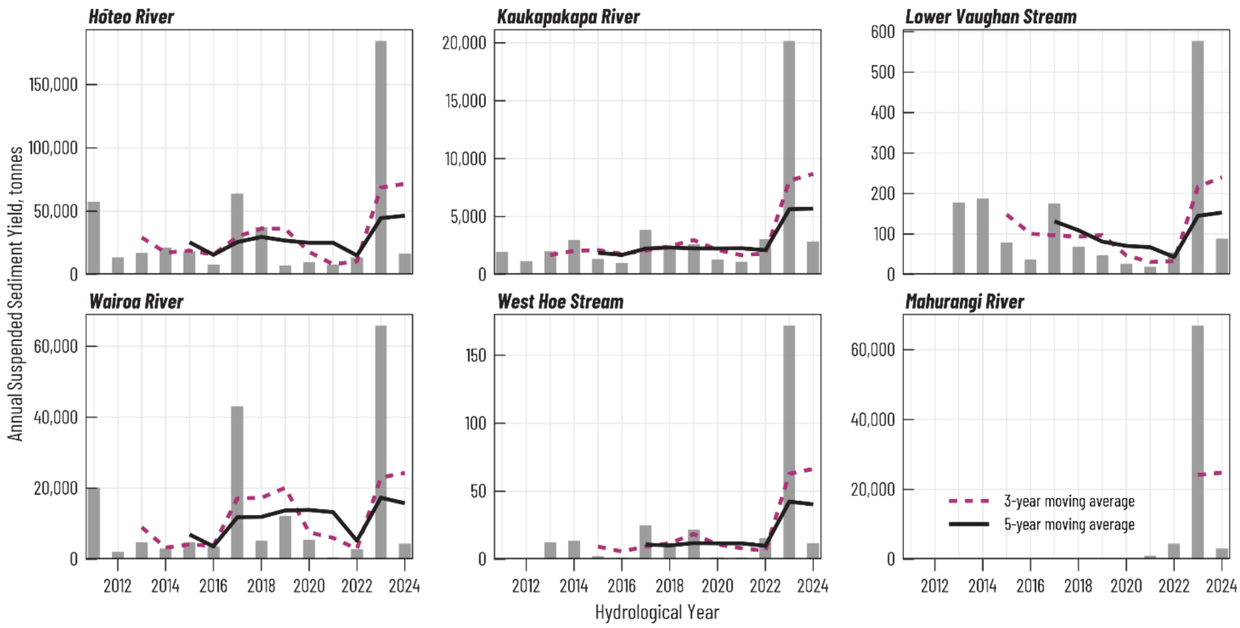

Figure 16. Inter-annual variability of suspended sediment yield estimated using discrete SRCs for hydrological years. The dashed and solid lines represent the 3-year and 5-year moving averages.

Table 11 (continued on following page). Estimated annual suspended sediment yields (tonnes) for rivers in the Auckland region reported for full calendar and hydrological years using event-based rating curves.

Year	Hōteo River		Kaipara River		Kaukapakapa River		Lower Vaughan Stream		Mangemangeroa River	
	Calendar	Hydrological	Calendar	Hydrological	Calendar	Hydrological	Calendar	Hydrological	Calendar	Hydrological
2010	–	–	–	–	–	–	–	–	–	–
2011	46,618	49,025	–	–	1,836	1,858	–	–	–	–
2012	13,340	6,164	5,217	–	2,948	1,625	103	–	742	–
2013	14,657	13,589	7,457	6,521	2,289	2,907	70.4	93.9	345	856
2014	10,003	13,939	3,944	6,239	1,294	2,190	35	54.2	193	226
2015	1,138	8,105	2,421	3,359	517	832	16.2	33.3	133	104
2016	48,740	3,188	3,733	2,837	873	757	149	29.7	239	127
2017	39,762	82,635	5,699	5,074	2,013	1,758	231	311	1,288	1,286
2018	23,997	22,252	7,111	8,292	3,116	1,508	141	146	1,047	718
2019	4,126	5,255	2,458	2,394	1,044	2,431	14.1	50.2	85.5	563
2020	5,090	6,172	2,328	3,768	924	1,449	12.1	17.6	94.2	164
2021	6,545	3,362	38,527	1,133	3,610	838	29.3	10.7	226	17.9
2022	23,649	7,865	4,481	38,719	2,632	3,486	53.5	32.8	238	229
2023	120,478	133,891	45,416	46,120	9,192	9,733	244	245	1,516	1,527
2024	–	11,405	–	4,163	–	2,377	–	67.3	–	297
Mean (t/yr)	27,549	26,203	10,733	10,718	2,484	2,411	91.5	91	512	510
Median (t/yr)	14,657	9,755	4,849	4,618	2,013	1,808	61.9	52.2	238	263
St. Dev. (t/yr)	32,266	38,031	14,763	15,020	2,236	2,251	82.9	95.9	505	494
MK Trend (%/ y) (p-value)	1.13 (1)	−1.01 (0.91)	3.45 (0.63)	1.5 (0.95)	6.78 (0.3)	3.31 (0.51)	−1.17 (0.95)	−5 (0.63)	0.7 (1)	1.26 (0.95)
Uncertainty (%)	11.2		28.8		9.6		6.64		4.8	
Proportion total sediment yield sampled (%)	42.3		24.1		55.6		45.9		54	
Proportion total sediment yield estimated from extrapolated curve (%)	19.7		63.3		30.7		24.2		18.5	

Note: Additional statistics include Mann-Kendall (MK) monotonic trend estimates, expressed as % change per year, and computed only for sites with at least four full measured years; St. Dev–standard deviation; overall uncertainty of assessment (see Eq. 8) and percent of sediment yield derived from extrapolation above the sampled range.

Table 11 continued

Year	Ōrewa Stream		Te Muri Stream		Wairoa River		West Hoe Stream		Mahurangi River		Kōurawhero River	
	Calendar	Hydrological	Calendar	Hydrological	Calendar	Hydrological	Calendar	Hydrological	Calendar	Hydrological	Calendar	Hydrological
2010	599	858	–	–	–	–	–	–	–	–	–	–
2011	608	504	–	–	8,756	8,932	–	–	–	–	–	–
2012	547	599	–	–	3,054	1,444	11.5	–	–	–	–	–
2013	630	430	–	–	1,350	2,870	13.2	11.2	–	–	–	–
2014	215	551	25.5	7.88	4,052	2,811	2.82	10.7	–	–	–	–
2015	188	202	4.92	23.8	3,648	2,978	1.22	2.63	–	–	–	–
2016	585	271	84.7	9.5	4,024	4,411	7.28	2.19	–	–	–	–
2017	613	760	140	172	35,143	34,793	19.9	22.8	–	–	–	–
2018	1,201	596	69	64.8	9,756	3,954	18.1	10.2	–	–	–	–
2019	168	926	25	65	2,431	8,715	1.91	11.6	–	–	–	–
2020	142	209	3.85	12.4	605	2,578	1.06	1.84	–	–	–	–
2021	823	140	18.5	4.1	3,130	559	9.48	2.02	2,477	1,371	898	702
2022	2,357	828	21.2	21.3	3,775	3,169	19.5	13.1	11,126	4,303	3,303	982
2023	3,900	5,875	91	101	63,738	62,481	40.2	51.3	25,489	32,381	17,104	18,306
2024	–	447	–	15.2	–	5,777	–	10.1	–	3,619	–	2,339
Mean (t/yr)	898	880	48.3	45.1	11,036	10,391	12.2	12.5	13,031	10,419	7,102	5,582
Median (t/yr)	604	551	25.2	21.3	3,775	3,561	10.5	10.4	11,126	3,961	3,303	1,660
St. Dev. (t/yr)	1,033	1,404	45.4	52.1	18,197	17,256	11.3	13.7	11,623	14,695	8,745	8,513
MK Trend in % per year (p-value)	4.78 (0.27)	0.26 (1)	-0.75 (0.86)	2.87 (0.76)	2.22 (0.76)	3.66 (0.44)	13.3 (0.45)	1.54 (0.95)	–	35.9 (0.73)	–	26.3 (0.31)
Uncertainty (%)	10.9		8.5		19.2		5.86		15.3		17.4	
Proportion total sediment yield sampled (%)	57.9		49		45		53.8		36.2		8.9	
Proportion total sediment yield estimated from extrapolated curve (%)	14		7.62		25.5		11.8		35.7		83.9	

Note: Additional statistics include Mann-Kendall (MK) monotonic trend estimates, expressed as % change per year, and computed only for sites with at least four full measured years; St. Dev–standard deviation; overall uncertainty of assessment (see Eq. 8) and percent of sediment yield derived from extrapolation above the sampled range.

Table 12. Estimated annual suspended sediment yields (tonnes) for rivers in the Auckland region reported for full hydrological years using discrete and event rating curves. Event-based estimates duplicate Table 11. MK – Mann-Kendall monotonic trend estimates, expressed as % change per year; St. Dev – standard deviation.

Hydrological year	Hōteo River		Kaukapakapa River		Mahurangi River		Lower Vaughan Stream		Wairoa River		West Hoe Stream	
	Discrete	Event	Discrete	Event	Discrete	Event	Discrete	Event	Discrete	Event	Discrete	Event
2010	–	–	–	–	–	–	–	–	–	–	–	–
2011	57,197	49,025	1,928	1,858	–	–	–	–	20,231	8,932	–	–
2012	13,593	6,164	1,129	1,625	–	–	–	–	2,076	1,444	–	–
2013	16,946	13,589	1,992	2,907	–	–	178	93.9	4,702	2,870	12.2	11.2
2014	21,346	13,939	3,011	2,190	–	–	188	54.2	2,992	2,811	13.4	10.7
2015	18,145	8,105	1,329	832	–	–	78.4	33.3	4,751	2,978	2.27	2.63
2016	7,749	3,188	988	757	–	–	36.2	29.7	3,593	4,411	1.23	2.19
2017	63,861	82,635	3,868	1,758	–	–	176	311	43,092	34,793	24.7	22.8
2018	37,211	22,252	2,470	1,508	–	–	68.4	146	5,154	3,954	9.26	10.2
2019	6,960	5,255	2,592	2,431	–	–	47.7	50.2	12,099	8,715	21.7	11.6
2020	9,446	6,172	1,286	1,449	–	–	25.7	17.6	5,424	2,578	1.4	1.84
2021	7,950	3,362	1,113	838	1,033	1,371	19.3	10.7	505	559	1.14	2.02
2022	13,521	7,865	3,029	3,486	4,446	4,303	54.5	32.8	2,755	3,169	15.6	13.1
2023	184,571	133,891	20,174	9,733	66,952	32,381	577	245	65,842	62,481	172	51.3
2024	16,789	11,405	2,848	2,377	3,004	3,619	88.2	67.3	4,354	5,777	11.7	10.1
Mean (t/yr)	33,949	26,203	3,411	2,411	18,859	10,419	128	91	12,684	10,391	23.9	12.5
Median (t/yr)	16,867	9,755	2,231	1,808	3,725	3,961	73.4	52.2	4,727	3,561	12	10.4
St. Dev. (t/yr)	46,943	38,031	4,905	2,251	32,093	14,695	154	95.9	18,911	17,256	47.3	13.7
MK Trend in % per year (p-value)	−1.29 (0.74)	−1.01 (0.91)	3.63 (0.23)	3.31 (0.51)	36.9 (0.73)	35.9 (0.73)	−6.4 (0.37)	−5 (0.63)	1.62 (0.74)	3.66 (0.44)	3.92 (0.84)	1.54 (0.95)

7 Discussion

7.1 Significant event years and SRC extrapolation

Event SRC extrapolation was required at all sites because the highest flow events were not sampled or were inadequately sampled. The extent of extrapolation varied by site (see Table 11), averaging 30% of the load being estimated by the extrapolated part of the rating curve across all sites. This means that, on average, 30% of the estimated sediment load occurs during high-flow conditions, where prediction accuracy is lower, and uncertainty is higher. Across all sites the average uncertainty was ±12.5%.

Hicks et al. (2021) reported a lower average uncertainty of ±5.3% for all Auckland region sites. However, it is important to note that during the reporting period of 2009–2019, on average 70% of the total yield had been sampled, while during the 2009–2024 period (i.e. the full record presented in the current report) only 43% of the total yield has been sampled on average across all sites (see site specific values at Table 11 and Figure 17). This reduced sampling between 2020–2024 may be attributed to a number of factors, including challenges related to sampling during COVID-19, and damage to sites during significant events in 2023 which resulted in samples being unusable due to flooding of the sensors or sensors not operating due to damage in prior events.

For example, at the Kōurawhero River, 8.9% of the total sediment yield has been measured, the rest has been estimated, with 83.9% of the total sediment yield estimated using extrapolation. At the Kaipara River, 24% of the total sediment yield has been sampled, resulting in uncertainty of ±28.8%, which is five times greater than the uncertainty of ±5.5% reported by Hicks et al. (2021) based on a record of 69% of the total sediment yield measured.

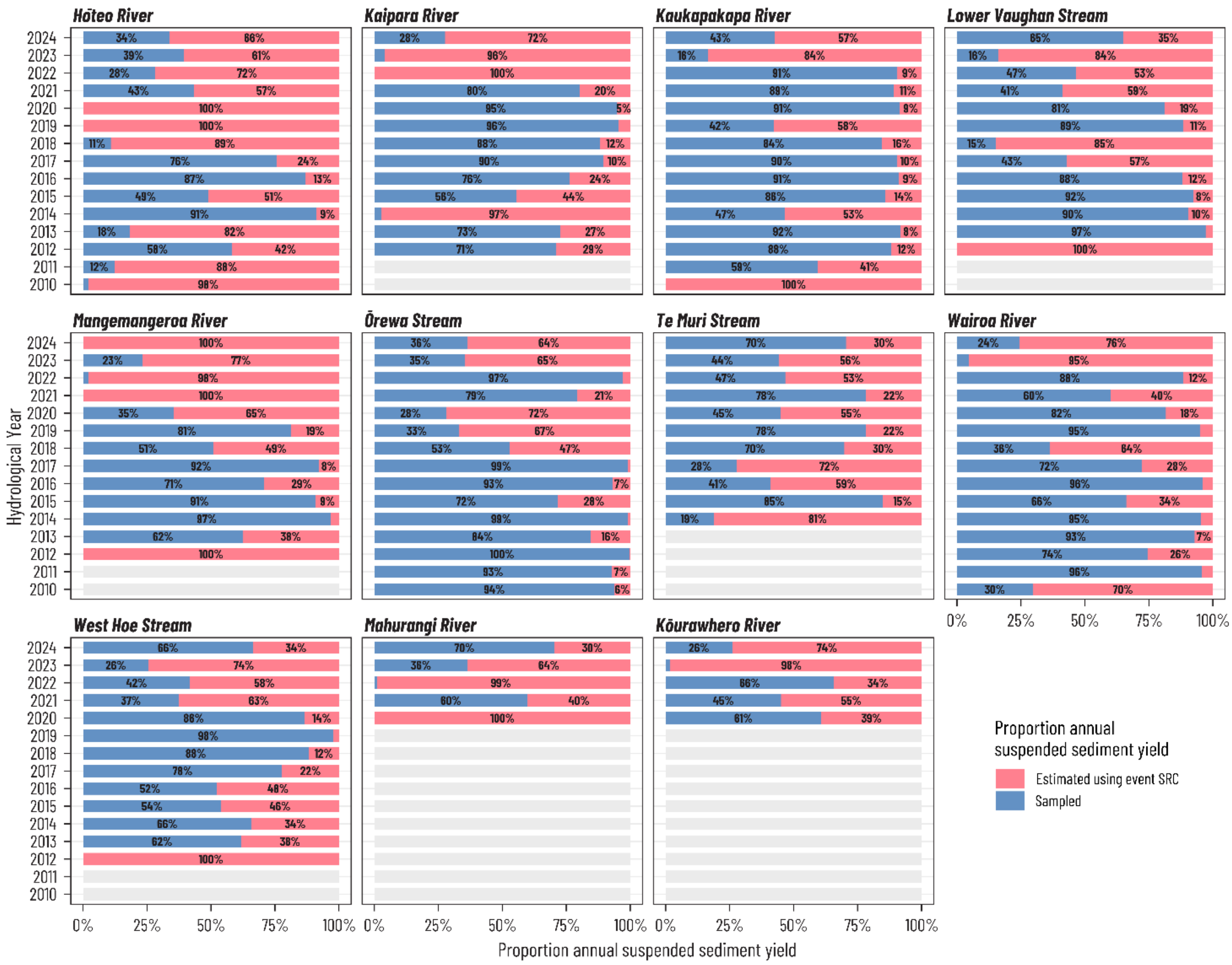

Figure 17. Proportion of annual suspended sediment yield sampled (blue) or estimated using event SRC (red).

The increased uncertainty (compared to Hicks et al. 2021) is also linked to the temporal distribution of the proportion of annual sediment yield sampled (see Figure 17). For example, during the 2020–2024 hydrological years at the Mangemangeroa River site, only 6.25% of the annual suspended sediment yield was measured, with the remainder estimated using event SRCs. We found that the early years of the event sampling campaign (e.g. before 2019) had better representation from sampled events compared to the 2020–2024 period. The average proportion of annual sediment yield sampled was 67% before 2019, whereas it dropped to 44% in the later period. Overall, 2023 was the least measured year, with only 22% of the annual sediment yield sampled. It is important to note that 2023 had the highest sediment yield of the past 15 years (Figure 15 and Table 11), and most of the sediment load estimated using SRCs was based on extrapolation. Most sites experienced challenges with sampling in 2023 due to floods inundating and damaging ISCO samplers (Figure 18). This resulted in samples needing to be discarded for major events, or in a number of cases, damaged the samplers which were non-operational for subsequent events.

Figure 18. Left image shows flood marks inside instrument shed at Kaukapakapa following Auckland Anniversary event in January 2023. Right image shows the instrument shed at Kōurawhero which was also flooded in the Auckland Anniversary event. Source: Photos provided by Auckland Council (EEMU) Hydrology team.

For example, at the Hōteo River site samples were collected for the first peak of the Auckland Anniversary event, but missed the recession and subsequent peaks. The instrument shed was inundated in Cyclone Gabrielle and samples were lost. At the Kaipara River site, the sampler was ripped out in the Auckland Anniversary event and no samples were collected, leaving the site non-operational during Cyclone Gabrielle. Similar issues occurred at the Kaukapakapa River, Kōurawhero River, Lower Vaughan Stream, Mahurangi River, Mangemangeroa River, Ōrewa Stream, and West Hoe Stream sites. The Auckland Anniversary event was not sampled at the Wairoa site due to the sampler not collecting for an unknown reason. Subsequently, the sampler ran out of bottles and only sampled the rising limb for the Cyclone Gabrielle event.

On the other hand, during the drought of the 2020 hydrological year (Johnson 2021), the sampled sediment yield on average accounted for 80% of the annual suspended sediment yield. However, at the Hōteo River and Mangemangeroa River sites, no samples were collected.

7.2 Comparison of sediment yield from event and discrete SRCs

Annual suspended sediment yields (SY) in this report were estimated using both the event SRC and discrete SRC methods (see Sections 5.3 and 5.4). While the temporal distribution of SY values followed similar trends, significant differences have been observed during the high-flow hydrological years of 2017 and 2023 (see Figure 19). Overall, sediment yields estimated using the discrete SRC were on average 1.66 times higher than those estimated with the event SRC for the same years with variation across the sites. For example, at the Hōteo River and Wairoa River sites, the sediment yield estimates were closely aligned, though the discrete SRC slightly overestimated values by between 10% and 20%. The most pronounced overestimations occurred at the West Hoe Stream (2.64 times higher) and the Mahurangi River (2.03 times higher).

The discrete SRC tended to overestimate actual SY due to a lack of water quality sampling effort during high-flow periods. This is evident in the results comparing sediment concentrations observed during storm events with those estimated from discrete sampling rating curves, with R^2 values ranging from 0.36–0.69 across sites. Both estimation approaches (event and discrete) required substantial extrapolation (see earlier discussion in Section 7.1). However, for the discrete SRC, only data collected during low-flow periods were available (see Table 4), necessitating greater extrapolation at higher discharge levels. For instance, at the West Hoe Stream site, the event SRC was fitted using 36 data points spanning discharges from 71 to 2,654 L/s (Table 6), whereas the discrete SRC relied on 129 points covering a much lower range of 1–107 L/s (Table 4). In both cases, the maximum recorded discharge exceeded 3,400 L/s. This meant that while the event SRC required extrapolation for 28% of the range, the discrete SRC had to extrapolate by 3,077%.

Given the limited water quality samples available, SY predictions using the discrete SRC method are highly prone to overestimation. To improve accuracy, additional sampling would be needed during hydrological events across different return periods. To overcome these limitations, continuous monitoring of SSC (suspended sediment concentration) could be undertaken using surrogate methods, such as turbidity or acoustic backscatter sensors calibrated with SSC samples, as recommended in the NEMS (Hicks et al. 2020). Such sensors provide the opportunity to continuously measure SSC across the full range of flows at a site, providing superior data to rating curves, provided sensors are well maintained and calibrated.

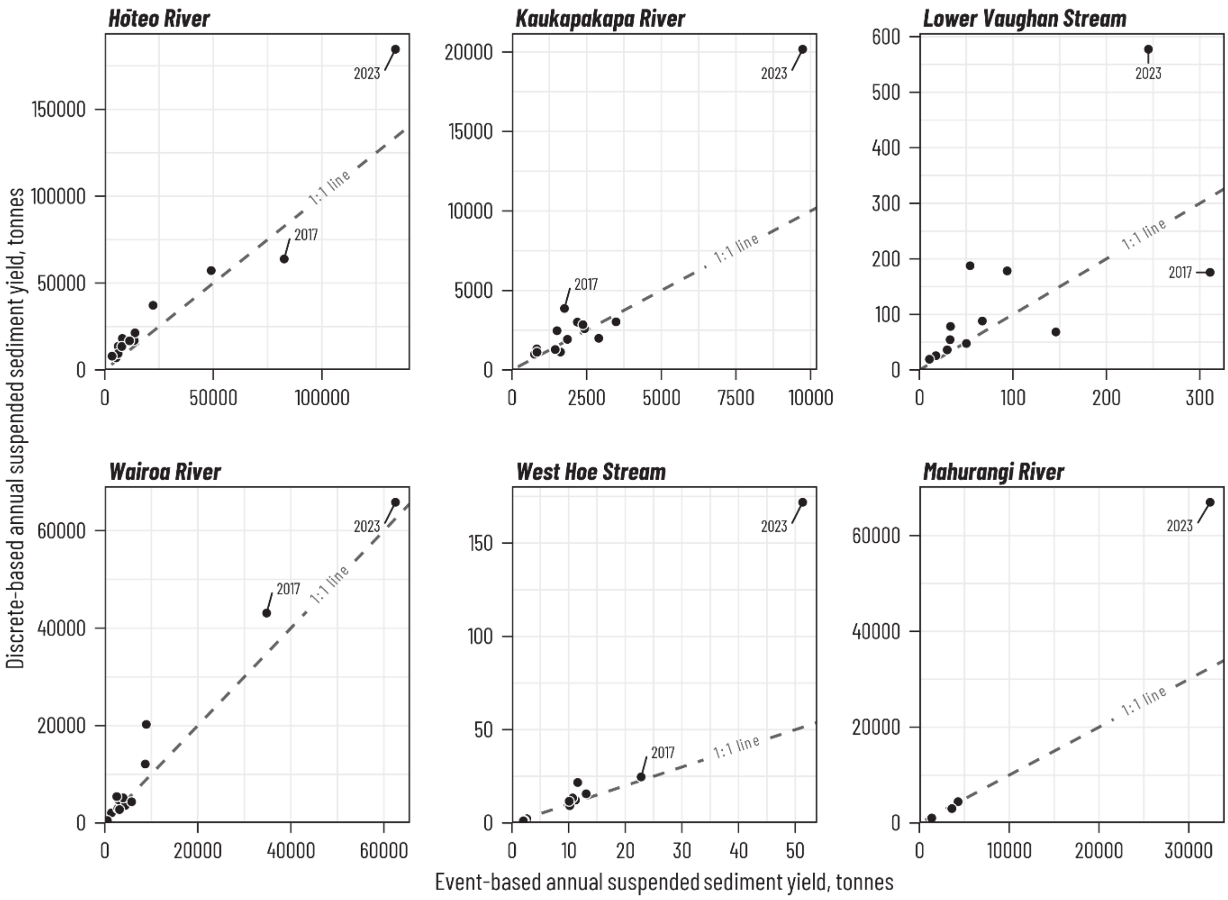

Figure 19. Scatterplots comparing estimated annual suspended sediment yield with event and discrete SRCs for hydrological years. The dashed line represents the 1:1 line.

7.3 Comparison of aggregation by calendar and hydrological years

The choice between calendar years and hydrological years for calculating annual totals affects how events are grouped, potentially influencing derived statistics – especially when significant events occur in close succession around the boundary between aggregation periods. A comparison of aggregating by calendar and hydrological year (Figure 20) suggests that summarising full records by calendar year tends to result in higher median sediment yield calculation compared to hydrological year aggregation. While differences in median values were noticeable for some rivers (Hōteo River, Kaipara River, Kaukapakapa River, and Wairoa River; see Figure 20), the Wilcoxon rank-sum test did not indicate any statistical significance at the $\alpha = 0.05$ level. The shift in medians is likely due to the reassignment of the July–September events to different cohorts, as the majority of sediment transport for the records occurs during high-flow events in these months (Figure 21).

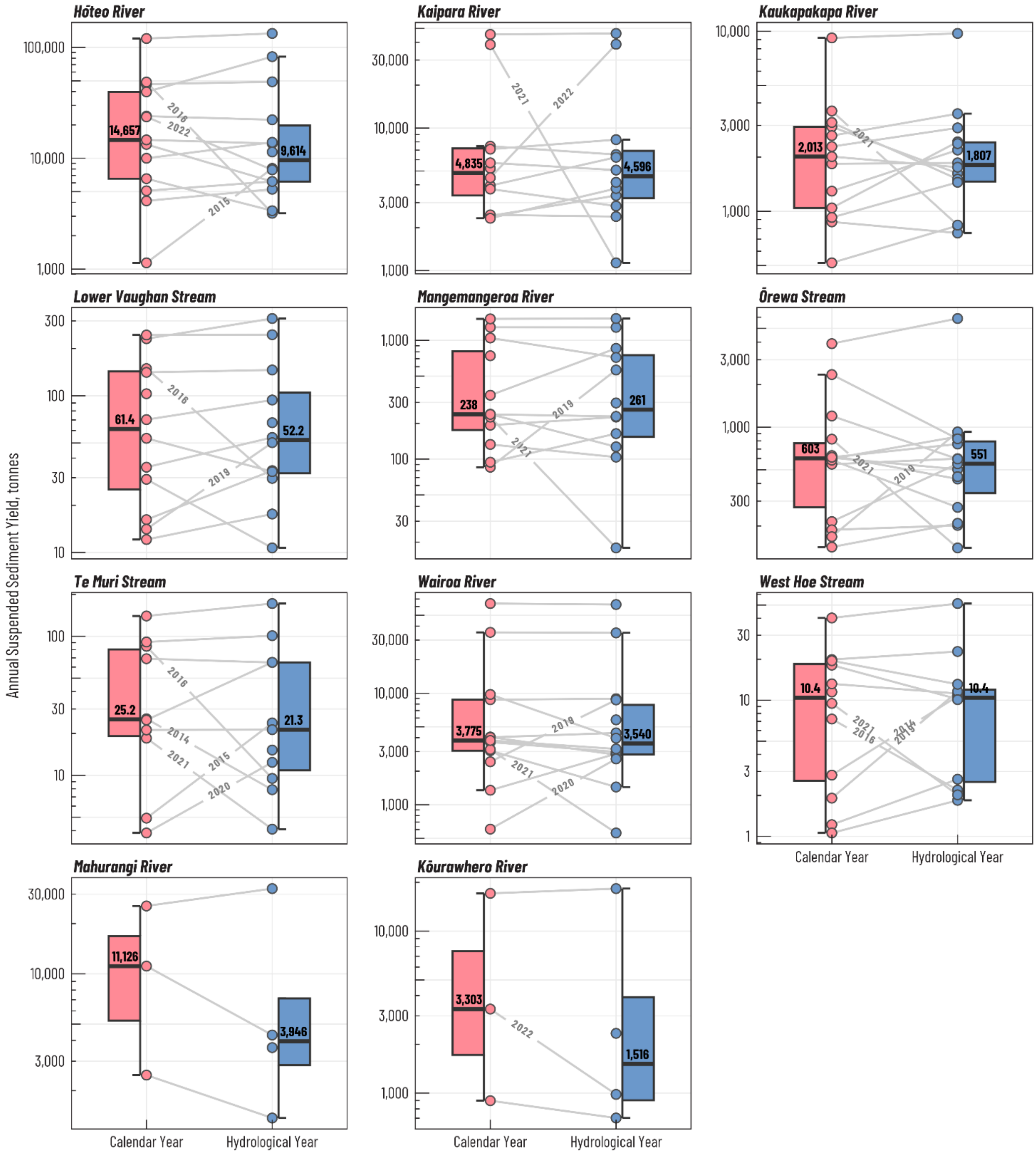

Figure 20. Event-based estimates of annual suspended sediment yields (tonnes) for calendar (red) and hydrological (blue) years. Year pairs with more than a twofold difference are labelled. The horizontal line inside the box represents the median (labelled in bold), At and the lower and upper hinges correspond to the 25th and 75th percentiles. Whiskers are 1.5 times the interquartile range from the hinge.

While neither the calendar year nor hydrological year aggregation approach is inherently incorrect, it may be preferable to select the one that best groups related or causally linked events together, such as where earlier rainfall or hydrological events may influence subsequent events. Intra-annual distribution of sediment yield across the eight sites with records spanning the 2012–2023 calendar years exhibits a bimodal distribution with two distinct peaks in February and August (Figure 21A).

However, the January–February peak is exclusively due to the exceptional 2023 year, with both the Auckland Anniversary Flood and Cyclone Gabrielle events occurring during January–February 2023. Excluding 2023 from the sample shows a more unimodal distribution, concentrated in March to September, with a peak in August (Figure 21B). A similar distribution is observed in the average number of hydrological events (both sampled and unsampled, see Section 5.5) per month; with a greater number of events typically occurring from May to September (Figure 21C). Calendar year aggregation is therefore more likely to group clusters of high-yield events together.

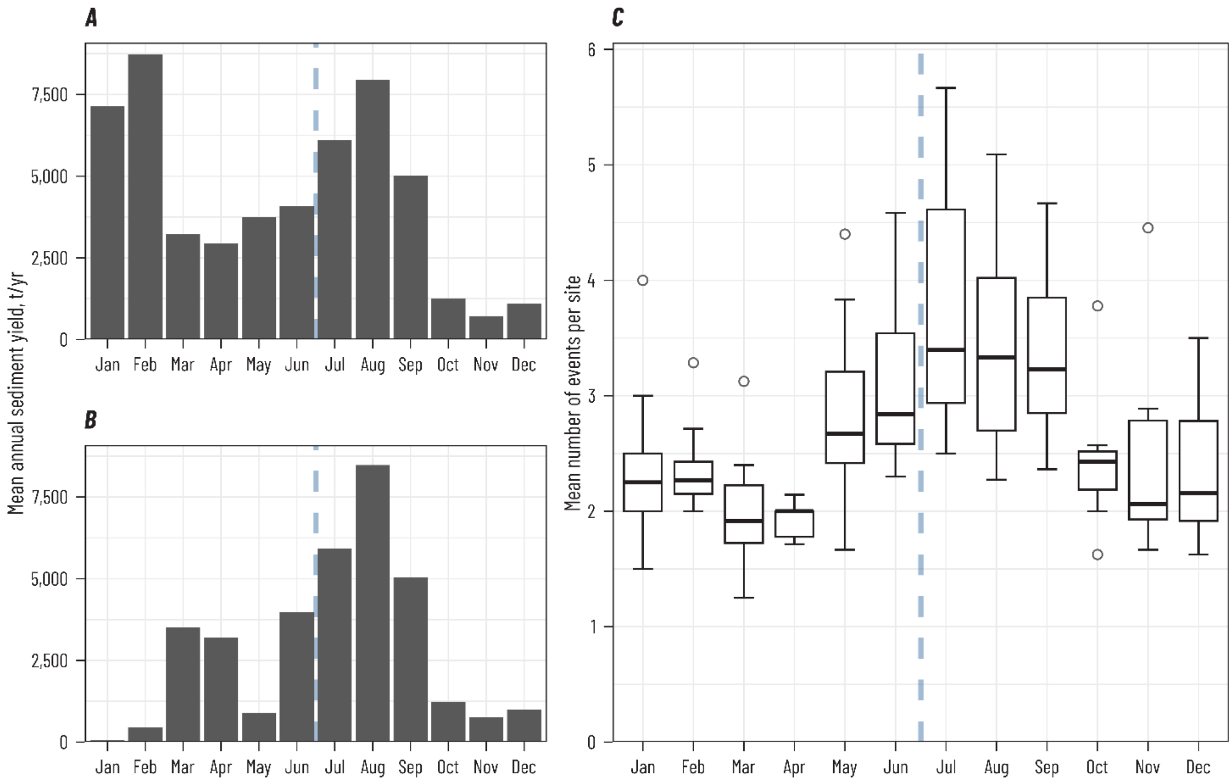

Figure 21. A: Distribution of mean annual sediment yield (t/yr) by month from eight sites (Hōteo River, Kaipara River, Kaukapakapa River, Mangemangeroa River, Ōrewa Stream, Lower Vaughan Stream, Wairoa River, West Hoe Stream) for the 2012–2023 period. B: Distribution of mean annual sediment yield (t/yr) from eight sites for the 2012–2022 period. C: Mean number of events per month per site (the same eight sites) across the region during the 2012–2023 period. Vertical dashed line separates the hydrological year boundary, which begin 1 July.

7.4 Spatial variation in sediment yields

Figure 22 illustrates the spatial variation in mean annual specific suspended sediment yield (SSY)across all eleven study sites. The SSY values are averaged over the entire monitoring period to June 2024, with record lengths varying by site, and classified using an arbitrary scale: low (<50 t/km^2/yr), medium (51–100 t/km^2/yr), high (101–150 t/km^2/yr), and very high (>150 t/km^2/yr), based on previous classifications (Hicks et al. 2021). However, it is important to note that the arbitrary class definitions are relative to the Auckland region only. The hill country catchments of the Mahurangi River, Te Muri Stream, and Mangemangeroa River sites fall into the regionally 'high' and 'very high' categories, while the mixed terrain and land cover catchments of the Hōteo River, Kōurawhero River, Ōrewa River, Kaipara River, and Wairoa River sites are classified as 'medium'. The remaining sites –Kaukapakapa River, West Hoe Stream, and Lower Vaughan Stream – which are primarily lowland or forested hill country catchments, are in the 'low' category.

Although the mean annual SSY estimates have changed (see Table 13) compared to the previous report by Hicks et al. (2021), site classifications remained the same, except for the Kaipara River and Ōrewa River sites which shifted from the low to the medium category. More significant changes appear when the SSY is estimated over the July 2020–June 2024 period. During this period, the SSY at the Te Muri Stream site decreased from 169 t/km^2/yr to 132 t/km^2/yr, meaning it was reclassified as 'low', while the SSY at Ōrewa River increased from 92 t/km^2/yr to 190 t/km^2/yr, moving it into the 'very high' category. This reflects differences in catchment states and hydrological regimes between the different record lengths, such as the catchment-wide reforestation effort in the Te Muri site catchment in the 2020–2024 period, and urban development since 2014 and significant flow events in 2023 in the Ōrewa River site catchment (discussed in Section 6.2). This highlights the sensitivity of such assessments to the length of the record used for deriving annual averages, with short periods introducing high uncertainty in mean annual estimates (Vanmaercke et al. 2012).

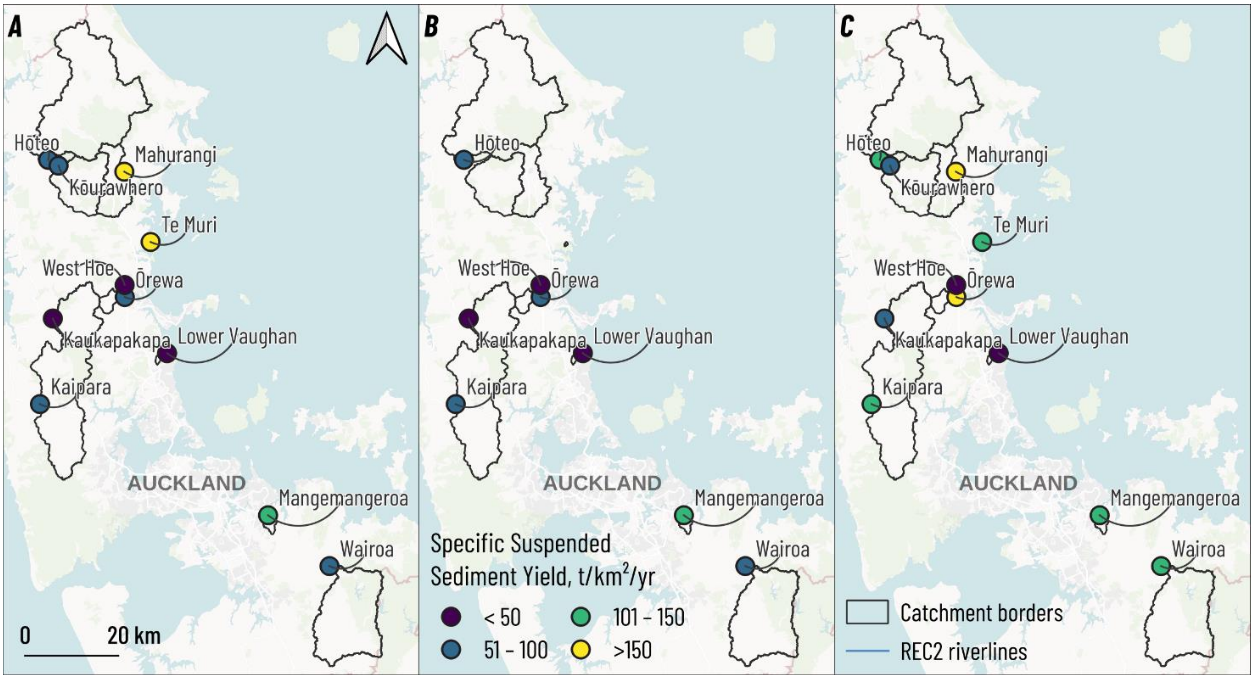

Figure 22. Spatial distribution of the mean annual specific suspended sediment yield (SSY, t/km^2/yr) across the Auckland region estimated for different periods using event sediment approach: A: Full record spanning from start of monitoring at each site to June 2024 (time spans therefore vary across sites). B: Time period from July 2012 to June 2024. C: Time period from July 2020 to June 2024. The specific sediment yield (SSY) classes are based on Hicks et al. (2021). Map data: Maptiler, OpenStreetMap contributors.

Table 13. Mean and standard deviation statistics of specific sediment yields (SSY, t/km^2/yr) in the Auckland region. St. Dev – standard deviation. For reference, previous SSY estimates by Hicks et al. (2021) are presented.

Site	Full record[a]			July 2012 – June 2024		July 2020 – June 2024		Previous estimates (Hicks et al. 2021)[b]		
	Range	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Range	Mean	St. Dev.
Hōteo River	2011-2024	97	141	96.2	149	145	234	2011–2019	81.5	66.5
Kaipara River	2013-2024	68.7	96.3	68.7	96.3	144	149	2012–2019	31.4	15.4
Kaukapakapa River	2011-2024	39.1	36.6	41	39.4	66.7	63.4	2011–2019	27.4	14.6
Lower Vaughan Stream	2013-2024	38.1	40.1	38.1	40.1	37.3	44.7	2012–2019	41.9	33.2
Mangemangeroa River	2013-2024	107	104	107	104	109	143	2012–2019	119.7	108.3
Ōrewa Stream	2010-2024	91.8	147	97.7	165	190	284	2010–2019	59.2	37.8
Te Muri Stream	2014-2024	169	195	—	—	132	165	2014–2019	172.4	127.8
Wairoa River	2011-2024	69.9	116	75.7	125	121	200	2011–2019	74.6	102.1
West Hoe Stream	2013-2024	23.5	25.7	23.5	25.7	36	41.3	2012–2019	18.9	14.8
Mahurangi River	2021-2024	221	311	—	—	221	311	—	—	—
Kōurawhero River	2021-2024	76	116	—	—	76	116	—	—	—

a Date range and yield statistics are for hydrological years.

b Date range and yield statistics are for calendar years.

7.5 Climate change impacts on erosion and sediment loads

Climate change impacts on erosion and sediment loads are expected to vary across catchments and regions, reflecting spatial differences in erosion processes and the magnitude and direction of change in their primary hydroclimatic drivers. Estimating the impacts of climate change on sediment loads therefore requires accounting for the range of erosion processes and their relative contributions to sediment loads across catchments and regions.

A range of erosion processes contribute to sediment loads in the Auckland region, including rainfall-induced shallow landslides, riverbank erosion, and surface (rill and sheet) erosion (Basher et al. 1997; Basher 2013; Hughes et al. 2021; Vale et al. 2022b; Smith et al. 2023). The extent and magnitude of these processes is primarily controlled by catchment attributes such as geology, terrain, land cover, and rainfall.

Shallow landslides are typically triggered by high-magnitude storm events (Reid & Page 2003; Smith et al. 2023). The contribution of landslides to catchment sediment loads is therefore expected to respond to changing magnitude-frequency of storms under future climate (Basher et al. 2020). Storm magnitude is expected to respond relative to changes in temperature, as the amount of precipitable water the atmosphere can hold increases per degree of warming (Carey-

Smith et al. 2018). Average air temperature is expected to increase in future climate scenarios across Auckland, likely resulting in increased storm activity and occurrence of shallow landslides.

Linear relationships have been illustrated between riverbank migration rates and discharge (Richard et al. 2005; Larsen et al. 2006; Nicoll & Hickin 2010; Hooke 2012, 2015). Riverbank erosion is therefore expected to change in relation to discharge under future climate. The mean annual flood (MAF) has been used to predict riverbank erosion in New Zealand (Dymond et al. 2016; Smith et al. 2019). While there is variation across climate models and scenarios, MAF is generally expected to increase under climate change in the Auckland region (Collins et al. 2018; Collins 2020), with variations across catchments.

Surface erosion rates are related to rainfall intensity (e.g. Basher et al. 1997), which has been found to relate to mean annual rainfall in New Zealand (Klik et al. 2015). Mean annual rainfall is anticipated to vary spatially across Auckland, and between climate scenarios, with patterns generally reflecting decreasing mean annual rainfall across the region, although increases may be expected in western areas. This means that the region may experience divergent directions of change in surface erosion rates.

To our knowledge, no regional assessment of future sediment loads considering the influence of different erosion processes and hydroclimatic drivers has been undertaken for the Auckland region. A national-scale estimate of the impacts of climate change on sediment loads was recently undertaken by Neverman et al. (2023). They estimated sediment loads delivered to the coast from the Auckland region may increase by 18% to 36% by mid-century (2040), and 14% to 75% by late century. Neverman et al. also predicted variations in sediment yield would vary spatially across Auckland under future climate conditions, with larger increases in areas of soft-rock hill country (i.e. in the Rodney and Franklin Wards), while yields in lowland areas tended to decrease by late century. These spatial variations are driven by differences in the dominant erosion processes in these domains, and divergent trends in their hydroclimatic drivers (e.g. increases in storm rainfall, while mean annual rainfall decreases).

It is important to note that Neverman et al. (2023) represented shallow landsliding only in soft-rock hill country, due to simplifications required for the modelling at a national-scale. However, storm-driven shallow landsliding also occurs in the hard-rock lithologies in the Auckland region and can be expected to increase under future climate. Neverman et al. (2023) may therefore have underestimated changes in sediment loads for catchments with hard-rock hill country in the Auckland region (such as in the Rodney, Franklin, and Waitākere Wards). Neverman et al. (2023) also did not differentiate between erosion process contributions to loads from urban areas, where changes in mean annual rainfall were used to estimate changes in load.

7.6 Differentiating between sediment sources for limit setting

Where sediment targets are not being met, erosion and sediment control practices and/or land management change are required to reduce erosion and sediment loads. The ability to achieve targets requires a sufficient proportion of the sediment load to be reduced through erosion and sediment control measures. Councils therefore require an understanding of the proportion of the sediment load derived from sources which could be reduced by mitigation measures, at locations where targets are set (i.e. SOE sites).

As presented in the current report, sediment monitoring data provides a means to quantify sediment loads from catchments, enabling assessment of baseline states, and tracking changes through time.

Sediment monitoring data can provide some information about sediment supply dynamics within a catchment but needs to be combined with other methods and information to give robust estimates of the contribution of erosion sources to sediment loads and to estimate the effects of mitigation efforts. For example, sediment fingerprinting has been applied to several catchments across New Zealand to estimate sediment source contributions, including in the Oroua River catchment, Manawatū (Vale et al. 2020), the Upper Mōtū catchment, Gisborne (Vale et al. 2021), and the Aroaro catchment, Auckland (Vale et al. 2022b). There is potential to apply sediment fingerprinting techniques to samples collected from sediment monitoring to identify temporal trends in sediment source dynamics (Vale et al. 2021), or use sediment monitoring data to support other sediment fingerprinting applications.

Such analyses can also be supported by modelling efforts to estimate the contribution of sediment sources to longer-term catchment sediment budgets. For example, Neverman and Smith (2023) used the SedNetNZ sediment budget model to identify the proportion of sediment load derived from un-mitigatable sources at SOE sites in the Taranaki region. They defined unmitigable sources as areas that would not typically be reduced by erosion mitigation measures. These are generally areas of natural land cover. Suspended sediment monitoring data, particularly long-term data, can be used to support such modelling efforts, including through calibration and validation. Modelling studies also allow for changes in sediment source contributions under future climate change and future mitigation scenarios to be estimated (Smith et al. 2022; Vale et al. 2022a; Neverman & Smith 2023; Vale & Smith 2024). This is useful for future catchment planning, as mitigation strategies may need to be altered for future conditions as the relative contribution of erosion sources changes.

8 Conclusions and recommendations

- We developed event-based sediment rating curves for 11 sites. For all models, the R^2 exceeded 0.8, and the CCC was above 0.9, indicating a strong model fit. Sediment rating residuals at four sites (Mangemangeroa River, Te Muri Stream, Wairoa River and Kōurawhero River) experienced significant temporal changes and required a time-trend adjustment of the sediment load estimates. Continued monitoring will be needed to identify future drift in the ratings.
- We developed rating curves from discrete water quality sampling data at six sites. Compared to event SRCs, discrete SRCs had lower model quality, with an average R^2 of 0.6 and a CCC of 0.68. At all sites except West Hoe Stream, manual adjustment of the rating extrapolation was required to obtain reasonable SSC estimates.
- Mean annual suspended sediment yields (SY) ranged from 12.5 to 26,203 t/yr across the monitoring sites from event-based rating curve estimates (for full hydrological years). Mean specific sediment yields (SSY) for the full records range from 23.5 to 221 t/km^2/yr, with the lowest values at West Hoe Stream, and highest at Mahurangi River. The Mahurangi River site also had the highest mean specific sediment yields for the July 2020 – June 2024 period. For the eight sites with data available for July 2012 to June 2024, estimated mean specific

sediment yields ranged from 23.5–107 at West Hoe Stream and Mangemangeroa River, respectively.

- Based on the classification used by Hicks et al. (2021), the Mahurangi River, Te Muri Stream, and Mangemangeroa River sites had 'high' and 'very high' average specific sediment yields over their monitoring periods, while the Hōteo River, Kōurawhero River, Ōrewa Stream, Kaipara River, and Wairoa River sites were classified as 'medium'. The remaining sites – Kaukapakapa River, West Hoe Stream, and Lower Vaughan Stream – have 'low' specific sediment yields.
- Changing from reporting by calendar year to hydrological year alters which events are aggregated together, influencing metrics such as annual totals, average annual yields, and year-to-year variability. This can also alter the perception of how variable annual yields are between sites. While neither approach is incorrect, it may be preferable to use the approach which groups periods with typically higher frequencies or magnitudes of events together, or which best groups events with prior hydrological events such as antecedent rainfall or high flows that may affect yields for subsequent events.
- During the reporting period of 2009–2019, an average of 70% of the total sediment yield has been sampled, while during the 2009–2024 period (i.e. the full record presented in the current report) only 43% of the total yield has been sampled on average. A number of factors contribute to the decreased sampling in the 2020–2024 period, including challenges related to COVID-19, and damage to sensors and loss of samples during the significant events of 2023. This has contributed to greater uncertainty in estimated yields, compounded by 2023 containing the largest flows in most sites, requiring greater extrapolation of rating curves.
- Statistically significant shifts in the SRCs were observed at the Kaipara River, Kaukapakapa River, Mangemangeroa River, Te Muri Stream, and Wairoa River sites. At the Ōrewa and Kōurawhero sites, shifts were could be seen, but were not statistically significant.
- Overall, sediment yields estimated using the discrete SRC were on average 1.66 times higher than those estimated with the event SRC for the same years with variation across the sites. Comparison of sediment yields estimated from event-based and discrete monitoring programmes highlights the challenges of capturing data across the range of events experienced in these catchments. Continuous monitoring methods, such as turbidity sensors, offer the potential to continuously monitor sediment loads and reduce the uncertainty in long-term sediment yield estimates produced by rating curve methods, provided they are adequately maintained and calibrated.
- The impact of future climate change on erosion and sediment loads is expected to vary spatially across the Auckland region, driven by divergent trajectories for surface erosion, riverbank erosion, and shallow landslides. The net effect on sediment loads will reflect the relative contribution of these erosion processes to catchment loads. Neverman et al. (2023) estimated climate change may increase sediment loads delivered to the coast by 14% to 75% by late century.
- Data from the sediment monitoring program can be used in combination with other methods, including sediment source fingerprinting and sediment budget modelling, to estimate the contribution of erosion sources to sediment loads to support catchment and regional planning efforts.

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Appendix 1 – Missing data infill

When the missing gaps where identified, Auckland Council provided either a peak water discharge estimate based on the measured water stage at the site, or an infill estimate based on the peak stage of a neighbouring site, using relationships from overlapping records. Equations used for infilling are listed below.

Table 14. Summary of the infill peak water discharges provided for missing events estimated based on the peak water stage during the missing event. If the equation is present, then the peak water stage (y, m) was first estimated from the neighbouring site peak water stage (x, m).

Site	Start	End	Neighbour site ID	Peak Stage at Neighbour	Date of peak stage	Equation used for peak stage	Estimated peak stage for site	Estimated peak discharge for site
Hōteo River	18-08-12	20-08-12	45705	3.59	20-08-12	$y = 1.159 \cdot x + 0.251$	4.4	64.3
	29-12-13	30-12-13	45705	2.12	29-12-13		2.7	32.6
Kaipara River	06-12-12	07-12-12	—	—	—	—	4.5	10.0
Kaukapakapa River	27-06-14	28-06-14	—	—	—	—	2.0	5.2
Lower Vaughan Stream	29-12-13	30-12-13	7516	0.15	29-12-13	$y = 2.527 \cdot x + 0.373$	0.8	0.1
Te Muri Stream	12-04-17	13-04-17	—	—	—	—	1.0	1.7
	04-07-19	05-07-19	7206	0.97	04-07-19	$y = 0.366 \cdot x + 0.132$	0.5	0.2
West Hoe Stream	27-06-16	30-06-16	7202	1.56	30-06-16	$y = 0.742 \cdot x - 0.632$	0.5	0.1
Kōurawhero River	25-05-24	27-05-24	—	—	—	—	1.2	1.3
	28-05-24	01-06-24	—	—	—	—	1.6	2.7
	20-05-24	23-05-24	—	—	—	—	1.8	3.1
	10-06-24	12-06-24	—	—	—	—	1.7	3.0
	14-06-24	22-06-24	45703	4.59	18-06-24	$y = 0.862 \cdot x - 0.145$	3.8	26.2
	23-06-24	26-06-24	—	—	—	—	1.8	3.1
	02-07-24	03-07-24	—	—	—	—	1.4	1.8

Appendix 2 – Sediment Rating Curves

Hōteo River

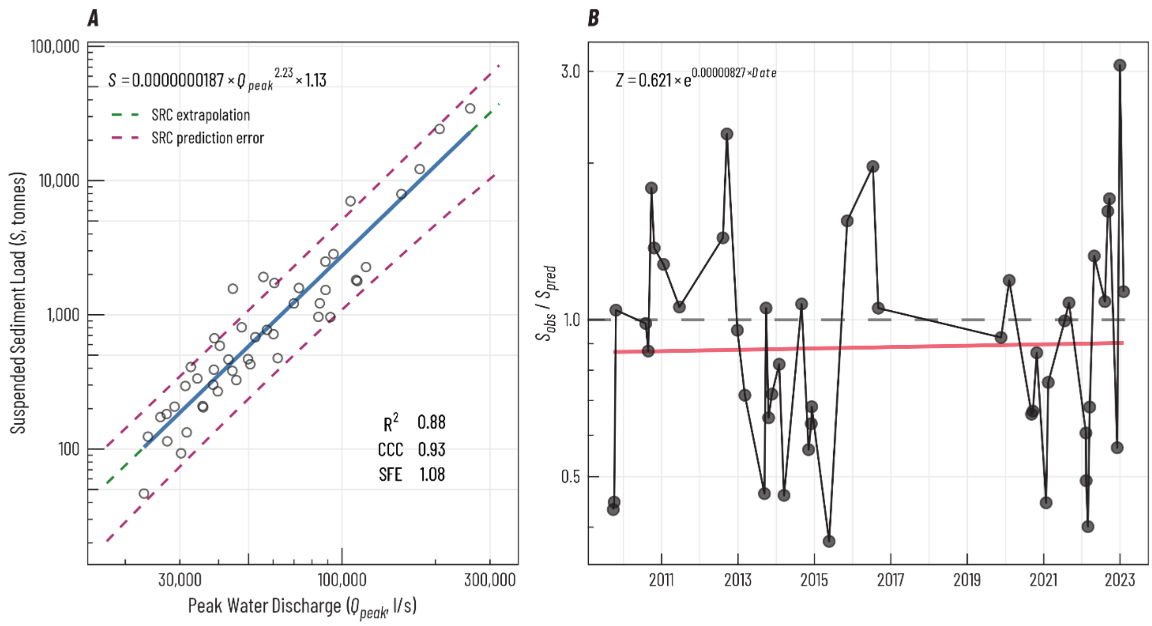

Figure A2.1. Suspended sediment event rating curve derived from 47 measurements taken at the Hōteo River (site No. 45703) for the calendar years 2010–2024. A: Relationship between event suspended sediment load and peak event water discharge on a $\log_{10}$ scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error. B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

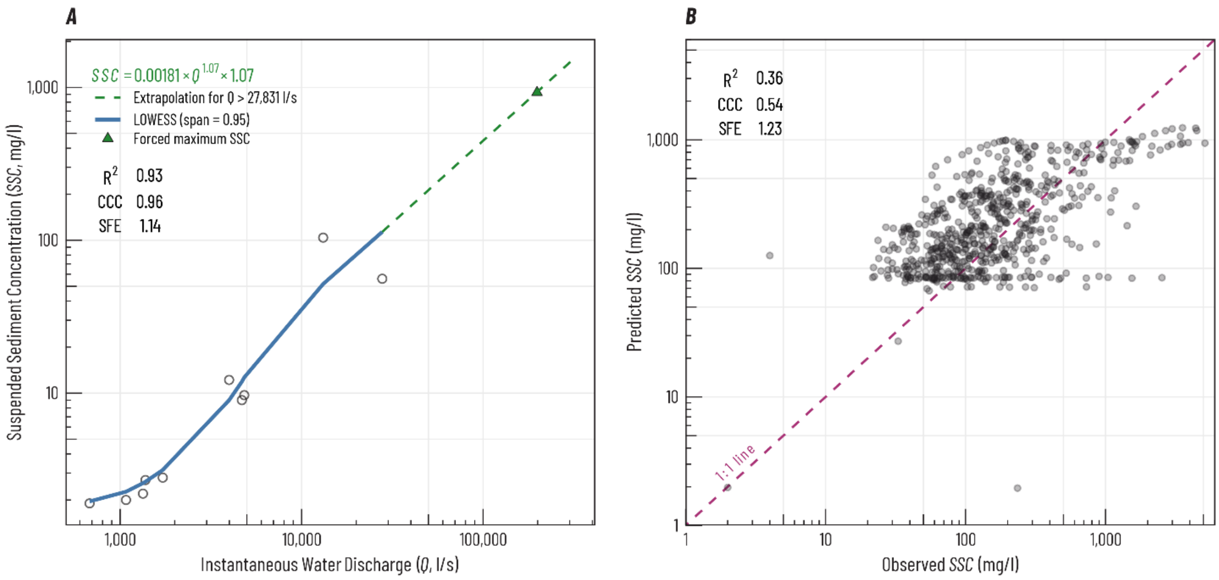

Figure 23. Discrete sampling sediment rating curve for the Hōteo River. A: Relationship between SSC and instantaneous water discharge on a $\log_{10}$ scale. The solid blue line indicates the fitted LOWESS model, while the green dashed line represents a linear extrapolation to the maximum known water discharge at the site. B: Independent validation of the discrete sampling rating curve with measured suspended sediment concentration during the storm event sampling.

Kaipara River

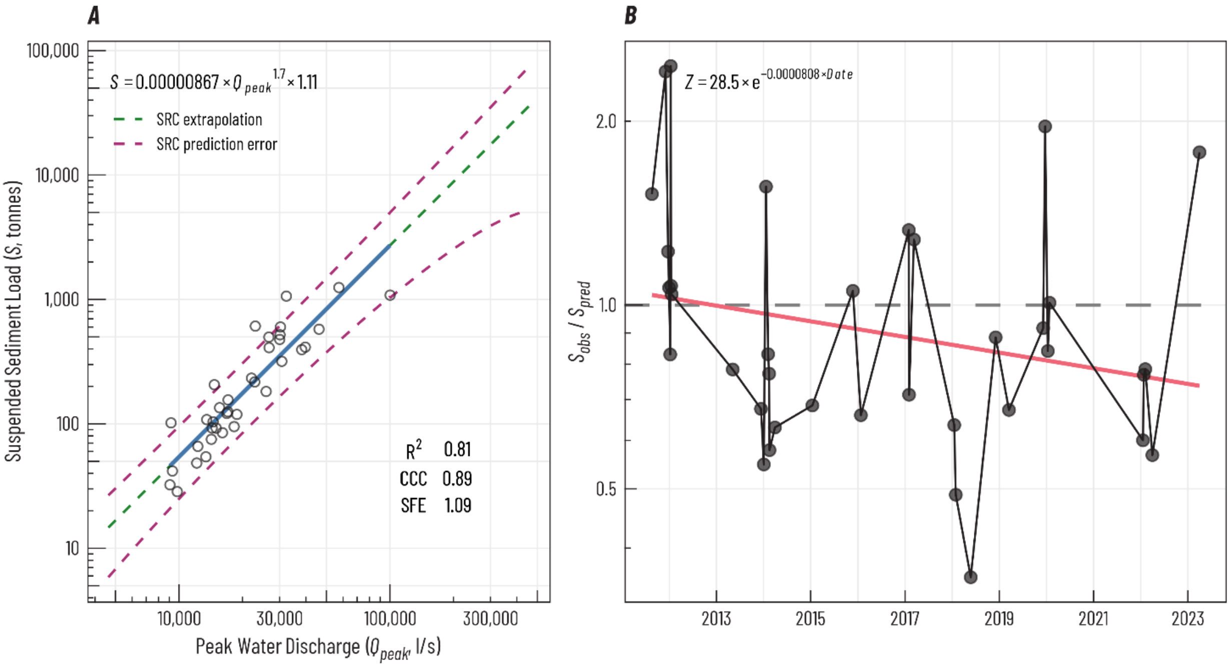

Figure A2.3. Suspended sediment event rating curve derived from 36 measurements taken at the Kaipara River (site No. 45311) for the calendar years 2012–2024. A: Relationship between event suspended sediment load and peak event water discharge on a $\log_{10}$ scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error. B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

Kaukapakapa River

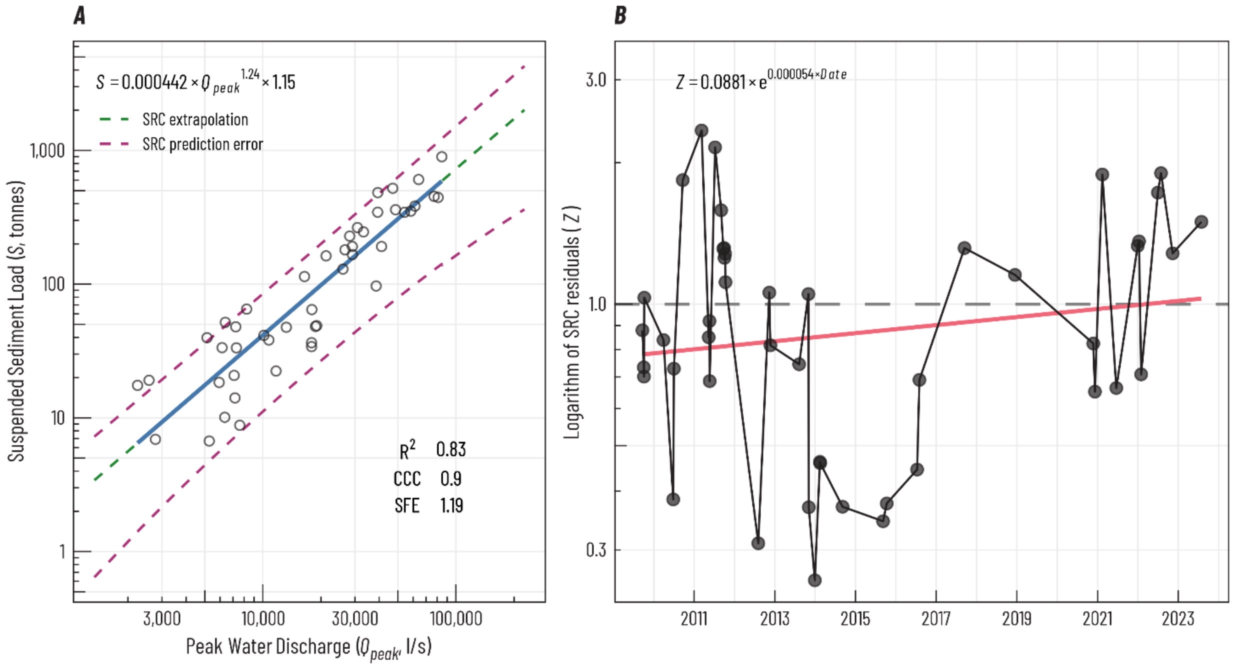

Figure A2.4. Suspended sediment event rating curve derived from 46 measurements taken at the Kaukapakapa River (site No. 45415) for the calendar years 2010–2024. A: Relationship between event suspended sediment load and peak event water discharge on a $\log_{10}$ scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error. B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

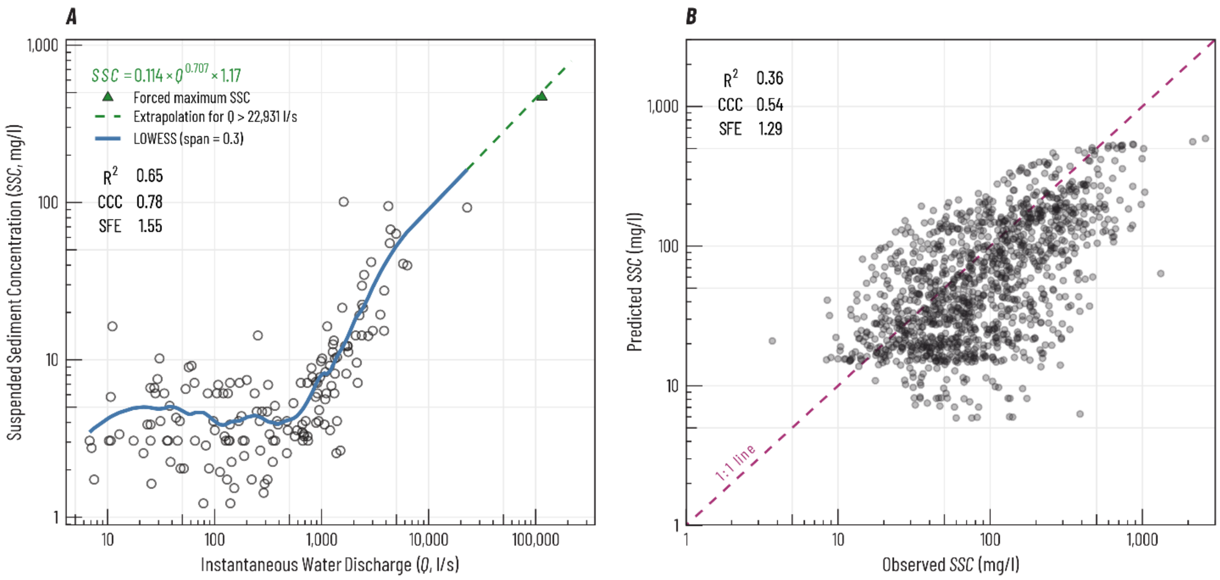

Figure 24. Discrete sampling sediment rating curve for the Kaukapakapa River. A: Relationship between TSS and instantaneous water discharge on a $\log_{10}$ scale. The blue line indicates the fitted LOWESS model, while the green dashed line represents a linear extrapolation to the maximum known water discharge at the site. B: Independent validation of the discrete sampling rating curve with measured suspended sediment concentration during the storm event sampling.

Lower Vaughan Stream

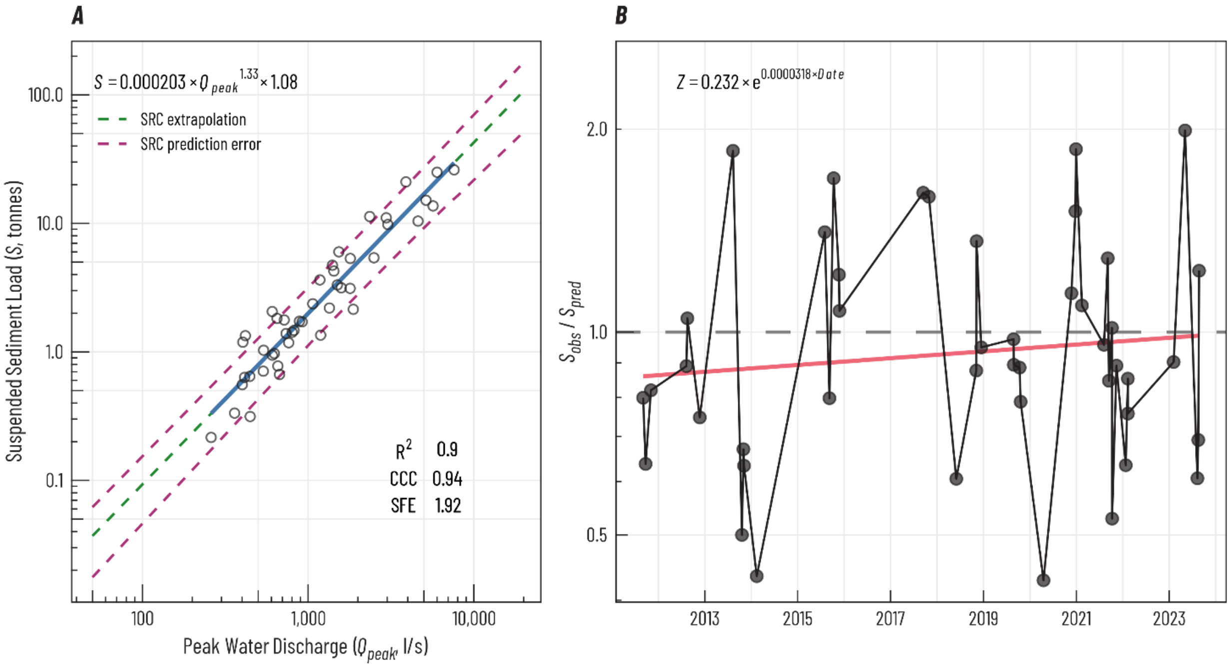

Figure 25. Suspended sediment event rating curve derived from 45 measurements taken at the Lower Vaughan Stream (site No. 7506) for the calendar years 2012–2024. A: Relationship between event suspended sediment load and peak event water discharge on a $\log_{10}$ scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error. B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

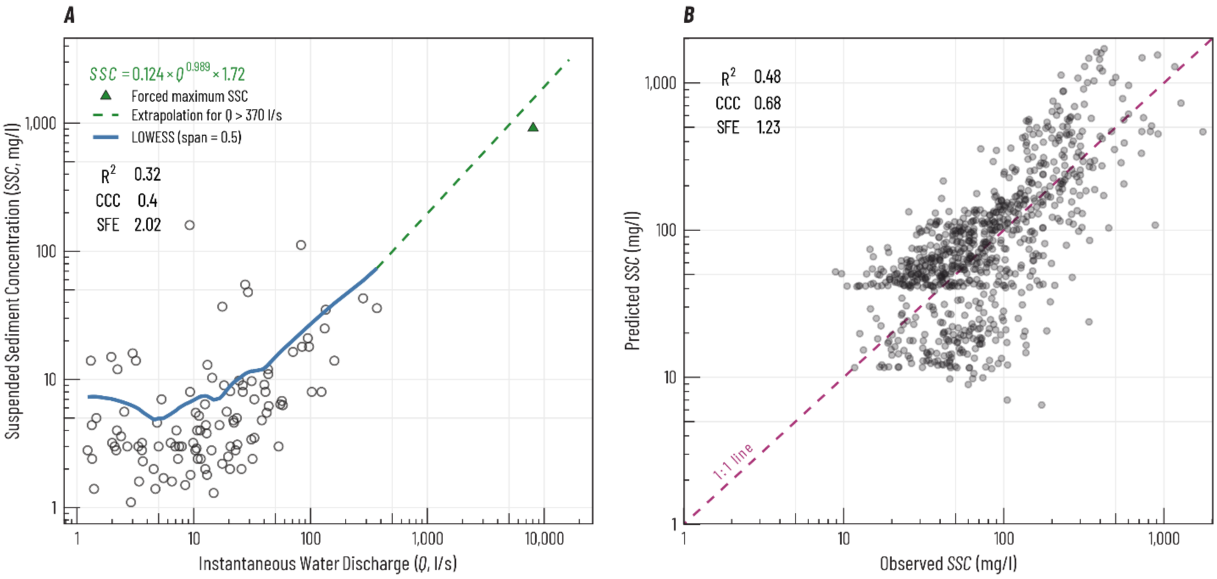

Figure A2.7. Discrete sampling sediment rating curve for the Lower Vaughan Stream. A: Relationship between SSC and instantaneous water discharge on a $\log_{10}$ scale. The blue line indicates the fitted LOWESS model, while the green dashed line represents a linear extrapolation to the maximum known water discharge at the site. B: Independent validation of the discrete sampling rating curve with measured suspended sediment concentration during the storm event sampling.

Mangemangeroa River

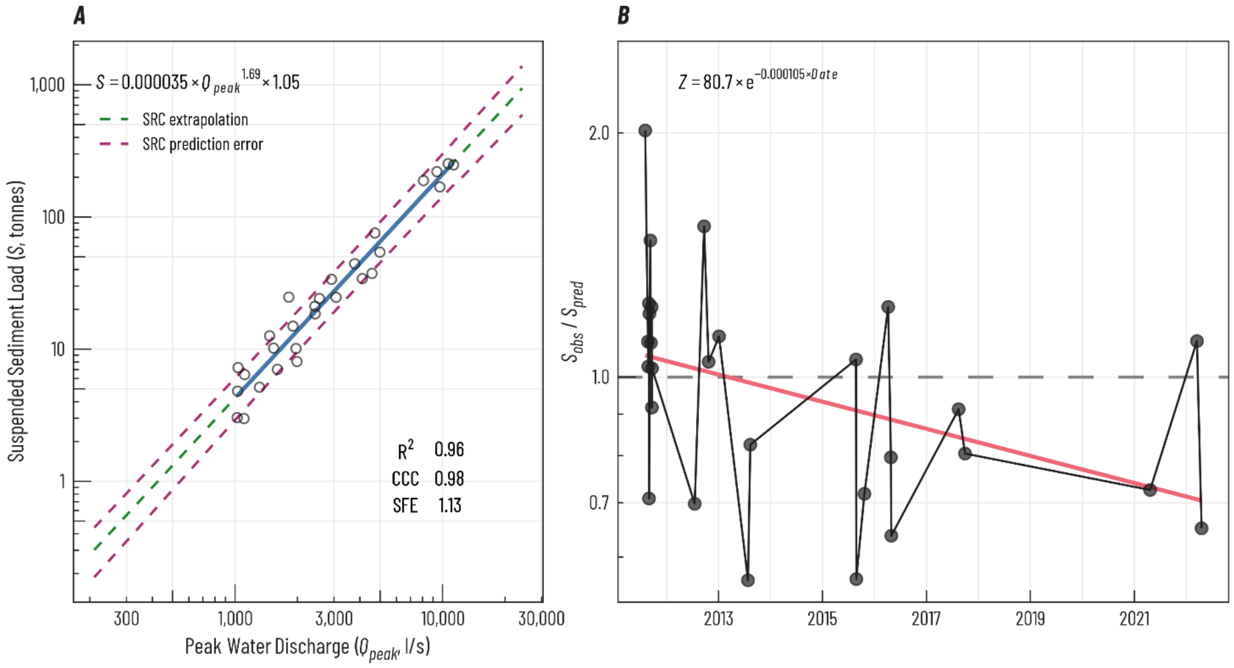

Figure A2.8. Suspended sediment event rating curve derived from 28 measurements taken at the Mangemangeroa River (site No. 8304) for the calendar years 2012–2024. A: Relationship between event suspended sediment load and peak event water discharge on a $\log_{10}$ scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

Ōrewa Stream

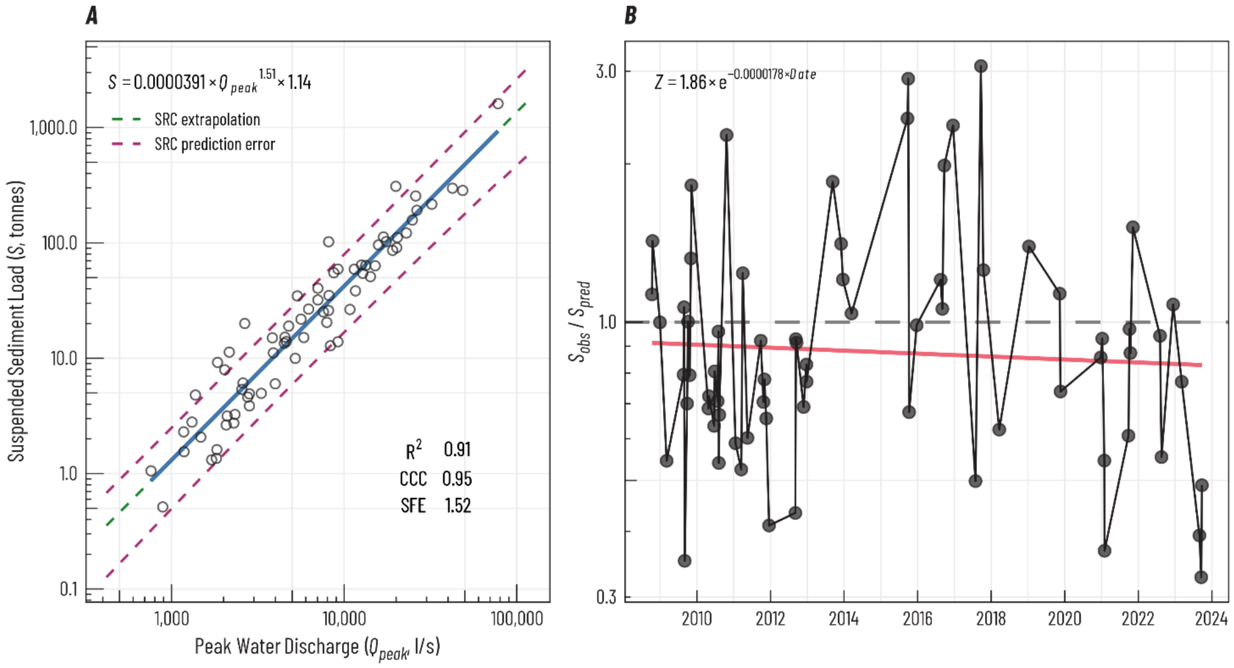

Figure A2.9. Suspended sediment event rating curve derived from 70 measurements taken at the Ōrewa Stream (site No. 7202) for the calendar years 2009–2024. A: Relationship between event suspended sediment load and peak event water discharge on a $\log_{10}$ scale. The blue line indicates the fitted linear model. B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

Te Muri

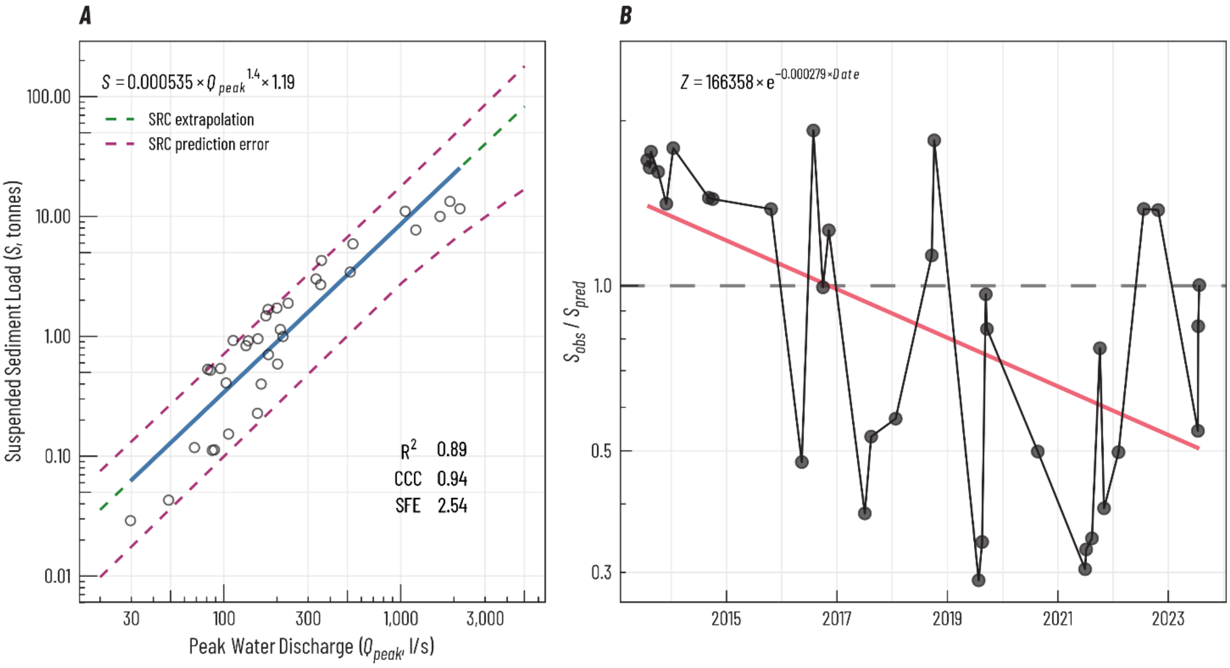

Figure A2.10. Suspended sediment event rating curve derived from 34 measurements taken at the Te Muri Stream (site No. 6995) for the calendar years 2013–2024. A: Relationship between event suspended sediment load and peak event water discharge on a $\log_{10}$ scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error. B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

Wairoa River

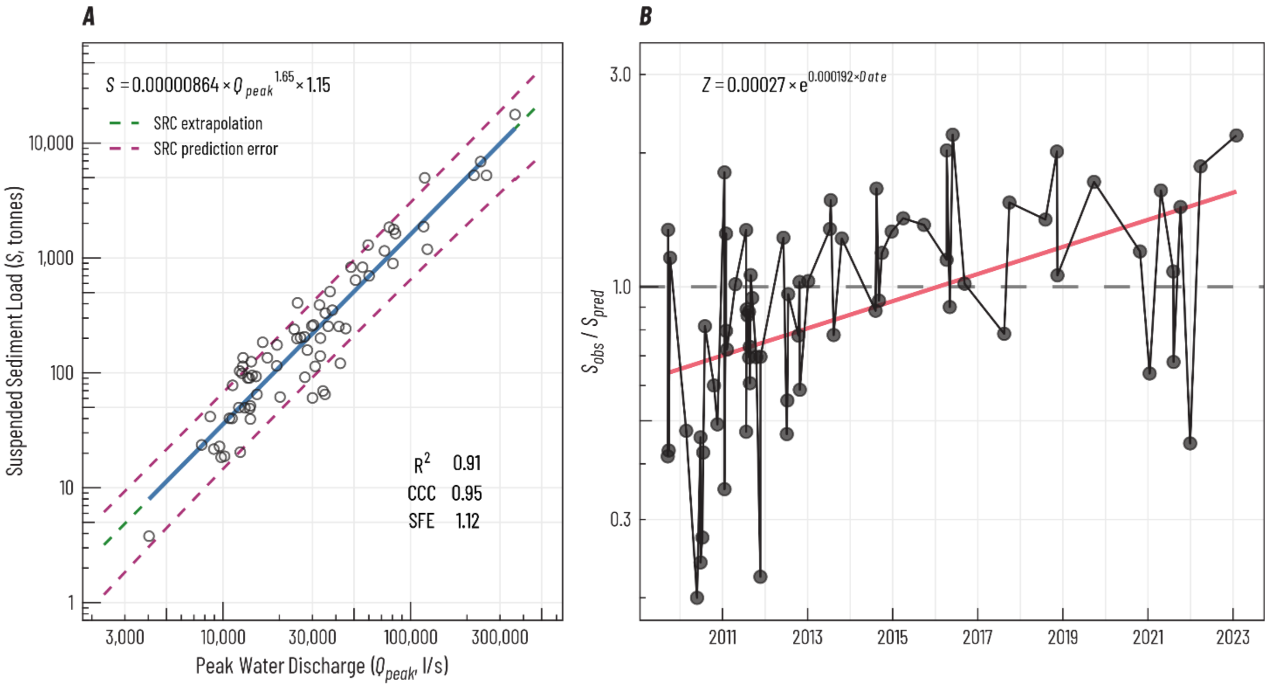

Figure A2.11. Suspended sediment event rating curve derived from 71 measurements taken at the Wairoa River (site No. 8516) for the calendar years 2010–2024. A: Relationship between event suspended sediment load and peak event water discharge on a $\log_{10}$ scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error. B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

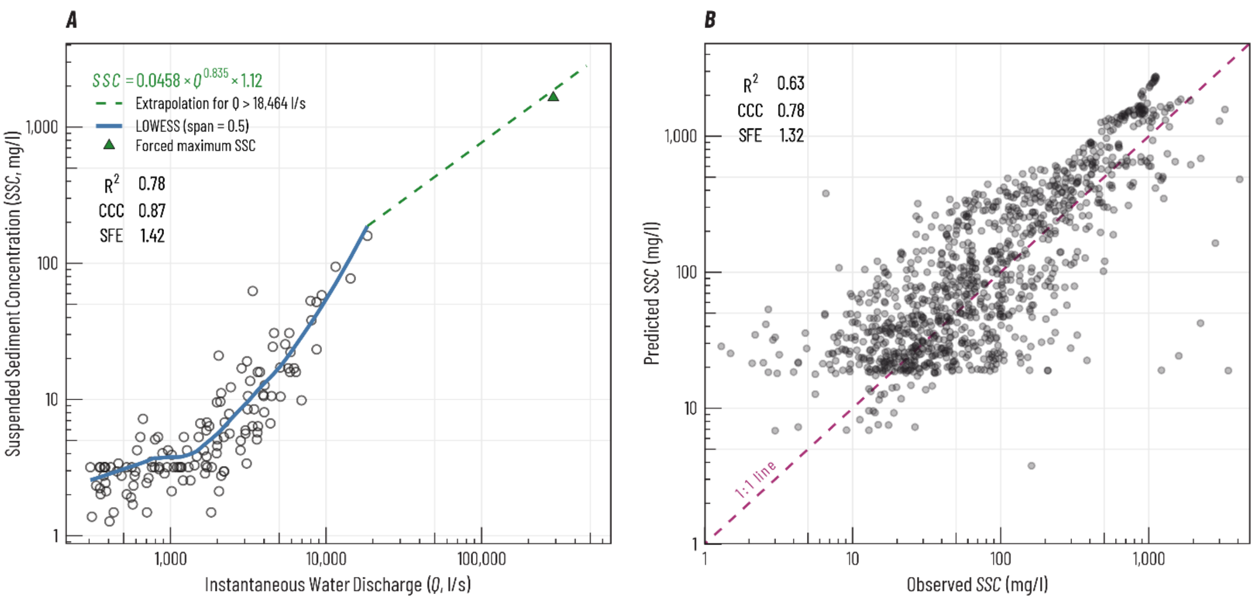

Figure 26. Discrete sampling sediment rating curve for the Wairoa River. A: Relationship between TSS and instantaneous water discharge on a log10 scale. The blue line indicates the fitted LOWESS model, while the green dashed line represents a linear extrapolation to the maximum known water discharge at the site. B: Independent validation of the discrete sampling rating curve with measured suspended sediment concentration during the storm event sampling.

West Hoe Stream

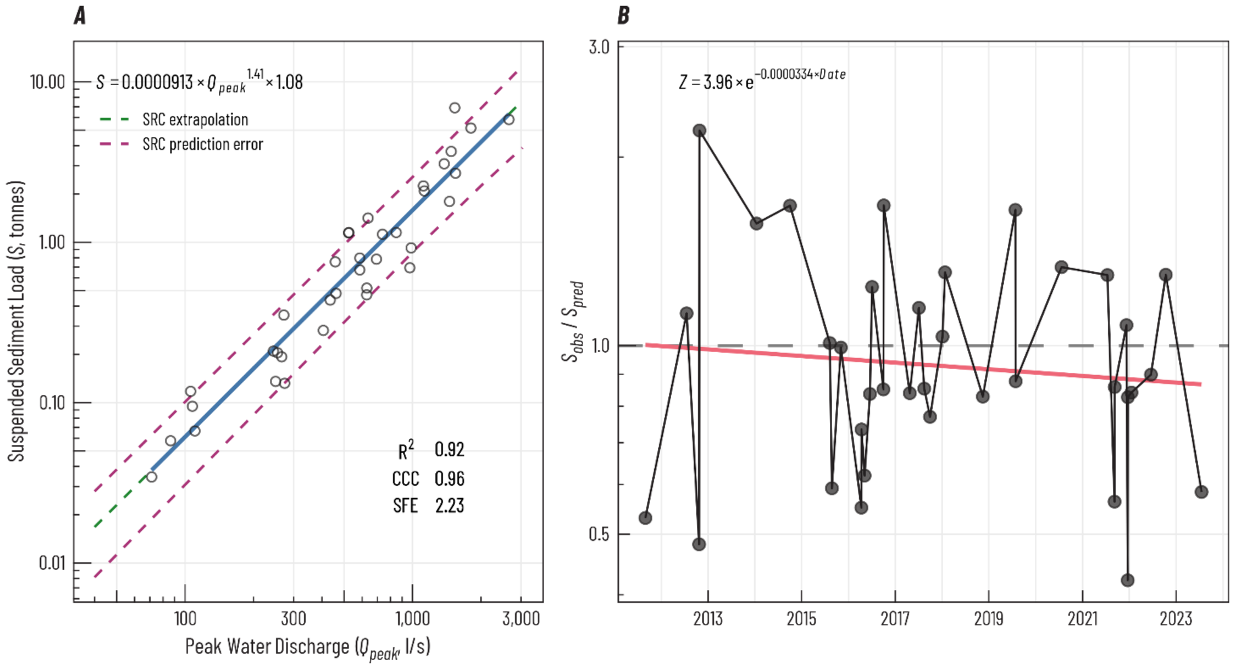

Figure 27. Suspended sediment event rating curve derived from 36 measurements taken at the West Hoe Stream (site No. 7206) for the calendar years 2012–2024. A: Relationship between event suspended sediment load and peak event water discharge on a $\log_{10}$ scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error. B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

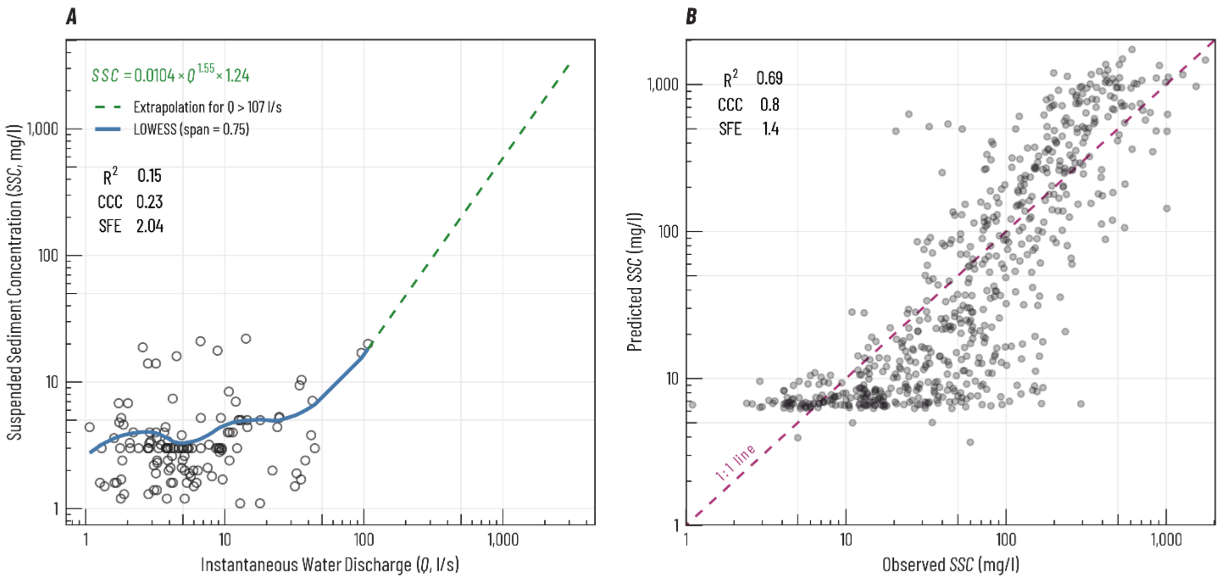

Figure A2.14. Discrete sampling sediment rating curve for the West Hoe Stream. A: Relationship between TSS and instantaneous water discharge on a log10 scale. The blue line indicates the fitted LOWESS model, while the green dashed line represents a linear extrapolation to the maximum known water discharge at the site. B: Independent validation of the discrete sampling rating curve with measured suspended sediment concentration during the storm event sampling.

Mahurangi River

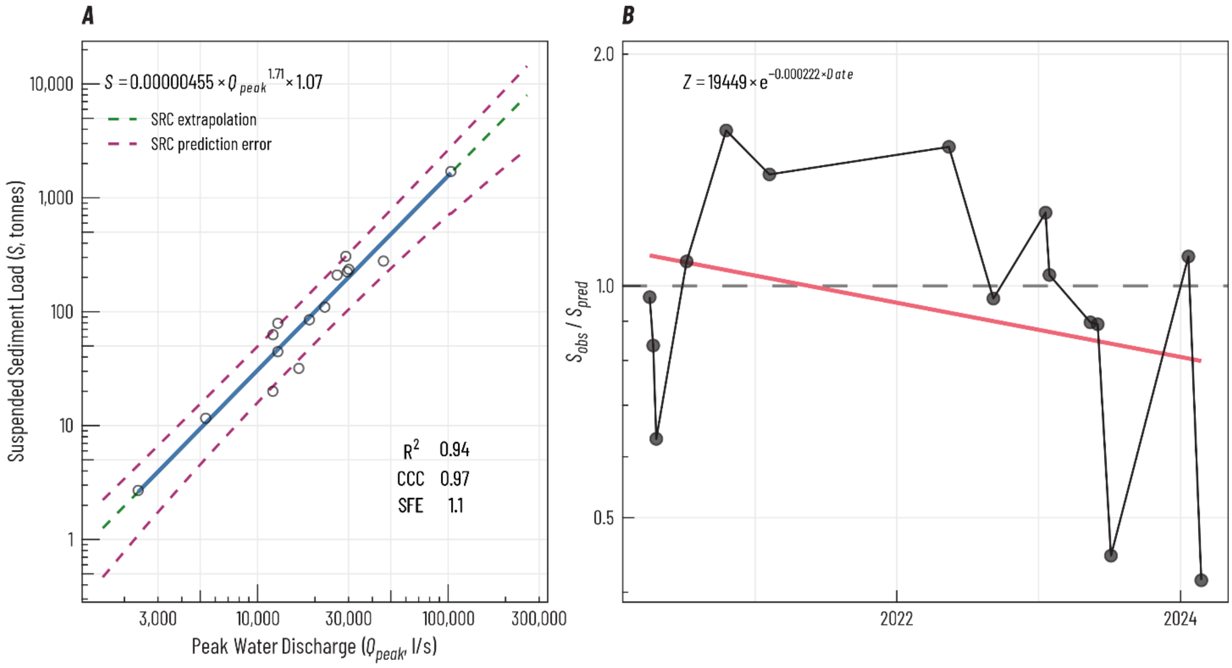

Figure A2.15. Suspended sediment event rating curve derived from 15 measurements taken at the Mahurangi River (site No. 6863) for the calendar years 2020–2024. A: Relationship between event suspended sediment load and peak event water discharge on a $\log_{10}$ scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error. B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

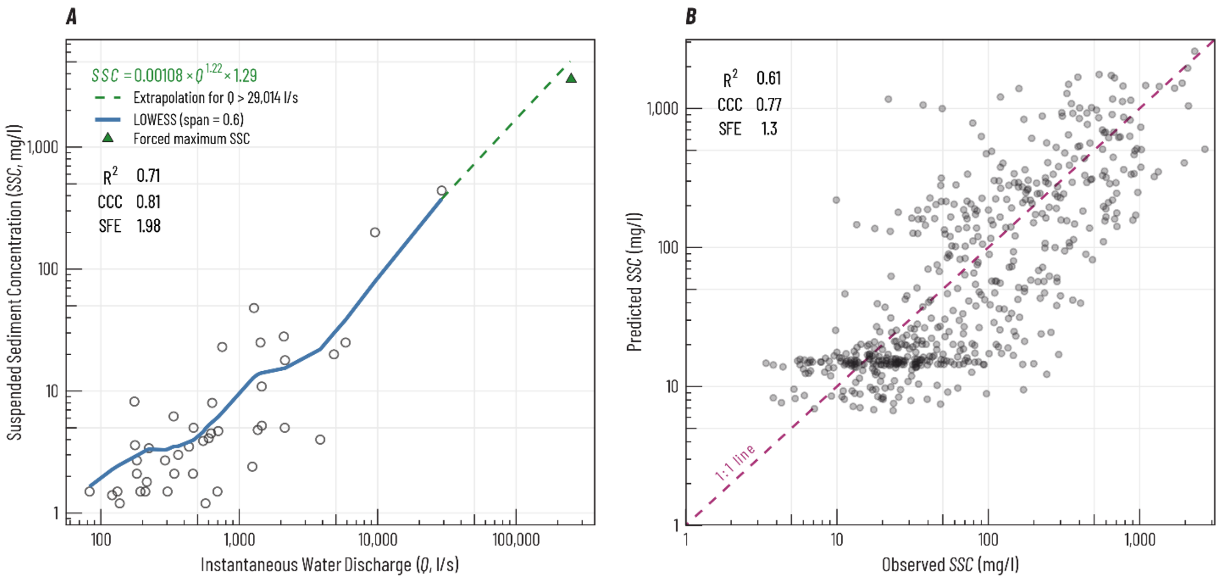

Figure A2.16 Discrete sampling sediment rating curve for the Mahurangi River. A: Relationship between TSS and instantaneous water discharge on a $\log_{10}$ scale. The blue line indicates the fitted LOWESS model, while the green dashed line represents a linear extrapolation to the maximum known water discharge at the site. B: Independent validation of the discrete sampling rating curve with measured suspended sediment concentration during the storm event sampling.

Kōurawhero River

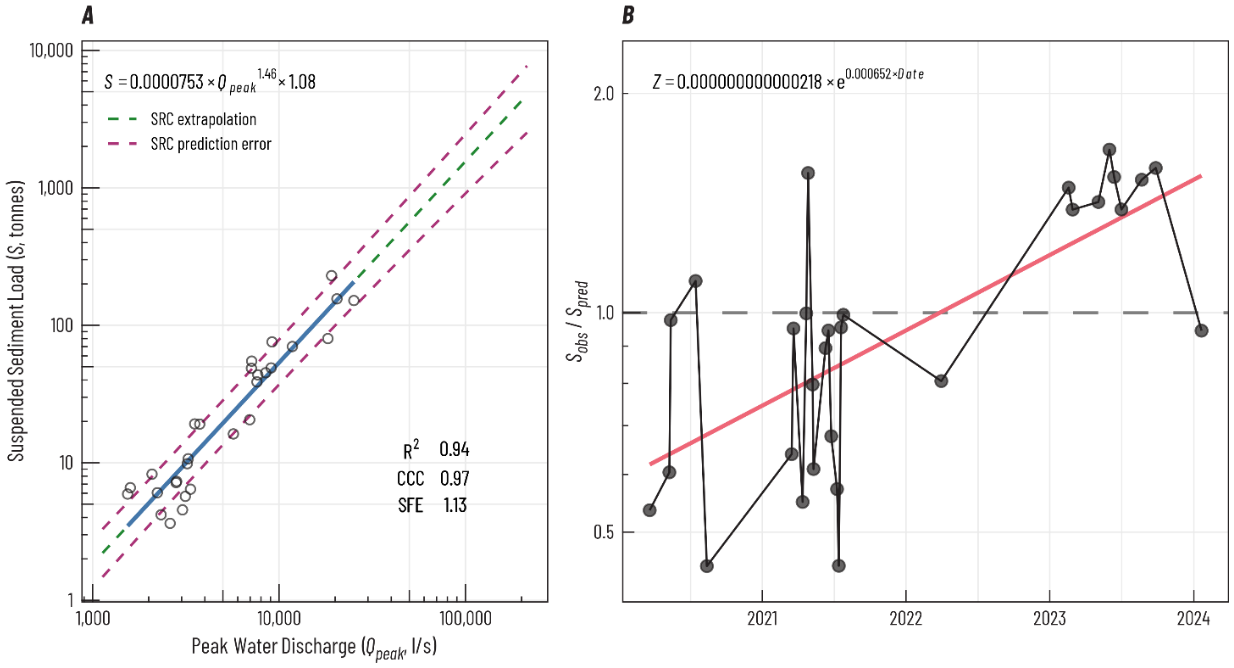

Figure 28. Suspended sediment event rating curve derived from 29 measurements taken at the Kōurawhero River (site No. 45731) for the calendar years 2019–2024. A: Relationship between event suspended sediment load and peak event water discharge on a log_{10} scale. The blue line indicates the fitted linear model (the SRC), while the green dashed line represents a linear extrapolation to the maximum and minimum known water discharges at the site and purple dashed line a SRC prediction error. B: Distribution of the model residuals (Z), expressed as a natural logarithm of observed sediment load (S_{obs}) divided by predicted load (S_{pred}), over time. The red line shows the time trend.

Appendix 3 – Sub-period event sediment rating curves

Table A3.1 Summary of the sub-period event sediment rating curves for Auckland Region rivers, using data collected prior to 2024. Rating curves are presented in a power form of $S = a \times (Q_{peak}/\overline{Q_{peak}})^b \times BCF$ (see section 5.6). In the table n is the total number of events used for the development of the sub-period SRCs. The t-statistic tests the difference between SRC slopes; ANCOVA (analysis of covariance) determines whether the vertical offset parameters differ significantly among factor groups in equal-slope regression models, based on comparisons of their adjusted means. Statistically significant differences are highlighted in bold. BCF is the bias correction factor; R^2, CCC and SFE are the metrics used to assess the SRC quality; and Mean $\overline{Q_{peak}}$ is a geometric mean of the peak water discharge during the sub-period.

	Sub-period	n	Mean $\overline{Q_{peak}}$, L/s	Model	R^2	CCC	SFE	t-stat	t-stat p-value	ANCOVA p-value
Kaipara River	2012–2017	22	20,879	$S = 206 \times (Q_{peak}/\overline{Q_{peak}})^{2.06} \times 1.08$	0.87	0.93	1.07	2.81	**< 0.01**	**0.02**
	2018–2024	14	19,629	$S = 149 \times (Q_{peak}/\overline{Q_{peak}})^{1.35} \times 1.08$	0.83	0.91	1.09			
Kaukapakapa River	2010–2021	38	19,582	$S = 89 \times (Q_{peak}/\overline{Q_{peak}})^{1.28} \times 1.17$	0.83	0.91	1.2	−0.43	0.67	**0.01**
	2022–2024	8	9,474	$S = 55.3 \times (Q_{peak}/\overline{Q_{peak}})^{1.4} \times 1.06$	0.90	0.95	1.12			
Mangemangeroa River	2010–2014	17	2,286	$S = 19.2 \times (Q_{peak}/\overline{Q_{peak}})^{1.58} \times 1.04$	0.91	0.95	1.12	−1.95	0.06	**< 0.01**
	2015–2024	11	3,607	$S = 31.9 \times (Q_{peak}/\overline{Q_{peak}})^{1.87} \times 1.02$	0.99	0.99	1.07			
Ōrewa Stream	2009–2013	36	6,685	$S = 20.8 \times (Q_{peak}/\overline{Q_{peak}})^{1.53} \times 1.08$	0.95	0.958	1.76	1.67	0.15	0.5
	2014–2017	12	4,774	$S = 23 \times (Q_{peak}/\overline{Q_{peak}})^{1.27} \times 1.07$	0.9	0.95	1.19	−2.26	0.08	0.1
	2018–2024	22	5,842	$S = 16.8 \times (Q_{peak}/\overline{Q_{peak}})^{1.66} \times 1.15$	0.91	0.95	1.46			
Te Muri Stream	2010–2019	18	313	$S = 2.34 \times (Q_{peak}/\overline{Q_{peak}})^{0.99} \times 1.02$	0.96	0.98	1.61	−6.29	**< 0.01**	**< 0.01**
	2020–2024	16	135	$S = 0.36 \times (Q_{peak}/\overline{Q_{peak}})^{1.85} \times 1.09$	0.92	0.96	2.89			
Wairoa River	2010–2014	44	24,213	$S = 124 \times (Q_{peak}/\overline{Q_{peak}})^{1.55} \times 1.13$	0.86	0.92	1.14	−0.64	0.53	**< 0.01**
	2015–2024	27	34,969	$S = 402 \times (Q_{peak}/\overline{Q_{peak}})^{1.64} \times 1.07$	0.95	0.97	1.09			
Kōurawhero River	2019–2022	20	5,797	$S = 19.2 \times (Q_{peak}/\overline{Q_{peak}})^{1.59} \times 1.03$	0.95	0.98	1.12	0.83	0.41	0.56
	2023–2024	9	3,854	$S = 20.4 \times (Q_{peak}/\overline{Q_{peak}})^{1.48} \times 1.01$	0.98	0.99	1.08			