Manaaki Whenua
Landcare Research

Upper Mōtū catchment sediment sources study

Prepared for: Gisborne District Council

March 2021

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Contract Report: LC3937

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Contents

Summary

Project and Client

- The Mōtū River is considered an at-risk river in the Gisborne region due to the combination of high natural values, ecological significance, and a high potential for degradation as a result of land use intensification. Although sediment is central to the concerns within the catchment, there is limited information on erosion and sediment sources in the Upper Mōtū catchment.
- A study was undertaken by Manaaki Whenua – Landcare Research for Gisborne District Council to investigate sediment sources in the catchment. This involved an application of the sediment fingerprinting technique, comprising (1) geochemical analysis and characterization of the main sediment sources in the catchment, (2) discrimination of sources using selected geochemical tracers, and (3) determination of relative contributions from catchment sources to downstream sediment.

Objectives

The objectives were to:

- conduct a pilot-level sediment fingerprinting study to sample and geochemically characterize the main erosion sources in the Upper Mōtū catchment
- determine relative sediment contributions from catchment sources in the Upper Mōtū
- evaluate these results in relation to the geomorphological understanding of the catchment.

Methods

- The main erosion sources in the Upper Mōtū catchment were geochemically characterized. These were agricultural surface soils (representing sheet/rill erosion), agricultural subsoils (representing shallow landslide and gully erosion) and alluvial channel banks (representing bank erosion). An additional greywacke bedrock source representing sediment from a quarry was also characterized. While this sediment represents quarry sediment, it also represents other greywacke sources from around the catchment. A total of 35 source samples were collected across the catchment.
- Downstream sampling targeted fine sediment within the channel. These consisted of fine sediment drapes exposed and submerged below the water level as well as undisturbed overbank deposits resulting from previous high flows. A total of 13 sediment samples were collected.
- Samples were dried and sieved to retain the <63 µm fraction and underwent particle size analysis (PSA) and geochemical analysis using x-ray fluorescence (XRF) and laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). Tracers showing evidence of non-conservativeness were removed and then a subset selected using stepwise linear discriminant function analysis that selects tracers to maximize source discrimination.

- The selected tracers were used to determine relative contributions from each source to the downstream sediment using MixSIAR, a Bayesian mixing model.

Results

- The following 13 tracers were selected: MgO, Al_2O_3, CaO, Th, Na_2O, Pb^{206}, Ni, Co, Ta, Ga, TiO_2, SrO, K_2O. Leave-one-out cross-validation and principal component analysis showed good discrimination between the 4 sources.
- The dominant sediment source was estimated as channel bank for both channel sediment (~ 95%) and flood sediment (~ 96%).
- Subsoil, greywacke bedrock and surface soils provide minor contribution to downstream sediment. Source contribution 95% confidence interval in decreasing order for:
  - channel sediment is estimated to be 87.2 – 99.4% from channel bank, 0.1 – 9.9% from subsoil, 0.0 – 4.4% from greywacke, and 0.0 – 1.3% from surface soils.
  - flood sediment is estimated to be 89.7 – 99.2% from channel bank, 0.1 – 8.7% from subsoil, 0.1 – 2.5% from greywacke, and 0.0 – 1.6% from surface soils.

Conclusions

- The sediment fingerprinting results align with geomorphological understanding of the catchment where active bank erosion is widely observed, while there is negligible evidence of widespread mass movement or slope failures delivering sediment to the channel.
- Similar results between channel and flood sediment deposits suggests erosion process source contributions are relatively consistent between low and high flows.

Recommendations

- Erosion mitigation strategies should continue to target channel bank erosion to effectively reduce fine sediment loads in the catchment.
- Further sediment fingerprinting analysis could be performed using additional sediment samples collected on an ongoing basis to leverage the initial investment in catchment source sampling, which does not need to be repeated.
- Additional sediment information (e.g. suspended sediment load) for the Upper Mōtū catchment would complement the proportional source contribution results from sediment fingerprinting. For instance, sediment load data could be used to identify temporal trends in sediment source dynamics. These data could be obtained from continuous sediment monitoring or sediment load modelling.

1 Introduction

The Mōtū River is considered by Gisborne District Council to be the most at-risk river in the region (Gisborne District Council 2021). This is due to the combination of high natural values, ecological significance, and a high potential for degradation because of land use intensification.

A Mōtū Catchment Plan is being developed under the National Policy Statement for Freshwater Management (NPS-FM) and the Tairāwhiti Resource Management Plan (TRMP). The Mōtū Catchment Plan will set objectives, limits, and targets for managing water quality (Gisborne Disctrict Council, 2020). The plan will also set out actions to achieve these objectives, limits, and targets.

Many aspects of water quality in the Mōtū River are very good and is reported as one of the most pristine river environments in the district (Gisborne District Council n.d.). However, some water quality attributes deteriorate downstream. Of particular concern is suspended sediment (clarity), which falls below the National Bottom Line of the NPS-FM at all monitoring sites. The degradation of water quality within Gisborne District has an effect downstream and into the Bay of Plenty.

Because suspended sediment is a central water quality issue for this catchment, it is important to better understand the dominant sources of sediment to better target management interventions. There has been some research looking at water quality monitoring and best management practices (Ballantine & Davies-Colley 2009); however, no specific research on sediment sources has been carried out within the Mōtū Catchment.

Manaaki Whenua – Landcare Research was contracted by Gisborne District Council to provide an analysis of sediment sources in the Upper Mōtū catchment. This analysis uses the sediment source fingerprinting technique to trace sediment collected in the river back to catchment sources and is supported by an assessment of the catchment geomorphology. Sediment fingerprinting differentiates catchment sources based on source-specific organic and geochemical sediment markers or 'fingerprints'. These fingerprints can then be used to determine relative source contribution to downstream sediment.

2 Objectives

The objectives are to:

- conduct a pilot level sediment fingerprinting study to sample and geochemically characterize the main sediment sources in the Upper Mōtū catchment
- determine relative sediment contributions from catchment sources in the Upper Mōtū
- evaluate these results in relation to the geomorphological and erosion-process understanding of the catchment.

3 Upper Mōtū catchment

3.1 Site description

The Upper Mōtū catchment is situated in the Gisborne district, draining a 249-km^2 area upstream of the Mōtū Falls (Fig. 1). The headwaters to the south of the catchment flow north to the Bay of Plenty through a moderately gentle gradient channel before transitioning to a deeper gradient downstream of the Mōtū Falls. The catchment is predominantly Class VI & VII (NWASCO 1975) hill country (64% of catchment area) rising to an elevation of ~1000 m a.s.l. along the western and southern borders of the catchment.

Agricultural pasture is the dominant landcover (65%) followed by indigenous forest and in indigenous hardwoods (29%) (Fig. 2). Most agricultural farming is sheep and beef with some deer farming. There are two dairy farms in the catchment and several other farms provide dairy support for dairy farms in the Bay of Plenty. The beef farming present is often intensive and situated adjacent to the river. These land uses (with limited stock control) contribute to degrading water quality; however, the natural geography of the area also contributes.

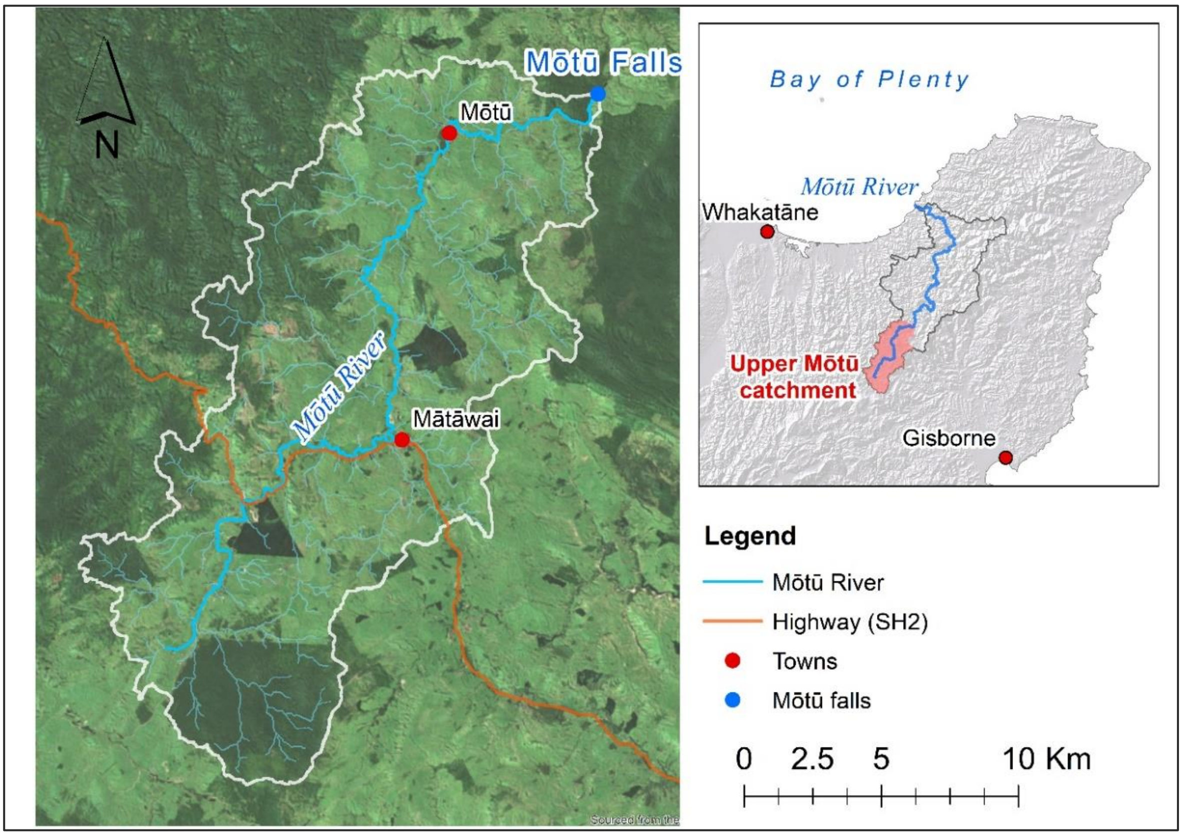

Figure 1. Upper Mōtū catchment located above the Mōtū Falls. The Mōtū River flows north through to the Bay of Plenty.

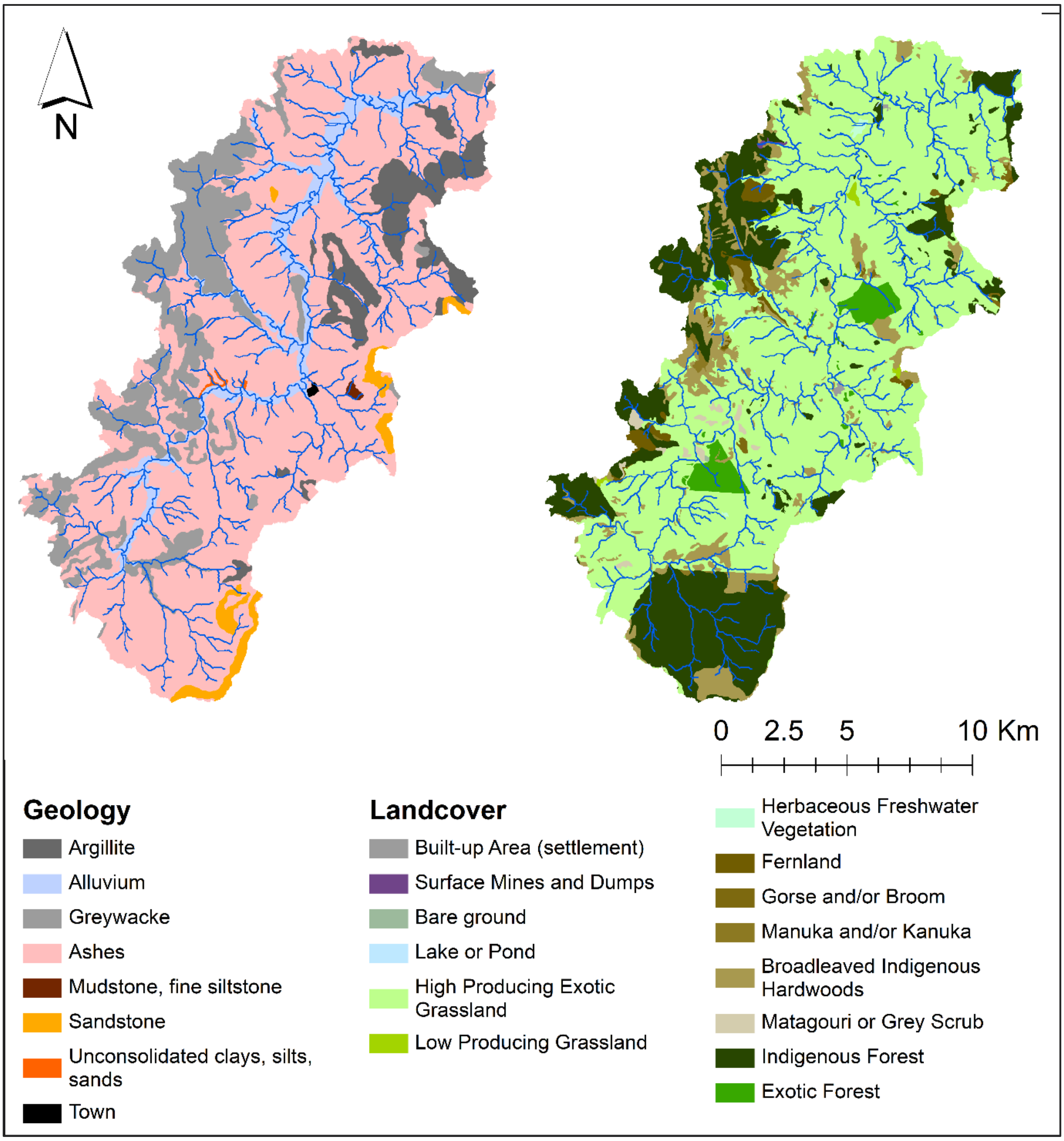

Figure 2. Geology of the Upper Mōtū catchment (left) derived from NZLRI toprock; and Landcover of the Upper Mōtū catchment (right) derived from LCDBv5.

3.2 Geomorphology

The catchment is predominantly underlain by younger Cretaceous-aged sedimentary rock covered by tephra-fall ash layers on the hill slopes and alluvium deposits in the floodplain. Rock is mostly greywacke/sandstone and argillite which is exposed in the steeper headwaters, although mudstone/siltstone and unconsolidated clays, silts and sands exist in localised deposits (Fig. 2). The catchment has been successively covered by tephra-fall ash layers originating from the Okataina and Taupo volcanic centres representing eruptions spanning ~1,718 to ~45,000 ka BP (ages referenced from Hopkins et al. (2020)). The soils are mostly allophanic brown and orthic pumice soils with high tephra content, well drained although stonier and shallower on the steep slopes (Ballantine & Davies-Colley 2009).

The Mōtū Falls mark the outflow of the Upper Mōtū catchment and constitute a nick point of exposed indurated sandstone/greywacke basement rock (Karekare Formation of Mazengarb & Speden 2000) (Fig. 3). This has slowed the rate of channel incision relative to below the falls where the channel is deeply incised and has a steeper gradient. In effect, the Mōtū Falls form a barrier upstream of which sediment has in the past accumulated to form an extensive area of alluvial terraces and a modern-day floodplain.

Alluvial terraces are preserved at multiple elevations within the catchment (Fig. 4). The highest terraces are several tens of metres above the modern-day floodplain. Four of the oldest terraces are aggradation surfaces correlated with cold/cool climate episodes of the Otiran glaciation, when retreat of the tree line facilitated higher rates of erosion in the headwater tributaries (Berryman et al. 2000). The sediment generated infilled valley floors forming floodplains now preserved in the terrace sequence following alternating periods of aggradation and channel incision. Lateral bank erosion over time has reduced the extent of the terraces to a discontinuous series of remnant surfaces.

With the termination of glacial-age aggradation, climate warming favoured fluvial incision. As the climate warmed, the spread of vegetation to higher elevations reduced the rate of sediment supply. In response to a reduction in sediment supply, rates of channel incision increased resulting in the narrowing of channels and of areas of floodplain deposition. In the last c. 15,000 years (Holocene period) there have been a further seven periods of terrace formation. A significant period of widespread hillslope adjustment in response to rapid river incision initiated the reactivation of deep-seated landslides between ca 13,600 and ca 9,500 cal. yr BP and was synchronous across all headwater tributaries (Bilderback et al. 2015; Marden et al. 2014). Within the Mōtū catchment, sediment generated during this period accumulated across the width of the middle reach of the Mōtū Valley, as evidenced by the high remnants of alluvial terrace, and of truncated alluvial fans.

3.3 Erosion Sources

Large-scale slope failures have been rare in recent times. Conversely, and particularly since the clearance of indigenous forest, the initiation of shallow soil slip and debris avalanche of negligible to moderate severity, on slopes 16 – >35° (NWASCO 1975), during times of increased storminess has provided a significant but episodic source of sediment. Though gullies are highly connected to water courses, those in the middle to upper reaches of the Mōtū are generally of small extent, shallow, and only a few remain active at any one time. Similarly, while relict earthflows are present in the landscape, there are no known incidences of earthflow activity contributing sediment to the river system in the recent past. In Holocene times, and relative to shallow hillslope landslides and bank erosion, it is unlikely that either gullies or earthflows have been a significant a source of sediment in the Mōtū catchment.

Figure 3. Mōtū Falls showed exposed bedrock and marking the outflow of the Upper Mōtū catchment.

Figure 4. Alluvial terraces in the background and active bank erosion on the Upper Mōtū river.

The principal present-day source of sediment is likely derived from channel bank erosion of the Mōtū River and its tributaries (Fig, 4). Bank material comprises unconsolidated pebble to cobble-sized gravel, sand-sized clastic and tephric material, and finer-grained overbank sands, silts and clay deposited during floods within historic times. Much of this material has previously been stripped from catchment slopes, delivered to stream channels during previous episodes of shallow landsliding, and subsequently re-deposited and/or reworked during flood events.

Within the last decade, concerns have been raised as to the role of stock trampling while accessing unfenced waterways in contributing to bank collapse thereby elevating the nutrient and sediment load of the Mōtū River (Ballantine & Davies-Colley 2009).

4 Method

4.1 Source and sediment sampling

Sampling aimed to characterize the main contemporary sediment sources. These were determined to be agricultural surface soils (0–4 cm; representing sheet/rill erosion), agricultural subsoils (typically 1 m depth; representing shallow landslide and gully erosion; Fig. 5) and alluvial channel banks (representing bank erosion; Fig. 6). A request was also made to characterize sediment originating from active quarries. Rock and sediment samples were collected from the greywacke bedrock material in and around an active quarry site to represent this source. It is important to note that while this material will represent quarry sediment, it also represents other greywacke sources from around the catchment, for example, debris avalanche in steep headwater areas and perhaps unsealed gravel roads. A total of 35 source samples were collected across the catchment (Fig. 7), with sampling details outlined in Table 1. All samples were collected as composite samples. This consists of multiple depth-integrated scrapes (Fig. 8) collected within a designated area to represent the target source material. The bulk sample is then then homogenised and mixed in a bucket, then sub-sampled into bags.

Downstream sediment samples consisted of fine sediment within the channel typically occurring as exposed and submerged sediment drapes (Fig. 9). This sediment provides a snapshot of source contribution under contemporary conditions. Preserved sediment deposits from a previous high flow event were identified in the field and presented an opportunity to sample and independently determine source contributions to these deposits (Fig. 10). Therefore, source contributions for both current conditions and a high flow event were determined. A total of 13 sediment samples were collected.

Figure 5. Example of exposure used for sampling subsoil sources used to represent shallow landslide erosion.

Figure 6. Example of active bank erosion sampled to represent the channel bank source.

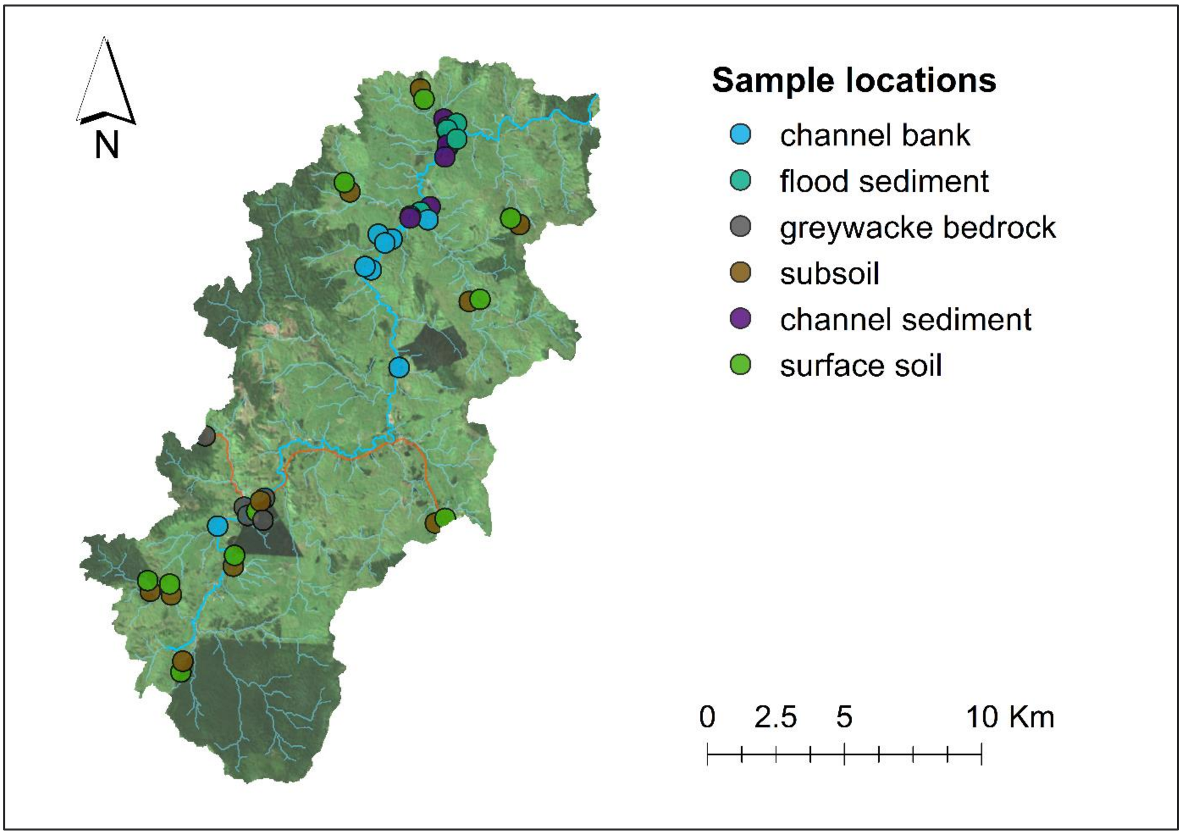

Figure 7. Sample locations for sources and sediments.

Table 1. Descriptions of source and sediment sampling in the Upper Mōtū catchment

Sediment Source	Description
Surface Soil	Surface soil samples were taken from the upper 4 cm of the steeper hill country terrain to represent sheet and rill erosion from the hill slopes (*n* = 10).
Subsoil	Subsoil samples were taken from depth integrated (typically ~ 1 m) scrapes of the hill country terrain to represent landslide and gully erosion (*n* = 10).
Channel bank	Depth integrated scrapes from exposed channel banks were sampled to represent contemporary bank erosion (*n* = 10).
Greywacke bedrock	Sediment samples were taken from rock and sediment in and near active quarry works. This material is primarily greywacke bedrock and covering sediment. This reflects sediment from the quarry as well as material from debris avalanche that occur in the headwaters (*n* = 5).
Channel sediment	Fine sediment samples were collected from within the channel. These typically occurred as exposed and submerged deposits/drapes within the channel (*n* = 9).
Flood sediment	Fine sediment samples were collected from deposits trapped within tree branches/vertices at or above bank full discharge (*n* = 4).

Figure 8. Vertical integrated sediment sampling of a subsoil profile (left) and channel bank (right).

Figure 9. Example of submerged channel sediment deposit.

Figure 10. Example of flood sediment deposit trapped in trees branches.

4.2 Sample Analysis

Samples were air dried at 40°C, manually disaggregated, and sieved to retain the <63 μm fraction. Due to the high volume of water collected with the channel sediment, these were first wet sieved to <63 μm and then air dried at 40°C.

Particle size analysis (PSA) and geochemical analysis using x-ray fluorescence (XRF) and laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) were conducted. Sample preparation for XRF involves heating samples to 850°C overnight to oxidize all elements and combust any organic material, and then fusing the sample to form glass discs for analysis. The glass discs were analysed using a Spectro X-LAB 2000 X-ray Fluorescence Spectrometer for SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, BaO, SO_3, and SrO. Samples were then analysed using Perkin-Elmer SCIEX ELAN DRC II Inductively Coupled Plasma-Mass Spectrometer with an attached Laser Ablation unit (LA-ICP-MS). LA-ICP-MS elements analysed include Sc, V, Cr, Co, Ni, Cu, Ga, Ge, Rb, Y, Zr, Nb, Cs, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ta, Tl, Pb^{206}, Pb^{207}, Pb^{208}, Th, U.

4.3 Tracer Selection and Source Discrimination

Sediment fingerprinting requires selection of a subset of tracers that statistically discriminate sediment sources while also retaining their geochemical signature during transport downstream. The tracer selection procedure involved first removing tracers that show evidence of non-conservativeness and then selecting a subset to maximize discrimination of sources. Tracers were removed based on evidence of 'non-conservative' behaviour identified through tracer-particle size relationships and source mixing polygons (Smith et al. 2018). If downstream samples fall outside the plotted polygons, these tracers are removed. Increasing specific surface area (SSA) associated with finer particle sizes can influence the geochemical behaviour of individual tracers, so non-conservative behaviour can also be partially identified if strong correlations exist between SSA and tracer concentration (Smith et al. 2018).

A two-step statistical approach was then applied to select the optimum set of tracers for discriminating sources. First, a Kruskal-Wallis non-parametric test was used to identify tracers that show significant differences between two or more source groups. This was carried out for each tracer based on 95% confidence interval or an α level of 0.05 for the critical p-value. Next, a multivariate stepwise Discriminant Function Analysis (DFA) based on minimization of Wilks' lambda was applied to determine the most suitable subset of tracers that maximise source discrimination. DFA allows for prediction of group membership based on linear combinations of predictor variables and Wilk's lambda is a measure of the between-group variability to within-group variability, whereby minimizing the value increases between-group distance and reduces within-group distance.

4.4 Source apportionment

The resulting subset of selected tracers was used to quantitatively determine the main source contributions to downstream sediment using a Bayesian mixing model called MixSIAR (Stock & Semmens 2016). This was executed within 'R' (R Core Team 2019) using 'R' package MixSIAR v3.1.10. The simulations used three MCMC chains of length 3×10^6 with a burn-in of 1.5×10^6 resulting in 9,000 posterior estimates. Sediment samples consisted of replicate samples so both 'process' and 'residual' error structures were used. A generalist prior ($\alpha = 1$) was applied and model convergence was assessed using Gelman–Rubin diagnostic whereby the Gelman–Rubin value will be near 1 at convergence. Values < 1.05 are generally considered acceptable. The mixing model was run for both channel sediment and flood deposit sediment samples.

5 Results

5.1 Particle size and organic matter

Lower Specific Surface Area (SSA) and higher median particle size (D_{50}) indicate channel bank and greywacke have a coarser particle size distribution than subsoil and surface soil sediment sources. Downstream sediment is typically finer than source sediment but plots within the range of source values (Table 2; Fig. 11). Likewise, channel and flood sediment values for Loss on Ignition (LOI), which represents organic matter content, plot within range of source values. Subsoil and surface soil source materials show higher LOI and organic matter content than channel bank and greywacke sources. Channel sediment also has higher organic matter content than flood sediment. Differences between source and sediment particle size and organic matter provide the basis for a tracer selection technique to remove tracers showing non-conservative behaviour related to particle size.

Table 2. Summary statistics showing mean and standard deviation (s.d.) for Specific Surface Area (SSA), Median particle size (D_{50}) and Loss on Ignition (LOI)

Source	Specific Surface Area (SSA) (m^2 g)		Median particle size (D_{50}) (µm)		Loss on Ignition (LOI) (%)	
	mean	s.d.	mean	s.d.	mean	s.d.
Channel bank	0.28	0.12	25.4	5.6	8.9	2.0
Greywacke bedrock	0.26	0.06	24.8	1.7	6.1	1.9
Subsoil	0.45	0.20	19.1	8.1	18.7	3.3
Surface soil	0.39	0.06	23.9	4.1	21.8	4.6
Channel sediment	0.40	0.10	18.5	5.9	13.5	2.0
Flood sediment	0.51	0.05	13.8	2.0	8.0	1.1

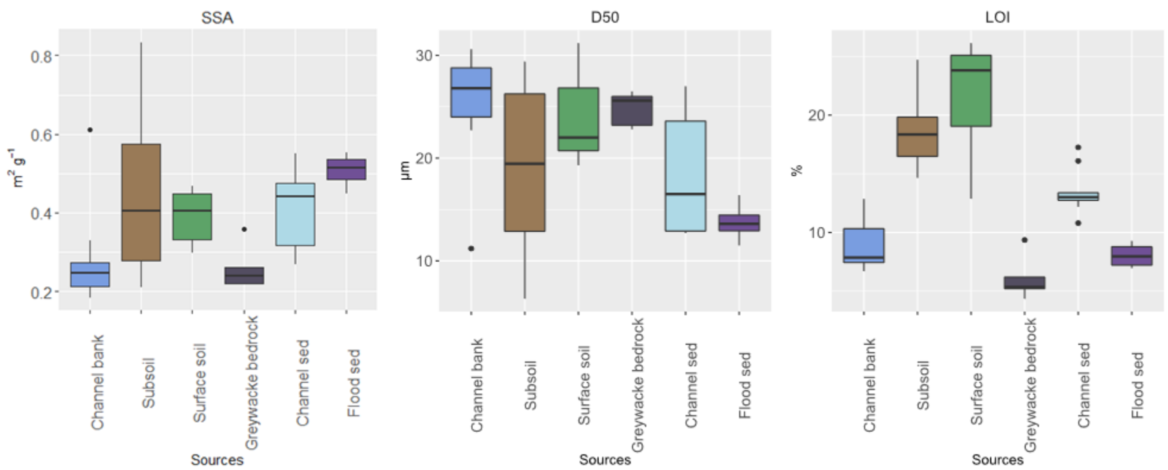

Figure 11 Boxplots for Specific Surface Area (SSA), Median particle size (D_{50}), and Loss on Ignition (LOI) by source.

5.2 Tracer Selection and Source Discrimination

A total of 18 tracers were removed based on evidence of non-conservative behaviour, leaving the following set of 30 tracers available for selection: TiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, SrO Sc, Co, Ni, Cu, Ga, Ge, Nb, Cs, La, Ce, Pr, Nd, Dy, Er, Tm, Yb, Ta, Tl, Pb^{206}, Pb^{207}, Pb^{208}, Th. The selection of tracers to maximise source discrimination based on minimization of Wilks' lambda resulted in the following 13 tracers: MgO, Al_2O_3, CaO, Th, Na_2O, Pb^{206}, Ni, Co, Ta, Ga, TiO_2, SrO, K_2O (Table 3; Fig. 12).

Table 3. Selected tracers based on stepwise-discriminant function analysis showing wilks' lambda

	variable	Wilks' lambda	F.statistics diff	p.value diff
1	MgO	0.17263	40.3	5.75E-15
2	Al_2O_3	0.038441	28.6	1.62E-12
3	CaO	0.018406	8.7	1.09E-05
4	Th	0.008247	9.6	4.43E-06
5	Na_2O	0.004691	5.8	4.49E-04
6	Pb^{206}	0.003075	3.9	6.07E-03
7	Ni	0.00146	8.0	3.56E-05
8	Co	0.000975	3.5	1.15E-02
9	Ta	0.000568	4.9	1.71E-03
10	Ga	0.000383	3.2	1.81E-02
11	TiO_2	0.000245	3.6	1.07E-02
12	SrO	0.000165	3.0	2.44E-02
13	K_2O	0.0000865	5.5	1.03E-03

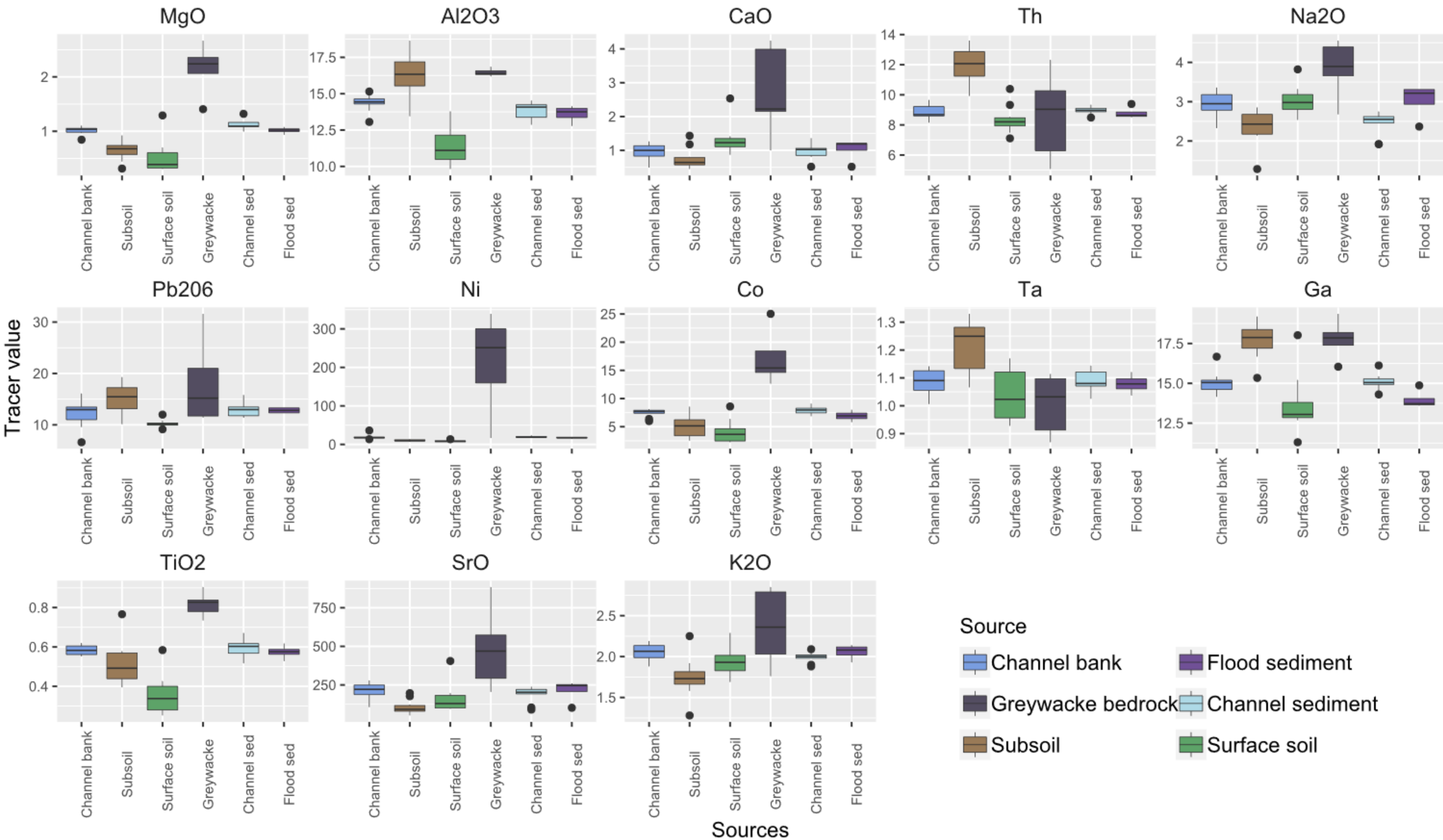

Figure 12. Boxplots of tracers for source and channel group.

Leave-one-out cross-validation indicated predicted group membership is mostly in line with actual group membership (Table 4) although one greywacke bedrock and one surface soil sample were predicted as channel bank. Principal component analysis showing the first two components indicates clear discrimination between the 4 sources (Fig. 13).

Table 4. Leave-one-out cross-validation showing predicted group vs actual group

		Predicted Group				
	Source	**Channel bank**	**Greywacke bedrock**	**Subsoil**	**Surface soil**	**Total**
Actual Group	Channel bank	10	0	0	0	**10**
	Greywacke bedrock	1	4	0	0	**5**
	Subsoil	0	0	10	0	**10**
	Surface soil	1	0	0	9	**10**
	Total	**12**	**4**	**10**	**9**	**35**

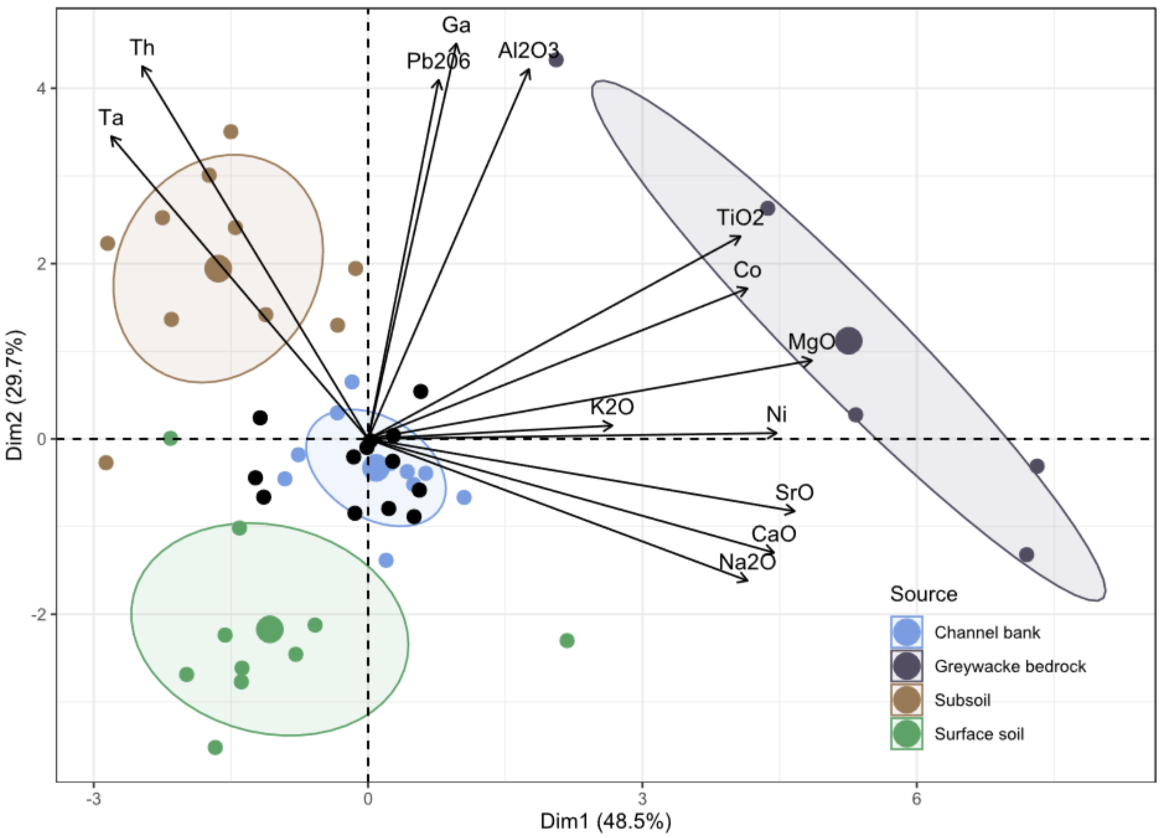

Figure 13. Principal Component Analysis (PCA) showing source discrimination in relation to tracers with 95% confidence interval. Black dots indicate sediment samples.

5.3 Source apportionment

MixSIAR modelling showed good model convergence, indicated by Gelman-Rubin diagnostics being <1.05 and well resolved posterior density plots. This is reflected in the variation in modelled proportional source contributions (Fig. 14).

The dominant sediment source is estimated as channel bank for both channel sediment (~ 95%) and flood sediment (~ 96%) (Table 5). Subsoil, greywacke bedrock, and surface soils all provide minor contributions to downstream sediment. Relative source contributions were similar between channel sediment and flood sediment. Source contribution at 95% confidence interval in decreasing order for:

- channel sediment is estimated to be 87.2 – 99.4% from channel bank, 0.1 – 9.9% from subsoil, 0.0 – 4.4% from greywacke bedrock, and 0.0 – 1.3% from surface soil.
- flood sediment is estimated to be 89.7 – 99.2% from channel bank, 0.1 – 8.7% from subsoil, 0.1 – 2.5% from greywacke bedrock, and 0.0 – 1.6% from surface soil.

Table 5. Summary of sediment source estimates from sediment fingerprinting for both channel sediment and flood sediment

	Source	Mean (%)	SD (%)	Median (%)	95 % Confidence Interval	
					2.5 %	97.5 %
Channel Sediment	Channel bank	94.9	3.2	95.5	87.2	99.4
	Greywacke bedrock	1.6	1.2	1.4	0.0	4.4
	Subsoil	3.2	2.7	2.4	0.1	9.9
	Surface soil	0.3	0.4	0.2	0.0	1.3
Flood Sediment	Channel bank	96.0	2.5	96.5	89.7	99.2
	Greywacke bedrock	0.8	0.6	0.6	0.1	2.5
	Subsoil	2.8	2.3	2.2	0.1	8.7
	Surface soil	0.4	0.4	0.3	0.0	1.6

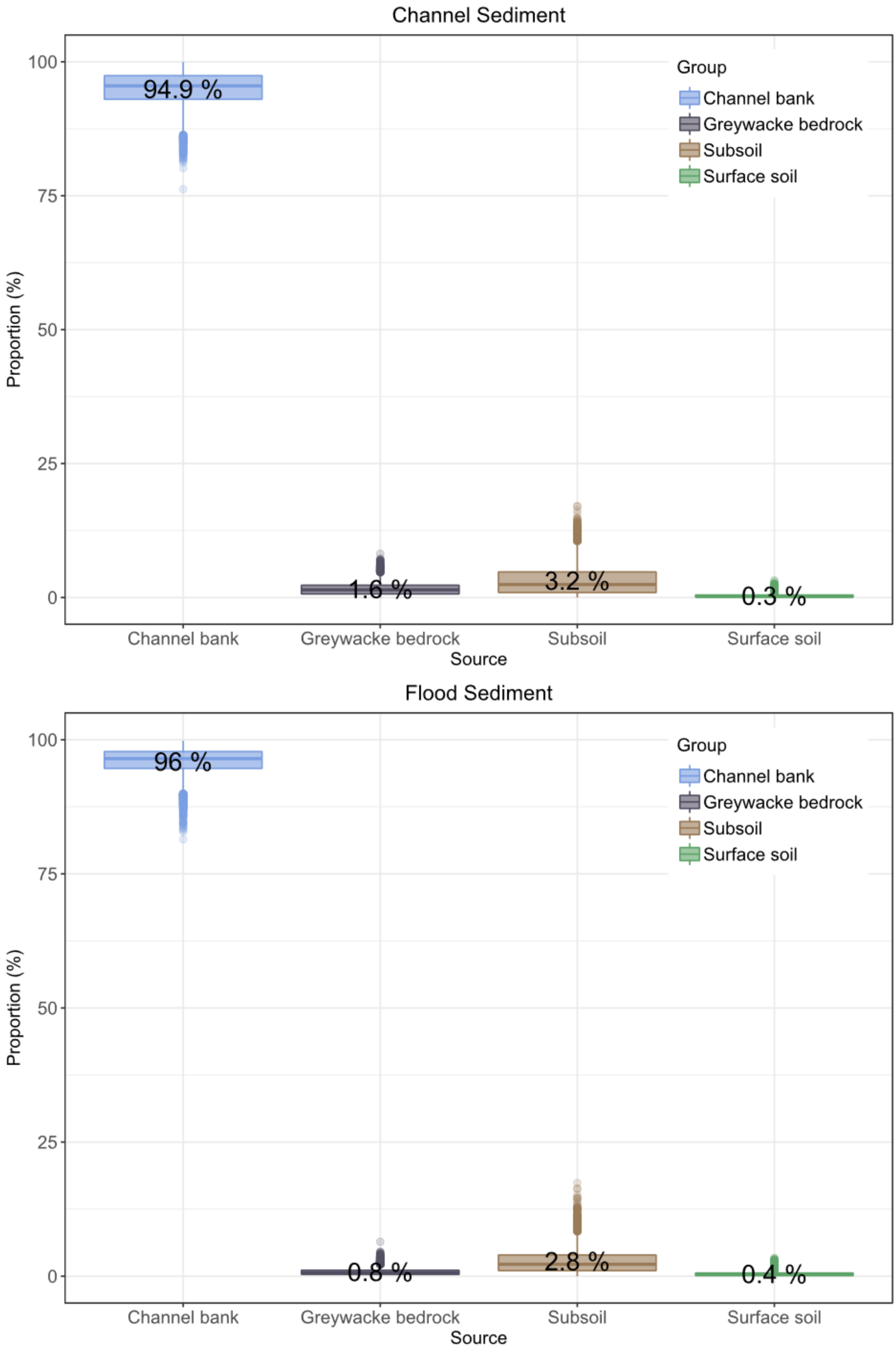

Figure 14. MixSIAR source estimates for channel (top) and flood sediment (bottom). Text indicates mean estimate.

6 Conclusions

Channel bank is estimated to be the dominant source of contemporary fine sediment to the Upper Mōtū river for both channel (~ 95%) and flood sediment (~ 96%). Subsoil, greywacke (which represents quarry sediment), and surface erosion sources provide minor contributions. This aligns with the geomorphological understanding and visual assessment of the catchment. There is negligible evidence of widespread mass movement or slope failures, especially ones that are well connected to the channel network and capable of delivering significant quantities of subsoil to the channel. Subsoil is mostly exposed in the form of farm tracks and road cuttings, which are likely to be the main subsoil contribution. There is limited evidence of bare ground capable of generating significant surface erosion in the catchment. Greywacke bedrock (representing quarry) does not appear to be a significant source of sediment in the catchment. This finding does not rule out the possibility that this source may contribute larger proportional contributions of sediment during specific flow conditions, but this was not evident from the channel and flood deposit samples collected.

Similar proportional source contributions for both channel and flood sediment suggest sources of erosion are relatively consistent between low and high flows, with the flood deposit samples corresponding to approximately bankfull discharge. The lack of evidence for slope failures or subsoil sediment contributions during the high flow event, represented by the flood deposits, reflects the relatively stable landscape. With no hydrological or rainfall data it is unclear what size event the sampled flood deposits may represent; however, larger events may trigger landslides and deliver significant quantities of sediment under the right conditions.

7 Recommendations

Channel banks are clearly the dominant sediment source in the Upper Mōtū catchment. This is confirmed by the sediment fingerprinting results and conforms with our understanding of the geomorphology and associated erosion process within this catchment, and with observations of the extent of active bank erosion. Erosion mitigation strategies should continue to target channel bank erosion to address sediment concerns in the catchment although some sediment is to be expected as part of natural erosion processes in the catchment. Fencing off streams, stock exclusion, buffer strips and re-vegetation are all measures commonly employed for stream bank stabilization and interception. Stock exclusion zones and buffer strips have the added benefit of intercepting other agricultural runoff contaminants (e.g. E. coli, Phosphorus, and Nitrogen), and increasing ecological diversity (DairyNZ 2012). A significant amount of channel fencing and riparian planting appears to have been carried out in recent times so there may be an opportunity to monitor the impact this has on sediment-related water quality in the catchment going forward.

Further sediment fingerprinting analysis would be of benefit for understanding how sediment sources change over time and can be carried out at a relatively low cost. Sediment fingerprinting requires an initial upfront investment to characterize the sediment sources in a catchment. However, once established it is relatively straightforward and cost-effective to sample and analyse additional downstream sediment samples. Sampling protocols can be tailored to address specific questions. These can range from repeat channel or overbank sediment sampling to establish how sediment sources are changing or responding to specific events; installation of time-integrated sediment sampler to trap sediment representative of the flow conditions over a specified time period (e.g. Phillips et al. 2000); or spot sampling during high flow events to provide source information for flows generating the highest sediment loads. This was a pilot-level study, so it is also possible to scale up the number of sources characterized as well as the spatial distribution of sampling.

Additional Upper Mōtū sediment information would be useful to provide context to the relative source proportions estimated using sediment fingerprinting. Sediment load information combined with source proportions from sediment fingerprinting could provide added insight into temporal trends in sediment dynamics. Event-scale suspended sediment load data could be obtained by establishing continuous sediment monitoring stations that enable calculation of discharge and suspended sediment concentration (SSC). Alternatively, models exist for estimating catchment suspended sediment loads on a mean annual basis (e.g. SedNetNZ) and could be employed to estimate sediment load for the Upper Mōtū catchment. A wider study of the whole Mōtū catchment would also provide information about the sediment contribution from the Upper Mōtū relative to the middle and lower reaches of the Mōtū River.

8 Acknowledgements

We thank Gisborne District Council for initiating this work and assisting with land access permissions.

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Appendix 1 – Mean and standard deviations for selected tracers

Sources		MgO	Al_2O_3	CaO	Th	Na_2O	Pb^{206}	Ni	Co	Ta	Ga	TiO_2	SrO	K_2O	n
Channel bank	**mean**	1.017	14.38	0.96	8.813	2.958	12.179	19.32	7.464	1.089	15.044	0.583	214	2.05	10
	s.d.	0.075	0.599	0.254	0.507	0.315	2.649	6.248	0.724	0.046	0.689	0.025	54.238	0.105	
Subsoil	**mean**	0.649	16.329	0.761	12.054	2.355	15.235	10.362	5.128	1.217	17.725	0.517	106.8	1.744	10
	s.d.	0.178	1.526	0.31	1.199	0.454	2.926	2.322	2.172	0.094	1.143	0.109	46.425	0.249	
Surface soil	**mean**	0.519	11.335	1.323	8.353	3.02	10.262	8.52	4.083	1.038	13.651	0.357	159.9	1.945	10
	s.d.	0.306	1.265	0.455	0.93	0.37	0.757	2.337	2.049	0.095	1.825	0.102	93.950	0.18	
Greywacke bedrock	**mean**	2.147	16.466	2.723	8.598	3.835	18.18	213.396	17.23	1.005	17.764	0.8166	484.8	2.358	5
	s.d.	0.469	0.259	1.366	2.942	0.742	8.436	128.741	4.830	0.11	1.208	0.064	265.737	0.473	
Channel sediment	**mean**	1.123	13.883	0.98	8.978	2.444	12.97	19.887	7.901	1.086	15.091	0.597	187.333	1.993	9
	s.d.	0.09	0.569	0.24	0.273	0.313	1.345	2.076	0.715	0.038	0.533	0.043	53.544	0.069	
Flood sediment	**mean**	1.015	13.608	1.026	8.793	3.028	12.815	17.375	6.923	1.079	13.978	0.574	213.5	2.058	4
	s.d.	0.061	0.602	0.34	0.404	0.449	0.561	1.664	0.928	0.035	0.599	0.037	74.7	0.093	