CSSI-based sediment source tracking study for the Maitai River, Nelson

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Contents

Tables

Figures

Executive summary

The proliferation of toxic cyanobacteria (*Phormidium*) blooms in the lower Maitai River is thought to be associated with fine sediment washing into the river from the catchment. Fine sediment typically carries phosphorus bound to the sediment particles, and this phosphorus can be released by *Phormidium,* stimulating its growth. Nelson City Council commissioned the National Institute of Water and Atmospheric Research Ltd to investigate the sources of sediment in the Maitai River system using a forensic compound specific stable isotope (CSSI) technique to answer several key questions:

1. Is plantation forestry contributing a disproportionate percentage of sediment to the river compared to other land uses in the catchment?

2. Is bank erosion contributing a disproportionate percentage of sediment to the river, and if so where are the hot spots?

3. Is it possible to get an estimate of the proportion of sediment from urban runoff?

Sampling for this study was undertaken in December 2016 and the results obtained represent a ‘snapshot’ for the spatial distribution of deposited sediment down the Maitai River from all sources at that time.

Application of the CSSI technique to the Maitai River system found that the land use sources of sediment changed moving downstream from the Maitai Dam. The main sources of fine sediment below the Maitai Dam were recently harvested forest, pine forest subsoils and hill country pasture. Further downstream, sediment sources were dominated by gorse and broom signatures from harvested or recently replanted forest. In the lower reaches, bank erosion became the major sediment source.

These results indicate that plantation forestry blocks, whether recently harvested or covered in gorse and broom, are contributing a substantial amount of sediment to the Maitai River, and to the tributaries draining into the river in the upper and middle reaches. For example, deep scarring associated with the pine harvest and hauler lines on steep hill slopes in the Brook Stream sub-catchment produces almost 20% of the sediment in the lower Maitai River. Areas of mature production forest and native forest are unlikely to be producing substantial amounts of sediment runoff during rainfall events due to extensive leaf canopy protecting the soil from the erosive energy of the rain drops.

Because bank material is often reworked with successive flood events, the distinctive pine signature and signatures of gorse and broom and pasture found in the sediment in the middle reaches of the Maitai River have been blended into an amorphous “bank” signature in the lower Maitai River. Distinctive bank source signatures were found, and obvious areas of bank erosion occur downstream of Groom Creek with an extensive area of bank erosion immediately upstream of the Kaka Hill Tributary. This latter bank erosion may have affected the estimate of sediment contribution from the Kaka Hill Tributary.

There was no indication of a substantial change in the Maitai River’s sediment source contribution through the urban reach in Nelson City. However, the large amount of sediment from Brook Stream may have masked a sediment signature from this source. A more detailed evaluation of the variety of urban soil sources relative to the sediment in the lower Maitai River would be required to identify the proportion of sediment in this reach originating from urban sources.

The main conclusions from this study are:

1. There is no fixed relationship between land use area and the sediment yield from that land use, especially when the plant community (e.g., pine) can be harvested, thereby changing the soil erodibility factors. The sediment yields given in NZ River Maps are not absolute and do not account for changes in land use since they were input in 2008.
2. Native forest and mature pine forest plantations produce very little sediment. Preservation of native forest is an important way to mitigate sediment yield.
3. Harvesting forests produces substantial amounts of sediment. Elevated sediment loads persist for three to five years until canopy closure protects the soil again. Although pine forest is estimated to occupy 26 % of the watershed, only a small proportion of that forest is harvested at any time, emphasising the requirement for implementation of an appropriate management strategy to reduce sediment yield during harvesting.
4. Areas of harvested production forest that are not replanted or have been replanted, but before canopy closure, become colonised by gorse and broom, as well as other weed species. These plants do not provide the canopy cover of mature pine or native forest, and these catchments continue to bleed considerable amounts of sediment into the Maitai River during rainfall events. Mitigation of fine sediment requires a management strategy that highlights the requirement for replanting of harvested pine forest land.
5. Bank erosion is a major source of fine sediment. This material progressively moves downstream as a bedload, which merges with other sediment to become an amorphous sediment source in the lower reaches of the river. Management strategies should identify and require mitigation to target the sources of this sediment.
6. Pasture-derived sediment is likely to have elevated phosphorus content, which will support and stimulate cyanobacteria growth. Management strategies should identify and require mitigation of the sources of pastoral sediment, to reduce phosphorus loads entering the Maitai River.

1 Introduction

Fine sediment has been identified as a potential driver for toxic cyanobacteria (Phormidium) blooms in the Maitai River (pers. comm. Jo Martin, NCC). Cyanobacteria growth is exacerbated by elevated phosphorus (P) concentrations in the water, and fine sediment is the main transport vector for P aquatic ecosystems. Nelson City Council (NCC) commissioned the National Institute of Water and Atmospheric Research Ltd (NIWA) to investigate the sources of sediment in the Maitai River system using the compound specific stable isotope (CSSI) technique developed by NIWA. NCC raised several key questions they would like answered by this study:

1. Is plantation forestry contributing a disproportionate percentage of sediment to the river compared to other land uses in the catchment?

2. Is bank erosion contributing a disproportionate percentage of sediment to the river, and if so where are the hot spots?

3. Is it possible to estimate the proportion of sediment from urban runoff ?

This report presents the results of the CSSI study designed to answer these questions.

1.1 Background

The Maitai River rises above Nelson city in the forested hills, with predominantly volcanic basic and hard sedimentary geology, and includes a large headwater water storage reservoir on the North Branch (Maitai Dam, 36 m high, 32 ha area), and an intake weir on the South Branch which together provide water for Nelson City (Figure 1-1).

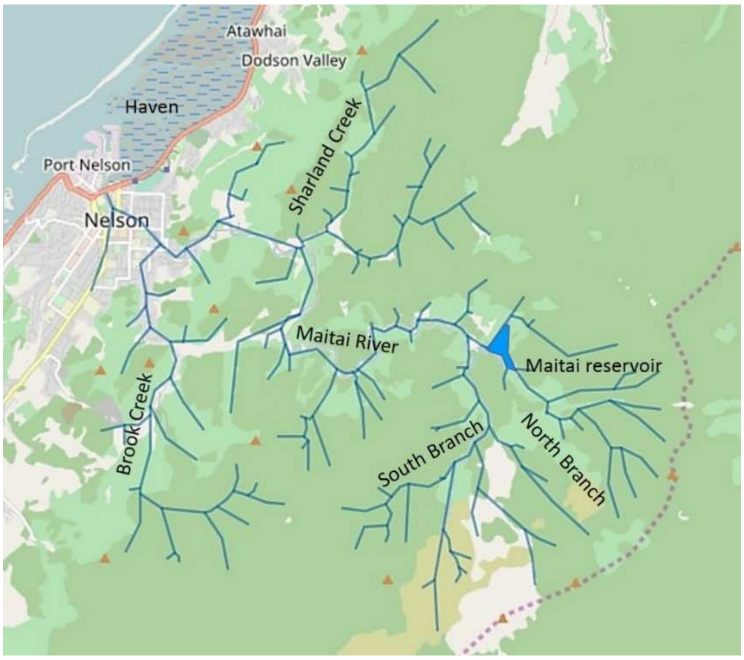

Figure 1-1: Maitai River system showing the main channel, tributaries and the Maitai reservoir. The Maitai River flows through Nelson city and discharges into the Haven (estuary behind the bolder bank) at the Port of Nelson.

Tributaries joining the upper part of the Maitai River from the reservoir downstream as far as the Sharland Creek confluence, come from steep land with different land use types including plantation pine forest, native forest, high country grassland/pasture, and gorse and broom on replanted forestry blocks before canopy closure and un-replanted harvested forestry blocks. Lower down the Maitai River, there is pastoral farming and urban development. These are the main land use classes in the Maitai River watershed (Table 1-1), which has a total area of 90 km^2.

Table 1-1: The main land use coverage (%) in the Maitai River watershed. Data extracted from the Land Cover database[1]

Pine forest	Native forest	Gorse & Broom	Pasture	Urban	Bank
26.7	46.3	15.6	6.6	3.6	1.2

Earth works, associated with unsealed roading infrastructure, walking and mountain biking tracks, the installation of a new water pipeline and deep scouring of the steep hill faces during harvesting of pine forests, are obvious potential sources of soil that could contribute to the sediment loads in the Brook Stream catchment. Less obvious sources include diffuse soil sources inputting sediments directly into the Maitai River from the catchments between tributaries, and bank erosion along the length of the Maitai River. Examples of the land use sites are shown in the photos in Appendix D.

Although the gradient of the Maitai River below the dam is classified as 'low', there are many boulder reaches with swift flowing water (greater than 0.2 m s^{-1}). These velocities do not allow fine sediment to settle in those reaches, and the bed of the river is essentially clean cobbles with sandy areas, although smaller particles do settle in backwaters along the river edge. Even in the reaches downstream of the Sharland Creek confluence, little sediment settles until the freshwater encounters the tidal reach where flocculation with the salt water aids settling. Consequently, at low flow, the Maitai River appears clear with a slight yellowish tint, which probably comes from the Maitai reservoir as that water appears to be dystrophic i.e., 'tea stained'. At high tide the lower river has a substantial cyanobacteria bloom.

The Maitai River has frequent spates, with 16-20 events per year exceeding 3 times the annual median flow (REC information in NZ River maps, https://shiny.niwa.co.nz/nzrivermaps/) in the main stem of the river and for different tributaries. This is a major factor limiting accumulation of fine sediment in the river bed. The 'flashy' response to rainfall means the Maitai River rises quickly during rain events, becoming highly turbid (Figure 1-2), with high suspended sediment concentrations which are discharged out into the Haven. For example, a heavy rainfall event over 11-15 April 2017 delivered up to 260 mm rain to the Maitai River catchment. This event was observed to produce bank full turbid water at Trafalgar Street Bridge on 12th April for a period of around 24 h. This would have generated an estimated peak flow of around 70-75 m^3 s^{-1}.[2]

[1] https://lris.scinfo.org.nz/layer/423-lcdb-v41-land-cover-database-version-41-mainland-new-zealand/

[2] Peak flow measured at the Avon Tec recorder was 111.348 m^3 s^{-1}, with a mean flow of 42.617 m^3 s^{-1} between 12-Apr-2017 at 03:30 am and 13-Apr – 2017 24:00 pm (pers. comm, Jo Martin, NCC.)

Figure 1-2: Maitai River at low tide A) under dry conditions (December 2016) and B) during a rain event (April 2017). During the 11-15 April 2017, high rainfall event, about 260 mm rain fell in the Maitai River catchment producing a bank full turbid flow. The water velocity was estimated to be about 2 m s^{-1} and the river was about 2 m deeper than normal beneath the 22-m width at Trafalgar Street bridge, giving an estimated flow of about 70-75 m^3 s^{-1} over a 24 hr period

If the suspended sediment concentration in the flood water was around 20 g m^{-3}, this single event could have transported more than 120 tonnes of sediment per day. However, when the flood water had subsided, there was little evidence of silt deposition on the river bed during the event, indicating that it had been mostly discharged into the Haven.

Where did this sediment come from?

2 Methods

2.1 Overview of the CSSI technique

The catchment sources of fine sediment deposited in the Maitai River were identified using the forensic compound specific stable isotope (CSSI) techniques developed by NIWA for this purpose (Gibbs 2008). The approach taken was to 1) assess the proportional contribution to downstream deposited fine sediment below each major tributary confluence using a linear two end-member mixing model applied to data on the sediment characteristics from upstream and downstream of the tributary and the tributary itself, and 2) deconstruct the deposited sediment at each sampling location into its source proportions by land use, and 3) sum the land use proportions.

The sediment characteristics used were percent organic carbon (%C), the bulk carbon-13 (^{13}C) signature of the sediment and the isotopic signatures of the fatty acid (FA) biomarkers produced by the plant communities growing on the land. The FA biomarker isotopic signatures are conservative and are not affected by decomposition processes that change FA concentrations.

The plant community growing on the land is used to define the land use. The CSSI technique relies on the fact that all plants produce a specific range of FAs from their root systems (Figure 2-1). Because each plant species uses a different photosynthetic pathway to produce these FAs, the isotopic signature of the carbon-13 (^{13}C) in the FA molecules is different for each plant species. These FAs are slightly water soluble, allowing them to disperse through the soil adjacent to the plant roots during rainfall infiltration. Because they are polar, the FAs bind to the fine soil particles and become biomarkers or labels for that soil and thereby provide a way to trace the land use origins of eroded soils.

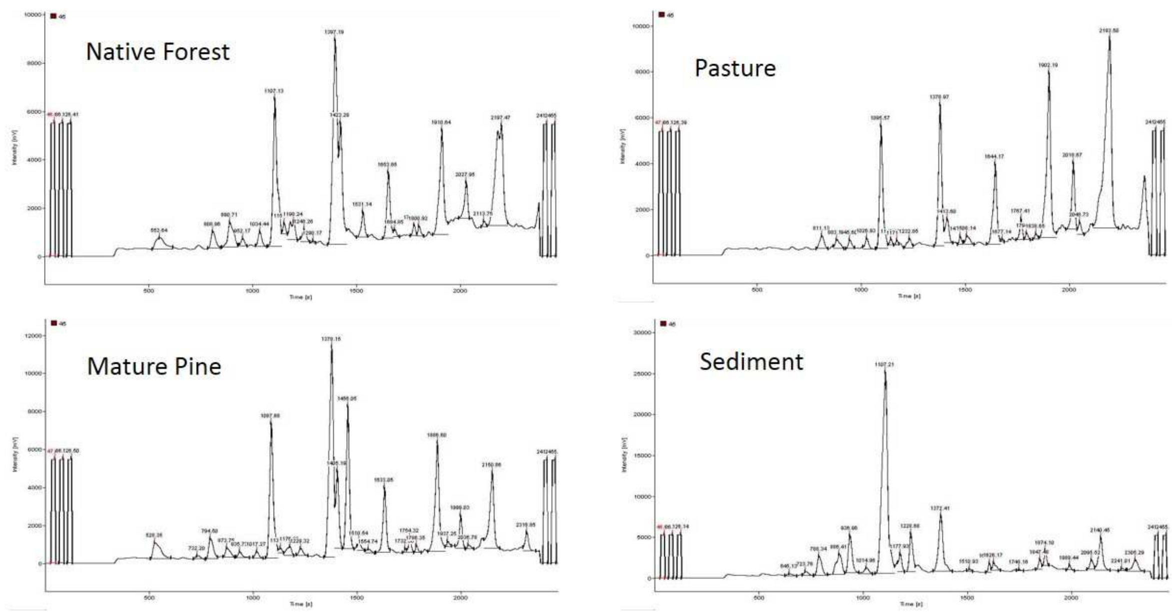

Figure 2-1: Chromatogram fingerprints of saturated fatty acids produced by three different plant species and an example of the fatty acid content of a deposited sediment. These are fatty acid concentrations as extracted from the soil. Each peak has an isotopic signature specific to the specified plant. While concentration decreases in the deposited sediment, the isotopic signatures remain unchanged.

The soil eroded from each land use mixes in the river and the resultant sediment is a mixture of all contributing soil sources in the proportions the soil was carried into the river. As the water flows downstream, other soil sources from riverside catchments, or sediment mixtures from tributaries, are added to the river, changing the relative proportions of each land use soil source in the sediment mixture. If a specific land use is not being eroded, it will contribute a disproportionally small amount to the downstream sediment mixture, or none at all.

Factors that influence the amount of erosion from any land use include the amount of leaf canopy that can protect the land from the erosive energy of rain drops, the extent of plant root mat that can hold the soil, the intensity of the rainfall, the slope of the land, the type of soil and the pre-rainfall event history of soil wetting or drying.

To identify the sources of soil contributing to a sediment mixture, the mixture is un-mixed or 'deconstructed' into its source soil components using a stable isotopic mixing model (SIMM). A SIMM requires reference information about the possible soil sources in the catchment. This information is obtained by collecting samples from each land use as a reference library of land use soil types for the river system.

The outputs from the SIMMs are calculated in terms of isotopic proportions and are corrected back to soil proportions post analysis using a simple linear scaling equation, based on the relative concentration of total organic carbon (%C) in each land use reference library soil sample (Gibbs 2008).

2.2 Errors and uncertainty

Because of the complexity of this forensic process, there will be compounding errors in each step and these provide a level of uncertainty in the final results. The analytical error terms are typically <± 0.5% and the modelling errors are likely to be <± 5%. The largest errors occur during sample collection and must be addressed in the sampling programme design.

To reduce sampling errors for the reference library, a set of 10 or more uniform sized small soil samples were collected from an area of about 100 m^2 in each land use type and combined into a single bulk sample. Where possible, three replicate bulk samples were collected from each land use type at different locations within the watershed. For the river sediment samples, it was assumed that the mixing within the river system prior to deposition of the sediment was sufficient to produce a homogeneous sample, allowing a single bulk sample to be collected at each river confluence site.

2.3 Sampling

2.3.1 River confluence sampling

A confluence sample comprises three river samples – one from the main stem upstream of the tributary, one from the tributary, and one downstream of the confluence with the tributary in the main stem of the river, far enough downstream to ensure that complete mixing has occurred. This distance is dependent on channel morphometry - a bend in the river or a riffle usually being sufficient to induce complete mixing.

River sediment samples were collected in December 2016 using a nylon hand trowel to scrape the surface layer from the deposited material (i.e., the most recently deposited sediment) from 23 confluence sites (Appendix A) down the Maitai River, in Sharland Creek and in Brook Stream (Figure 2-2). The samples were stored in sealed plastic bags at room temperature in the dark, pending transport to the laboratory, where they were sieved (2 mm mesh) and freeze dried ready for analysis.

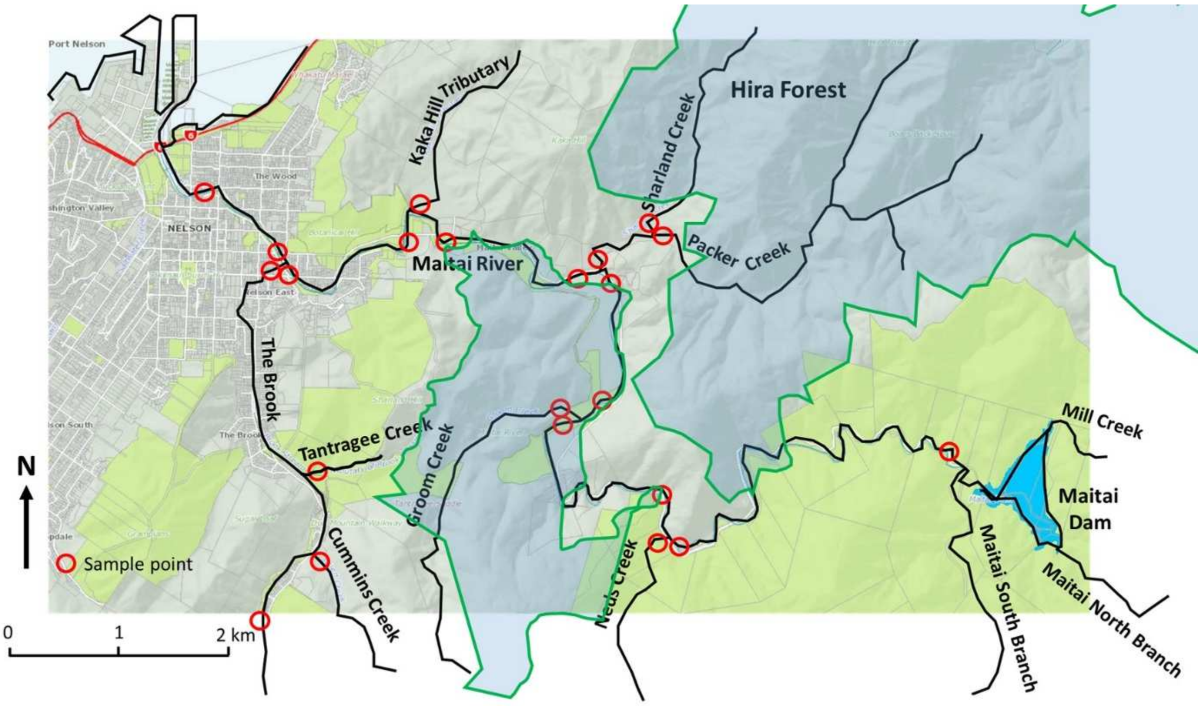

Figure 2-2: Site map showing the relative positions of the confluence samples (red circles) along the Maitai River, Sharland Creek and the Brook. The largest land use type block is the Hira Forest (grey) and other forest land, mostly indigenous native forest, is shown in green. The Kaka Hill Tributary drains primarily pastoral farm land.

Figure 2-3: Harvested pine forest hillside near the head of the Brook sub-catchment. A) shows the extent of soil disturbance across the face of the hill and **B**) the depth of the erosion control and roading earth works. Photos April 2016.

A library of 17 land use reference samples was created, comprising three pasture, four bank, two pine mature, three pine recently harvested, one pine subsoil, one gorse and broom on harvested pine forest land, one native bush, one road infrastructure and one deep subsoil (Appendix B). The latter sample was associated with the pipeline in the Tantragee Creek (underlying pine soil) and was likely to represent the deep scarring observed on the steep hills near the head of the Brook Stream sub-catchment where pine forest was harvested (Figure 2-3).

Access to the Hira Forest was not possible, so samples representing harvested *Pinus radiata* forest and associated subsoils were collected in adjacent pine forestry blocks, outside the Maitai River watershed. While use of these samples is unlikely to compromise the CSSI technique, they introduced additional uncertainty to the final results.

2.4 Isotopic modelling

2.4.1 Confluence modelling,

A linear two end-member mixing model was applied to each confluence sampling point using the data from the main stem of the river upstream and downstream of each tributary, and the tributary itself. This type of model is linear and meets the criteria of having n+1 sources for n tracers, giving the results low uncertainty i.e., at a confluence each tracer can be used separately in the two end-member mixing model. However, the degree of variability in some tracers render them unsuitable for this type of modelling, and these cannot be used. The following method was used for two end-member modelling:

The $\delta^{13}C$ isotopic signatures of the bulk soil and the FAs extracted from the soil were collated with the %C values, providing a set of up to 11 tracers. The river bed deposition samples were separated into confluence triplicates and the proportional contribution of the tributary at each confluence was determined using the two-end member linear mixing model. This model assumes that the %C or $\delta^{13}C$ isotopic value of each FA in the downstream site sediment mixture is the sum of the %C or the $\delta^{13}C$ isotopic values of the corresponding FA from the upstream sources, A and B, where A can be the tributary and B can be the main stem of the river.

$$\delta^{13}C_{mixture} = fA\delta^{13}C_A + fB\delta^{13}C_B \tag{1}$$

Where fA and fB are the fractions or proportions of each source. This equation can also be rewritten

$$1 = fA + fB \tag{2}$$

To solve for fA, equation (1) is rewritten as:

$$fA = (\delta^{13}C_{mixture} - \delta^{13}C_B)/(\delta^{13}C_A - \delta^{13}C_B) \tag{3}$$

and for fB, the equation is rewritten as:

$$fB = (\delta^{13}C_{mixture} - \delta^{13}C_A)/(\delta^{13}C_B - \delta^{13}C_A) \tag{4}$$

The caveat for the two-endmember mixing model is that the %C or the $\delta^{13}C$ value of each FA in the mixture must be on a straight line between the corresponding %C or the $\delta^{13}C$ values of each FA in the sources A and B.

Example

Theoretically, only tributaries upstream of the confluence contribute to the downstream mixture, and both upstream sources should be dissimilar. However, because current flow in a river system can rework deposited sediments, including those deposited prior to current land use patterns (winnowing), or there is an unknown source between the confluence and the downstream sampling site (e.g., bank erosion), there may be variability in the isotopic signatures of mixtures in the deposition zone resulting in non-valid values. These results from equation (3) and (4) are either negative values or values >1, and are discarded (Table 2-1). Identification of valid feasible results from the full suite of two end-member mixing model results can be confirmed with a linearity test (Figure 2-4). In this example, the tracer pair C18:0 and C20:0 biplot of the sources and mixture produced a valid straight line through all points indicating that both tracers can be used in the two end-member mixing model. In contrast, the tracer pair C18:1 and C20:0 (Figure 2-4) do not fit to a straight line through all points, indicating that one of the pair of tracers should not be used in the two end-member mixing model. Because the tracers C18:0 and C20:0 have already been accepted as valid tracers from the C18:0 vs C20:0 linearity test, the tracer C18:1 is the cause of the failure and should not be used.

The two end-member model can be run in a spreadsheet and the results can be averaged to give a mean and standard deviation (Table 2-1). Tracers %C, d13C and C18:1w9c were identified as invalid (see above) and those values were not included in the statistical evaluation of the example results.

Table 2-1: Example set of two end-member data with results including means and standard deviation. Source data are highlighted in yellow, A is the tributary and B is the main stem of the river upstream of the confluence. The mixture value must lie on the straight line between the values of A and B (Figure 2-4). See text for determination of invalid data..

	%C	d13C	c12:0	c14:0	c16:0	c18:0	c18:1w9c	c18:2w6c	c20:0	c22:0	c24:0	Mean	Stdev
Mixture	6.91	-25.51	-26.77	-28.29	-25.96	-28.32	-27.18	-26.17	-30.40	-30.15	-28.80		
Source A	4.26	-29.85	-30.45	-34.97	-34.77	-31.43	-30.94	-30.10	-32.37	-33.63	-33.53		
Source B	5.05	-26.13	-23.39	-24.36	-22.79	-24.46	-26.36	-22.60	-28.35	-26.89	-24.01		
FA	-2.36	-0.16	0.48	0.37	0.26	0.55	0.18	0.48	0.51	0.48	0.50	0.46	0.09
FB	3.36	1.17	0.52	0.63	0.74	0.45	0.82	0.52	0.49	0.52	0.50	0.54	0.09

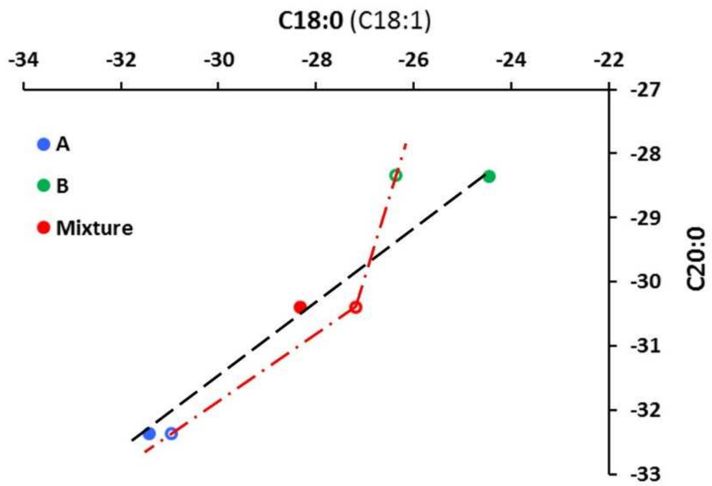

Figure 2-4: Linearity test used to confirm valid data for the two end-member mixing model. Solid dots are valid data (C18:0 vs C20:0). Open circles are invalid data (C18:1 vs C20:0). (See text). (Diagram by M. Gibbs).

Tracer C16:0 may also be invalid but has been included in the example to show that even borderline data will have only minor effects on the final result, although their inclusion will increase the variability of the output. In this example the results indicate that source A contributed 46% ± 9% and source B contributed 54% ± 9% of the sediment to the mixture in the deposition zone.

2.4.2 Soil source modelling

Land use source selection for the modelling process relied on a polygon analysis (Figure 2-5). In this procedure, a biplot is drawn including all sources and the mixture, using the isotopic values of pairs of FAs. In the example (Figure 2-5), the FAs used were oleic acid (C18:1) and arachidic acid (C20:0). All sources are plotted individually to allow appropriate source selection or grouping.

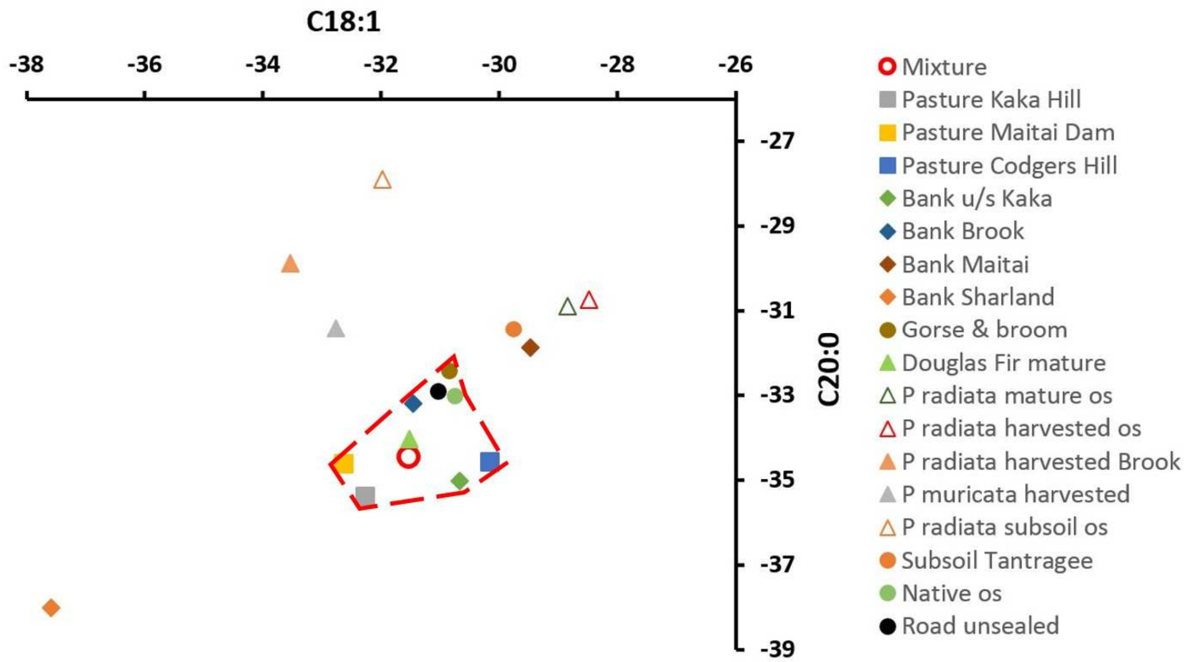

Figure 2-5: Example of a polygon analysis on a fatty acid (FA) biplot of the potential sources that could contribute to sediment at the site downstream of Kaka Hill Tributary. The red dashed line is the polygon that links the sources closest to the mixture. These sources are the most likely to be contributing based on the fatty acids C18:1 and C20:0. (os = sample collected outside the Maitai River watershed).

For a valid source selection, the mixture isotopic values must lie within the bounds of a group of land use soil source isotopic values that can be connected with straight lines (Figure 2-5), forming a polygon. In this example, the sources selected were those closest to the mixture, in terms of their CSSI signature and therefore not obscured from the mixture by other closer sources. The nine sources selected include the three pasture sources, two of the bank sources, the Douglas Fir source, gorse and broom, native forest and the unsealed road sources. Sources outside this polygon may also be valid but they are less likely to be contributing substantial proportions of soil to the mixture.

When used in the biplot, other combinations of FAs produced polygons with slightly different relationships between the sources and the mixture. Polygon analysis of all samples showed that best results were obtained using the FA tracers between C18:1 and C22:0. Outside this range, the results were mostly invalid. Consequently, all modelling used the FA tracers C18:1, C18:2, C20:0 and C22:0, giving us four tracers. It should be noted that just because these nine sources fall within the bounds of the polygon does not mean that they will all be contributing to the mixture in equal proportions, and the mixing model may determine that one or more tracers are only present in very small amounts, while others will be major sources in the mixture.

In a constrained model, four tracers can accommodate 5 sources. In this example there are 17 sources, which means the model is unconstrained i.e., there are too many sources. To resolve this problem some of the sources can be eliminated and the first cut would be to exclude those sources outside the polygon. An alternative approach is to combine sources from similar land uses and use the average value. This approach is taken in the Bayesian mixing model MixSIAR (Stock & Semmens 2015), where the mean value ± the standard deviation are used in the model to provide estimates of uncertainty. The data in Figure 2-5 shows substantial differences in the isotopic signatures from nominally similar land uses, but from different locations in the watershed (e.g., the bank material and the pine). These differences are likely to reflect the plant community growing with the main land use plant i.e., the understory beneath pine forest and the different plants that have colonised deposition material that form the river banks. The previous land use can influence the composition of pasture samples. These differences are too large to be combined in a single land use and need to be used as unique land uses, and as site-specific sources. In this case, source reduction can be achieved by using only those sources from sites closest to the mixture site i.e., a geographical constraint.

The Maitai River catchment is deeply incised and forest understory plant composition will be influenced by local variations in light and moisture. These factors have the potential to produce localised communities with different species abundances from those in a similar land use but in an adjacent valley with a different aspect and weather conditions. For this reason, a geographic constraint was applied to the Maitai River system by using the land use library samples closest to each river sampling point, in preference to averaging the sources of the same land use type. In the example (Figure 2-5), the bank erosion sample isotopic signatures were diverse and would have produced high uncertainty. Hence, the local bank erosion reference sample was used. In contrast, the pasture source samples gave a much tighter grouping around the mixture, and could have been averaged. That all pasture samples formed a tight group indicates that the grass is a more consistent plant community. The grouping around the Kaka Hill Tributary sediment is consistent with the Kaka Hill Tributary sub-catchment being predominantly pastoral land.

Low replicate numbers of each land use type and high variability within land use types precluded the use of Bayesian Mixing models to select source isotopic signatures. Consequently, SIMM modelling used IsoSource (Phillips and Gregg 2003). This model uses individual source samples and performs a numerical calculation of all possible combinations of the selected source isotopic signatures. The model then picks those combinations of sources that produce isotopic balances closest to the isotopic values of the mixture being tested, within a user defined tolerance from the isotopic value of the mixture. These are 'feasible' solutions, which are then ranked by their frequency of occurrence in the matrix of isotopic balances to produce a histogram of all feasible solutions. Because these feasible solutions are not produced from a model algorithm, there is no linkage between the results that can justify the use of one combination of sources over any other and all feasible solutions could be correct. Consequently, the accepted convention for reporting the results from the IsoSource model is to report the range of results instead of focusing only on the mean. Notwithstanding this, a comparison of IsoSource output with three other Bayesian SIMM output using the same input data found that the mean ±SD value from IsoSource was in good agreement with the mean ± SD from the other three models (Mabit et al. in press.).

In this study, IsoSource was used to identify the soil source proportions contributing to the sediment mixture at each confluence site and the results have been reported as mean ± SD feasible isotopic proportions. The mean value is used to convert isotopic proportions to soil proportions (Gibbs 2008).

For practical reasons (long run times), the number of sources and FA isotopes used in IsoSource is typically limited to nine and five, respectively. Furthermore, the model is more efficient with fewer sources. Consequently, the model was run iteratively, initially using the sources selected from the polygon test, then eliminating those sources where the previous iteration had determined little or no soil contribution to the mixture. This process continued until the sources being tested all showed significant positive proportional contributions to the mixture. At each iteration, the model gave "n" feasible solutions. At the optimum source combination and tolerance, the value of n is minimised, approaching 1, which would be a unique solution with no error. At n values greater than 1, the level of uncertainty is defined by the standard deviation about the arithmetic mean of the feasible solutions. Values of n up to around 1000 may be acceptable but indicate a possible missing source or the inclusion of an inappropriate source. The shape of the histogram indicates whether there is 'coupling' between some sources. These will have low broad peaks that can extend over more than 50% of the feasible solutions. Where two sources are coupled, they will have the same broad histogram shape. Removing one of these two sources from a model iteration often produces a well-defined peak and a reduction in the value of n. If the two sources can be averaged, they should be, but if they are very different land use types, the source with the highest organic carbon content ($\%C_{org}$) should be removed as this will contribute least to the mixture when the results are converted from isotopic proportions to soil proportions.

The results from all SIMMs are presented as calculated isotopic proportions. Isotopic proportions are associated with the carbon content of the soil sources. The carbon content of a soil sample is typically between 2% and 10%, but may range from 0.1 % (fine sand and clay subsoils) to 30% (organically rich surface soils from native forest and mature pine forest floors). A high organic carbon content source requires less of that source to achieve isotopic balance. Conversely, more of a low organic carbon content source is required to achieve isotopic balance. This relationship is defined by a simple linear scaling equation (Gibbs 2008), and this was used to convert the isotopic proportions to soil proportions.

2.4.3 Database information

Two national databases were used for assessing the potential sediment loads in the river and tributaries (predictions from the annual suspended sediment yield national model of Hicks et al. (2011) as presented in NZ River Maps[3], and the land use cover in each sub-catchment in the Maitai River watershed from the Land Cover Database (LCDB[4]). The NZ River Map database has a range of data nodes down the length of each river with a large range of river environment classification (REC) information at each node. The REC data are cumulative for each node down the river system such that the value at each node includes all values upstream of that node.

In this study we have used the REC information from NZ River Maps for catchment area and estimated annual sediment load at each sampling point corresponding with a node down the main stem of the river and in the tributaries. The REC from the Maitai River for annual suspended solids load are shown in Figure 2-6.

[3] https://shiny.niwa.co.nz/nzrivermaps/
[4] https://lris.scinfo.org.nz/layer/423-lcdb-v41-land-cover-database-version-41-mainland-new-zealand/

There is also REC information on land cover in the NZ River Maps database, but this only gives the major land use at each node whereas there are many different land uses in the catchment upstream of each node. To overcome this limitation, the complete land cover information upstream of each node was extracted from the LCDB.

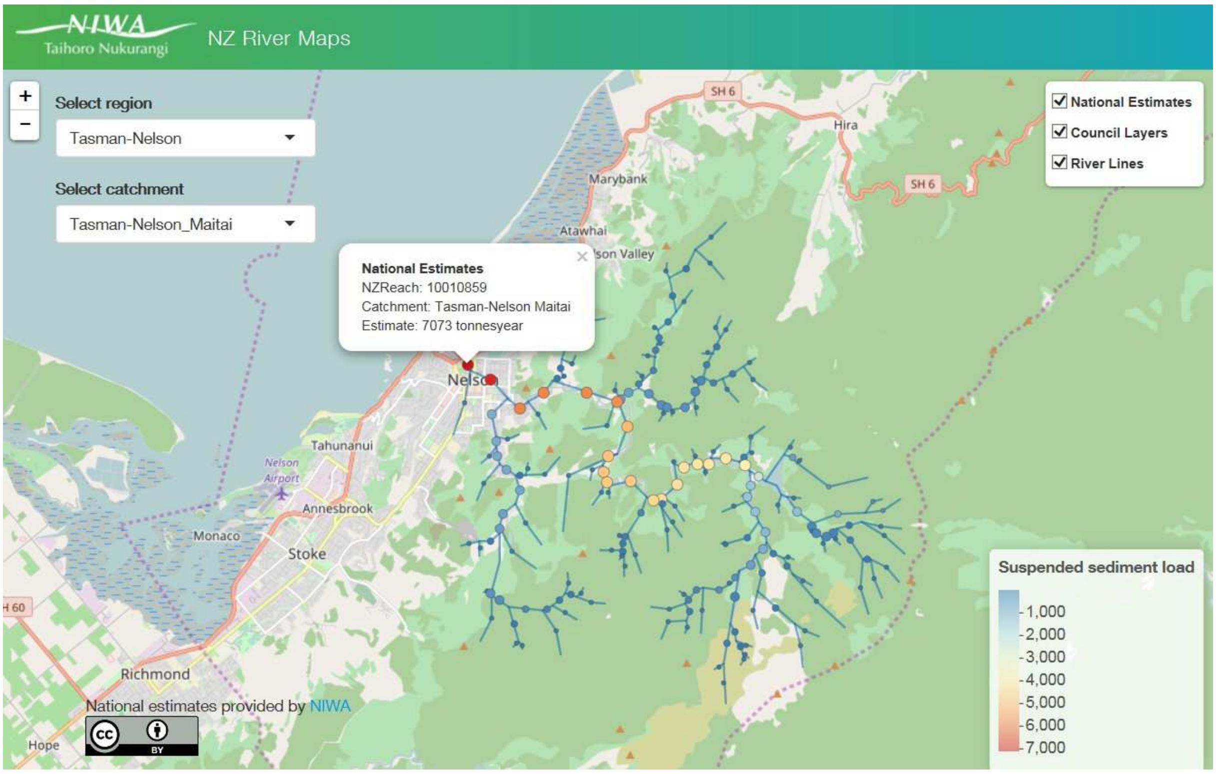

Figure 2-6: Example of the River Environment Classification (REC) for predicted Suspended Sediment load in the Maitai River from NZ River Map. Nodes are defined by round dots - clicking on any of them will produce a tab (example shown for the last node on the river) representing the cumulative information for the river system upstream from that node. Sediment loads are in tonnes per year.

Cautionary note:

Some of the REC information in NZ River Maps are not absolute values and represent the outputs of models that have been made at the national scale (Hicks et al. 2011). While these predictions are as accurate as possible (given the data used to make them), national predictions at unvisited sites are designed to represent regional patterns and should not be used to replace site-specific studies, i.e., the predicted REC values in NZ River Maps may differ from the observations made in the field.

3 Results

3.1 Confluence modelling

A linear two end-member mixing model was applied to sediment isotopic data at the confluence of each tributary entering the Maitai River (see section 2.4.1) (Table 3-1). In most cases, the two end-member mixing model result was the average of 3 or 4 valid calculations, giving the results relatively high certainty. The exceptions were Ned Creek, Sharland Creek and Brook Stream, where the modelling produced a single result, indicating potentially higher uncertainty in those results. The cause of this effect is unknown, but may indicate that an additional sediment source between the tributary and the downstream site may not be unaccounted for. This is certainly possible in the Brook Stream sub-catchment, where there is about 470 ha (5% of total watershed area) between Tantragee Creek tributary and the confluence with the Maitai River, including about 150 ha of urban land use (Table 3-1).

In Table 3-1, the CSSI sediment results and the NZ River Map Suspended Sediment Load estimates were normalised to 100% at the lower Maitai River site, the site furthest downstream in the catchment. Then these data were scaled lineally at each sampling location according to the proportional contribution at each tributary for direct comparison using the two end-member mixing model estimates for the CSSI results and the suspended sediment estimates for the NZ River Map results.

Table 3-1: Confluence analysis for the Maitai River plus Sharland Creek and Brook Stream sub-catchments. The column "% of total" shows the relative proportion of sediment derived from upstream at each location. Site locations are shown on Figure 2-2. Catchment areas and sediment load data were extracted from NZ River Maps (RM). The CSSI data were obtained from the two end-member mixing model results. The levels of uncertainty in the CSSI results are 8.4 ± 1.7 %. (-- = no data).

Sample number	Site name at confluence	Catchment area (ha)	% of total catchment area	Sediment load ($t\ y^{-1}$)	Sediment load % of total (RM)	Sediment load % of total (CSSI)
OA194/5	Maitai below Dam	3327	36.9	2350	33.6	2.4
OA194/7	u/s Neds	4003	44.4	4384	62.7	23.7
OA194/8	Neds	338	3.7	251	3.6	1.2
OA194/9	d/s Neds	4439	49.3	4703	67.3	--
OA194/11	u/s Groom	4605	51.1	4773	68.3	27.2
OA194/10	Groom	210	2.3	102	1.5	9.1
OA194/12	d/s Groom	4949	54.9	4991	71.4	--
OA194/15	u/s Sharland	4949	54.9	4991	71.4	36.3
OA194/14	Sharland	1555	17.3	757	10.8	14.1
OA194/16	d/s Sharland	6505	72.2	5758	82.4	--
OA194/23	u/s Kaka	6720	74.6	5813	83.1	50.4
OA194/20	Kaka	267	3.0	41.7	0.6	18.6
OA194/22	d/s Kaka	7064	78.4	5878	84.1	--
OA194/26	u/s Brook	7164	79.5	5912	84.6	69.0
OA194/25	Brook	1761	19.6	1023	14.6	31.0
OA194/27	d/s Brook	9008	100.0	6991	100.0	--
OA194/18	Lower Maitai	9008	100.0	6991	100.0	100.0
OA194/34	Sharland u/s Packer	734	8.2	224	3.2	8.0
OA194/33	Packer Ck	750	8.3	524	7.5	6.1
OA194/14	Sharland	1555	17.3	757	10.8	14.1
OA194/2	Brook u/s Tantragee	1155	12.8	789	11.3	19.8
OA194/3	Tantragee	133	1.5	38.4	0.5	11.2
	Urban ?	473	5.0	196	3.0	--
OA194/25	Brook	1761	19.6	1023	14.6	31.0

3.2 Land use Modelling

The isotopic mixing model results used to identify land use sources were corrected to soil proportions and then expressed in terms of % of total sediment in the river, normalised to the load at the lower Maitai River site (Table 3-2) (defined as 100%, assuming the deposited fine sediment signatures are representative of the total sediment load), as calculated for Table 3-1. This means that the % of total sediment at any site is the proportional contribution of sediment upstream of that site to the river system. If the mass transport of sediment (e.g., mass per time) is known at any point, these % of total sediment values can be converted to mass transport information. For example, the estimate of 120 t d^{-1} sediment transport during the April 2017 flood event (section 1.1) could be converted into sediment load in t d^{-1} at each site up the river and subsequently erosion rates expressed in t ha^{-1} d^{-1} from each sub-catchment. If the land cover areas are known for each sub-catchment, the rate of soil loss from each sub-catchment by land use can also be estimated.

The main land use soil sources contributing sediment to the Maitai River down its length were identified as pine harvested, pine subsoil, gorse and broom, pasture and bank, including subsoil (Table 3-2).

Table 3-2: Soil source contributions to the fine deposited sediment of the Maitai River system at each of the confluence sampling points. The column "% of total sediment" shows the relative proportion of sediment derived from upstream at each location normalised to 100% at the lower Maitai River site. The other columns show source contributions by land use in the % of total at each site. (Orange highlights include deep subsoils. -- = no valid estimate from the two endmember mixing model, use the value from the next site downstream.)

Sample number	Site name at confluence	% of total sediment	Pine mature	Pine harvested	Pine subsoil	Gorse & Broom	Pasture	Bank
OA194/5	Maitai below Dam	2.4	0.0	50.4	29.6	0.8	18.8	0.0
OA194/7	u/s Neds	23.7	0.0	43.9	20.9	0.5	11.6	22.3
OA194/8	Neds	1.2	0.0	3.3	0.0	0.0	0.0	95.0
OA194/9	d/s Neds	--	0.0	10.3	0.0	0.0	0.0	93.6
OA194/11	u/s Groom	27.2	0.0	9.7	0.0	0.0	0.0	93.9
OA194/10	Groom	9.1	0.0	0.4	1.8	88.7	0.3	8.4
OA194/12	d/s Groom	--	0.0	0.4	1.8	89.2	0.6	8.7
OA194/15	u/s Sharland	36.3	0.0	3.0	18.9	62.9	0.4	15.2
OA194/14	Sharland	14.1	2.9	6.2	1.3	69.4	0.0	20.3
OA194/16	d/s Sharland	--	2.7	8.2	1.2	65.0	3.9	19.0
OA194/23	u/s Kaka	50.4	2.6	7.9	1.3	61.5	7.5	17.9
OA194/20	Kaka	18.6	0.0	1.2	0.0	3.2	84.1	11.7
OA194/22	d/s Kaka	--	0.0	7.9	0.0	35.7	17.1	39.3
OA194/26	u/s Brook	69.0	0.0	39.5	7.9	18.7	8.9	24.9
OA194/25	Brook	31.0	0.0	1.9	0.0	0.6	9.9	87.4
OA194/27	d/s Brook	--	0.0	2.7	0.0	0.1	1.6	95.4
OA194/18	Lower Maitai	100.0	0.0	2.6	0.0	0.0	10.4	87.0
OA194/34	Sharland u/s Packer	8.0	0.5	0.0	30.5	68.8	0.0	0.9
OA194/33	Packer Ck	6.1	0.0	0.2	1.0	74.8	23.6	0.0
OA194/14	Sharland	14.1	2.9	6.2	1.3	69.4	0.0	20.3
OA194/2	Brook u/s Tantragee	19.8	0.0	14.7	0.0	3.3	0.0	82.2
OA194/3	Tantragee	11.2	0.0	0.0	0.0	0.2	3.6	96.0
OA194/25	Brook	31.0	0.0	1.9	0.0	0.6	9.9	87.4

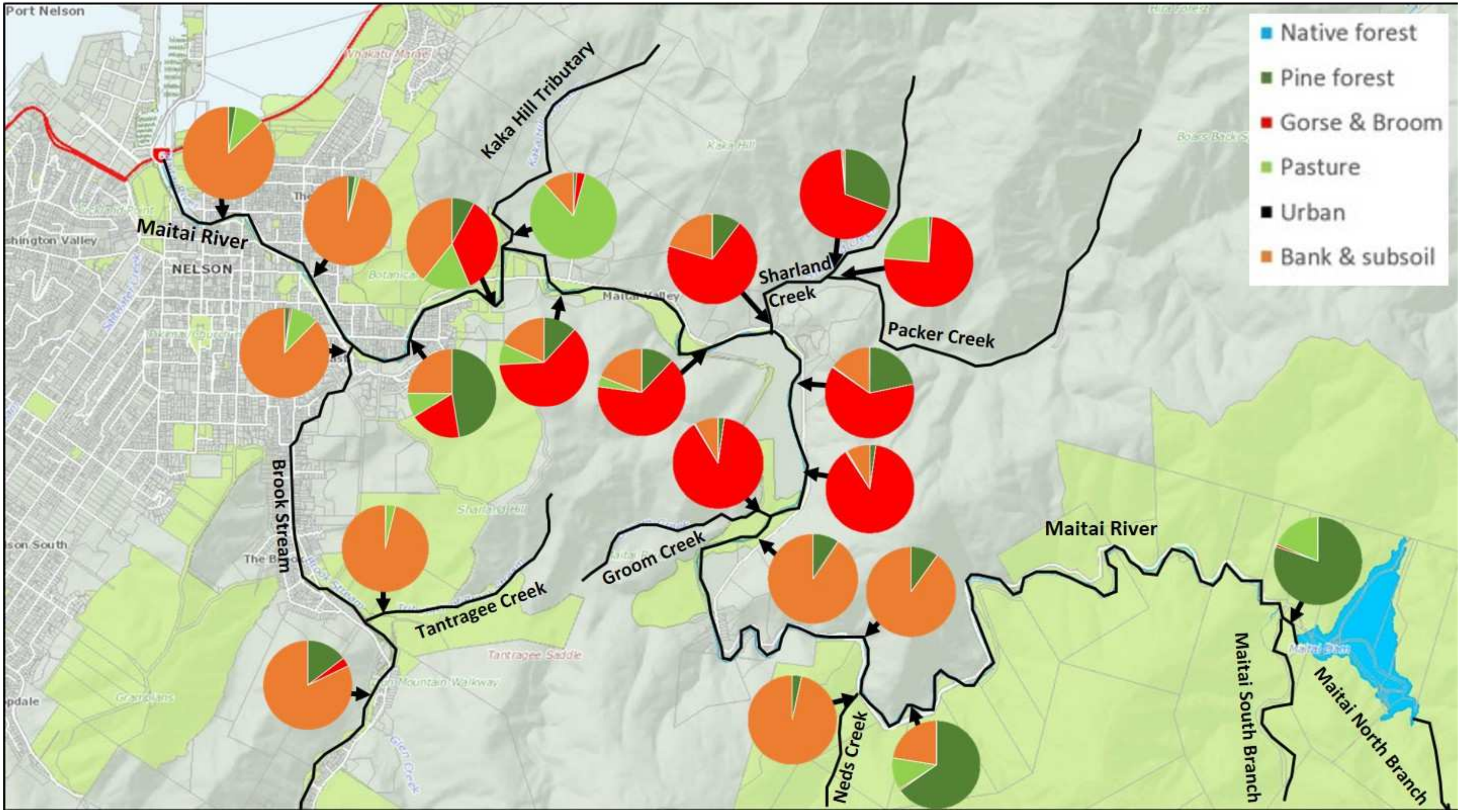

Figure 3-1: Pie chart map showing the relative proportions of each land use at each sampling site down the Maitai River and in the tributaries as determined using the CSSI technique. Arrows from each pie chart point to the general site location. Values for the Pie charts are from Table 3-2 combining all forms of pine into a single "pine" component. Sediment attributable to native forest was less than 1% at all sites. A comparison at each site between CSSI technique sediment source estimates from the deposition material and the proportional land cover estimates from the LCDB are provided in Appendix C. All CSSI technique results are best estimates using the data available and not absolute values.

The results in Table 3-2 give the % of land use at each location (**% of total sediment**) and include a separation of the % of that total value into its component parts i.e., the soil sources are expressed as % of each source that sum to the % of total value at that location. Soil sources that produced very low isotopic proportion values were omitted from the modelling during the iteration modelling process because their proportional contribution to the mixture would be below the confidence level of the CSSI method when the isotopic proportions were converted to soil proportions. Native forest, mature pine, urban and unsealed road sources were identified in some samples but at very low levels and were omitted during the final modelling process.

3.3 Land use proportions from the LCDB

Data from the LCDB estimates indicate that about 55% of the land in the Maitai River watershed is in native or indigenous forest and about 26% is in exotic pine forest, with about 8% of that as recently harvested pine forest (Table 3-3). These estimates were based on the available data at the time the LCDB data was updated in 2012 and there are likely to have been changes in relative proportions of some land use classes, especially between exotic pine and forest harvested, since that time.

Table 3-3: Land cover database (LCDB) estimates of catchment area and land use (%) in the catchment upstream of each sampling point. Land use classes have been grouped into those equivalent to the land use soil sources in Table 3 2 and are expressed as percentage of total land use upstream of each sampling point. Road includes banks, quarries, slips and river bed.

Sample number	Site name at confluence	Catchment area (km^2)	Native	Exotic Forest	Forest - Harvested	Pasture	Gorse & Broom	Urban	Road etc
OA194/5	Maitai below Dam	33.3	83.2	2.2	0.0	9.0	3.4	0.2	2.0
OA194/7	u/s Neds	40.0	78.1	6.1	0.8	7.8	4.9	0.2	2.1
OA194/8	Neds	3.4	83.9	4.2	0.3	0.4	11.1	0.0	0.0
OA194/9	d/s Neds	44.4	77.6	6.6	0.7	7.2	5.6	0.2	2.0
OA194/11	u/s Groom	46.1	75.2	7.1	2.4	7.2	5.7	0.4	2.0
OA194/10	Groom	2.1	17.9	5.2	64.7	8.1	3.3	0.8	0.0
OA194/12	d/s Groom	49.5	71.1	8.3	5.0	7.1	5.5	1.1	1.9
OA194/15	u/s Sharland	49.5	71.1	8.3	5.0	7.1	5.5	1.1	1.9
OA194/14	Sharland	15.6	12.6	60.6	23.7	2.1	0.2	0.0	0.9
OA194/16	d/s Sharland	65.1	57.1	20.8	9.5	5.9	4.2	0.9	1.7
OA194/23	u/s Kaka	67.2	55.4	21.8	9.3	6.2	4.5	1.2	1.6
OA194/20	Kaka	2.7	41.6	4.8	0.1	16.7	35.8	0.0	0.9
OA194/22	d/s Kaka	70.6	54.9	21.0	8.9	6.7	5.7	1.3	1.6
OA194/26	u/s Brook	71.6	54.2	20.7	8.8	6.6	6.4	1.8	1.5
OA194/25	Brook	17.6	62.1	10.4	6.3	7.1	7.5	5.8	0.7
OA194/27	d/s Brook	90.1	55.3	18.5	8.2	6.6	6.5	3.4	1.4
OA194/18	Lower Maitai	90.1	55.3	18.5	8.2	6.6	6.5	3.4	1.4
OA194/34	Sharland u/s Packer	7.3	18.5	66.5	12.9	0.6	0.0	0.0	1.5
OA194/33	Packer Ck	7.5	6.7	54.7	36.5	2.1	0.0	0.0	0.1
OA194/2	Brook u/s Tantragee	11.6	82.5	5.3	0.0	5.6	4.5	1.0	1.1
OA194/3	Tantragee	1.3	7.3	26.5	48.6	15.6	1.9	0.0	0.0

4 Data interpretation

The landscape in the Maitai River watershed was previously native forest, about half of which has been replaced with plantation forests of Pinus radiata, Douglas fir and other pine species, as well as pasture for farming, and urban development associated with the city of Nelson (Table 3-3). LCDB estimates indicate that about 55% of the watershed is covered with native forest and that about 26% of the watershed has been used for plantation pine forest, with about 8% “recently harvested” at the time of developing the database. Field observations indicate that the proportion of recently harvested pine forest may have increased since then, with ongoing harvested using normal clear-felling and log-hauling techniques. This has initially left the steep hillsides bare and vulnerable to erosion by rainfall events. In some areas it has also left extensive lengths of access road tracks across steep hill faces with some deep erosion scars potentially caused by focused road runoff and/or log hauling down the slopes. In normal production forestry blocks, the land would have been replanted with a new forest, which would have provided a strong leaf canopy to dissipate the energy of rainfall after three to five years. In the Hira Forest, there are several areas where replanting is not planned for a variety of reasons including a change in land ownership. Similarly, some private and Nelson City Council owned forestry blocks have not been replanted after harvest. Consequently, the exposed soil has been covered with weed species, including gorse and broom, and coarse pasture grasses that offer less protection against rainfall erosion than a forest canopy. These invasive weeds provide a unique CSSI signature which can also be traced.

4.1 CSSI land use predictions compared with LCDB information

The changes in soil source composition down the Maitai River reflect natural erosion processes, land use and the land use practices in the catchment upstream of the locations sampled and in the tributaries. These differences are illustrated in a series of pie charts for each sampling location (Appendix C), where the pie chart represents the % contribution of the soil source at that location as determined by the CSSI method compared with the LCDB estimates of land use class. In all cases, the CSSI values presented are means and are likely to have an uncertainty of about ± 5% about the mean.

Interpretation of the CSSI results is that these proportions represent soil that has been eroded from upstream sources and deposited in the river channel at the site sampled. One caveat is that, if a particular land use source in the catchment is not eroding or the erosion rate is very low, then that land use signature may not be detected in the deposited sediment. Furthermore, some land uses produce more sediment than others per unit area. Consequently, there is no reason to expect the CSSI results to match the proportional contributions of each land use class in the LCDB estimates (Table 3-3).

For example, the results from the Pakuratahi Land Use Study (Eyles and Fahey 2006), which included a comparison of sediment yield from paired forestry and pasture catchments, determined that over a 12-year period, “the farmed catchment produced almost four times more suspended sediment than the catchment in mature forest”. This means there will be minimal sediment from undisturbed mature pine forest plantations and native forest. However, the Pakuratahi Land Use Study also found that “during harvesting, sediment yields from the forested catchment were two and a half times more than the farmed catchment, and six times higher than before harvesting.” A study by Gibbs (2008) found that sediment yields from harvested pine forest could be much higher if the clear felling was on very steep land and the hauler lines crossed a stream channel, thereby providing connectivity between the erodible soil and downgradient river.

When the forests are harvested, higher sediment production will occur over a period of 3 to 5 years until canopy closure once more protects the soil from erosion by rainfall. During this period the amount of soil eroded will decrease as weed species colonise the bare land. These weed species, such as gorse and broom, provide a distinctive fingerprint signature that can also be used to define the land use status of the plantation forests.

Changes in sediment production are also likely following clearance of native forest, during cultivation of cropping land, and after clearance of land for urban development.

The Maitai River downstream the dam contributes about 2.4 % of the total sediment load in the river. This is consistent with small catchment area between the dam (dams are known to be sinks for sediment) and that site. The soil sources identified by the CSSI techniques are consistent with land use in the catchment but do not match the land use areas. Native forest covers 83% of this sub-catchment but there was little native forest sediment identified in the river sediment. Consequently, the pine signature becomes more dominant even though there is little pine (~2%) in this sub-catchment (Table 3-3). i.e., the proportion of pine sediment identified (~80%, Table 3-2) is disproportionately large compared to land this land use cover above this site.

Between the upper Maitai River site and Neds Creek, the CSSI estimate of proportion of sediment load in the total river load increases by 20% to 23.7% (Table 3-1) over a river distance of about 5 km (the distance from the Maitai dam to the sea is 15 km). The land use soil sources are the same as for the previous catchment but with an additional bank erosion component (Table 3-3). Again, the soil sources identified by the CSSI technique are also consistent with land use along this reach of the river but excludes native forest, which the LCDB estimates to be about 78% of the catchment (Table 3-3). The estimated pine forest sediment contribution to the river was about 65% (Table 3-2) and is disproportionately larger than the LCDB estimate of ~7% of it land use cover. However, there is an area of recently harvested pine forest land adjacent to this reach of the river that could account for that difference.

The sediment load coming into the Maitai River from Neds Creek was essentially from bank erosion and a relatively minor contributor to the total sediment load at about 1%. This is consistent with this catchment being largely undisturbed native forest.

There was a small (3.5%) increase in the % total deposited sediment load to 27.2% of the total river load between the site upstream of Neds Creek and the site upstream of Groom Creek (Table 3-1), a stream distance of about 1.5 km. The CSSI land use soil source predictions identified a decrease in the proportion of pine from ~65% down to ~10%, which was offset by the large increase in the proportion of bank erosion sediment up to ~90% (Table 3-2). Pine forest harvesting has occurred in the catchment adjacent to this reach of the river downstream of Neds Creek, but that land may have had poor connectivity with the river, or it had yet to rain sufficiently since harvesting to move surface soil from that land into the river.

Groom Creek was estimated to add a further 9% to the proportion of total sediment load from just 2.1% of the total catchment area (Table 3-3). The soil sources in the Groom Creek sediment were dominated by gorse and broom signatures (89%), with contributions from bank erosion and pine subsoil. The high gorse and broom component indicates harvested pine forest but not the recent harvest of a block of *Pinus muricata* in this sub-catchment (Figure 4-1 A). A possible explanation for failing to see this pine signature in the Groom Creek sediment is that there has been insufficient rainfall since harvesting to erode sediment from this block into the creek at the time of sampling.

Figure 4-1: Soil sources to the Maitai River could include A) recent pine harvest and B) bank erosion in the Maitai River upstream of the Kaka Hill Tributary confluence. Photos December 2016.

The pine subsoil signature increased by about 17% between the site downstream of Groom Creek and the site upstream of Sharland Creek (Table 3-2), a river distance of about 1.2 km. This may have been associated with the pine harvesting on the eastern side of Maitai Road between these two sites.

The % total sediment load in the Maitai River at the Groom Creek confluence was estimated to be about 36% and this increased to about 50% downstream of the Sharland Creek confluence. This is comparable to the catchment area proportion of 54% estimated from the LCDB (Table 3-1) but not the NZ River Maps estimated annual suspended sediment load of ~82% (Table 3-1). Sharland Creek, which drains from Hira Forest (Figure 2-2), was estimated to be contributing 14% of the total sediment load to the Maitai River based on the CSSI technique, slightly more than the ~11% estimate for annual suspended sediment load from the NZ River Maps (Table 3-1) for this tributary. The soil sources contributing to the sediment in Sharland Creek were mostly gorse and broom (70%) with bank/subsoil, harvested pine and a trace of Douglas fir also contributing. The gorse and broom sediment is from previously harvested production forest that has not been replanted or has been replanted but has yet to achieve canopy closure (Figure 4-2).

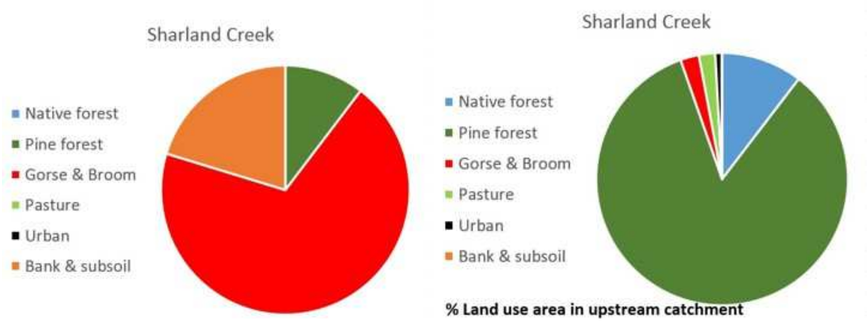

Figure 4-2: Land use soil sources in sediment from Sharland Creek (left) compared with land use areas (right) from the Land Cover Database as updated in 2012.

Separation of Packer Creek and Sharland Creek downstream of their confluence (Figure 2-2) indicated that about 40% of the sediment in Sharland Creek came from Packer Creek. This is in contrast with the NZ River Map estimate, which put that contribution at about 70%. The soil sources were similar for gorse and broom in both sub-catchments (Table 3-2), but there was a stronger pasture signature in the Packer Creek branch and more pine subsoil from the Sharland Creek branch.

Downstream from Groom Creek, a pasture soil source signature begins to appear, reaching about 4% of total sediment at the site upstream of the Kaka Hill Tributary (Table 3-2).

The Kaka Hill Tributary sediment was dominated by pasture (84%) and bank erosion (12%), with the remainder coming from gorse and broom, and pine. This is consistent with a predominance of pastoral farming in this sub-catchment, along with areas of native forest on the steeper slopes.

The % of total sediment in the Maitai River at the site downstream of the Kaka Hill Tributary confluence was estimated to be about 69% of the total load found at the lower Maitai site. At the Kaka Hill site the main soil sources contributing to the river sediment load were bank erosion (39%), gorse and broom (36%), pasture (17%), and harvested pine (8%). While some of the bank erosion material is likely to have come from pine subsoil and earth works, there were areas where bank erosion was occurring. A substantial area of bank erosion was observed at the ~90-degree bend immediately upstream of the Kaka Hill Tributary confluence (Figure 4-1 B) with potential for more pastoral sediment from a slip further upstream. The bank erosion immediately upstream of the Kaka Hill Tributary confluence (Figure 4-1 B) is probably the main source of sediment between the sites upstream and downstream of the Kaka Hill Tributary, and is likely to account for the 18.6 % contribution estimate from the CSSI technique versus the 0.6 % contribution estimate from NZ River Maps suspended sediment loads.

The apparent increase in harvested pine sediment at the site upstream of Brook Stream is unexpected (Table 3-2). A Google Earth review of the catchment between Kaka Hill Tributary and Brook Stream shows no evidence of any recent pine forest harvesting that would account for that land use signature, although this may have occurred since August 2016, when the Google Earth image was taken. However, the proportion of sediment derived from harvested pine at the site downstream of the Brook Stream confluence was similar to the proportion at the site downstream from Kaka Hill Tributary confluence (Table 3-2). This apparent discrepancy is unexplained. It may be due to inadvertently sampling a local patch of deposited sediment from an earlier event. The section of Maitai River downstream of the Nile Street bridge was relatively swift with a cobbled bottom and it was difficult to find sediment except on the banks.

Sediment from Brook Stream was dominated by bank (87%) and pasture (10%), with the remainder coming from gorse and broom, and harvested pine. The bank sediment in Brook Stream was mostly from three sources (i) deep subsoils associated with the Tantragee pipeline earthworks, (ii) the construction of the Brook Sanctuary pest-proof fence and walking tracks, and (iii) the deep scarring of the harvested pine forest near the head of the Valley (Figure 2-3). While gorse and broom type vegetation had colonised this area between April and December 2016, pine sediment was apparently still coming from that harvested pine site (Figure 4-3).

Construction of the Brook Sanctuary pest-proof fence, plus walking and mountain biking tracks are all potential sources of sediment to the upper Brook Stream but cannot be distinguished from the potential forestry sediment sources without site specific sampling. From satellite images (Google Earth), the area of bare land exposed by the forest harvesting relative to that exposed during construction of the fence and tracks suggests that forest harvesting is likely to have been the larger sediment source (Figure 4-4).

Separation of Tantragee Creek and Brook Stream tributaries at their confluence indicated that about 36% of the sediment in Brook Stream came from Tantragee Creek. The soil sources were similar in both sub-catchments although the upper Brook Stream had about 15% harvested pine sediment, which was not seen in Tantragee Creek. More than 95% of the sediment in Tantragee Creek came from the deep subsoil associated with the pipeline earthworks. Note that the deep subsoil has been included in the sediment attributed to bank erosion.

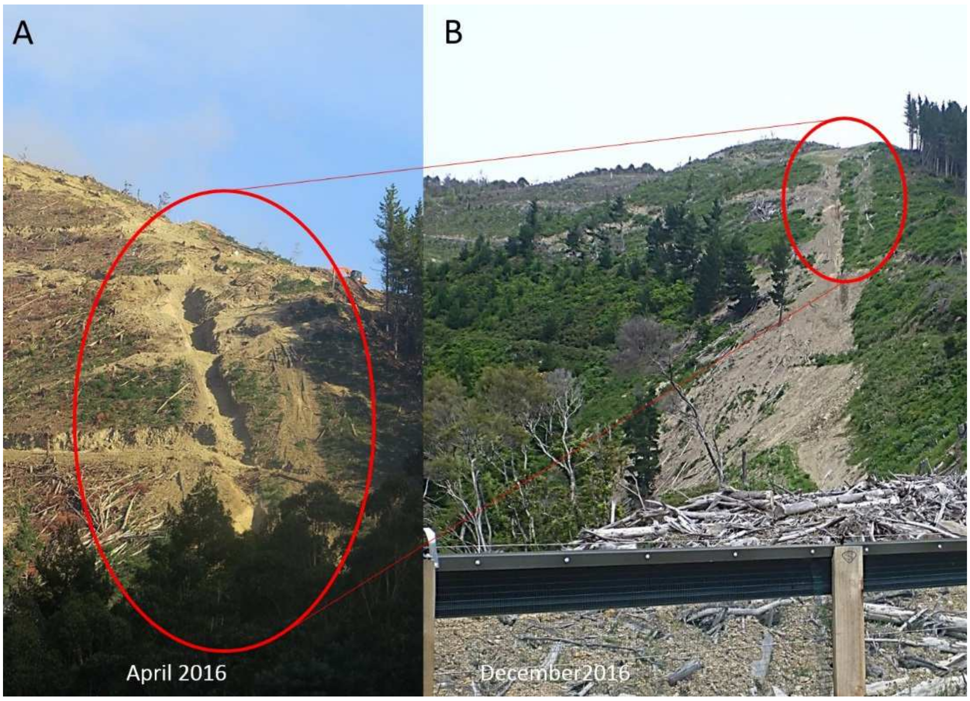

Figure 4-3: Harvested pine sediment eroding off the hill slope near the head of Brook Stream. A) Area circled was photographed in April 2016 (Figure 2-3). B) Same area (circled) photographed again in December 2016 showing considerable weed growth across the hill face as well as the bare soil on the slip face below the deep scarred hillside. The scree slope in (B) connects with Cummins Creek, which feeds into Brook Stream upstream of Tantragee Creek. Photo B was taken from within the Brook Sanctuary pest-proof fence, the construction of which is likely to have contributed some sediment to Brook Stream.

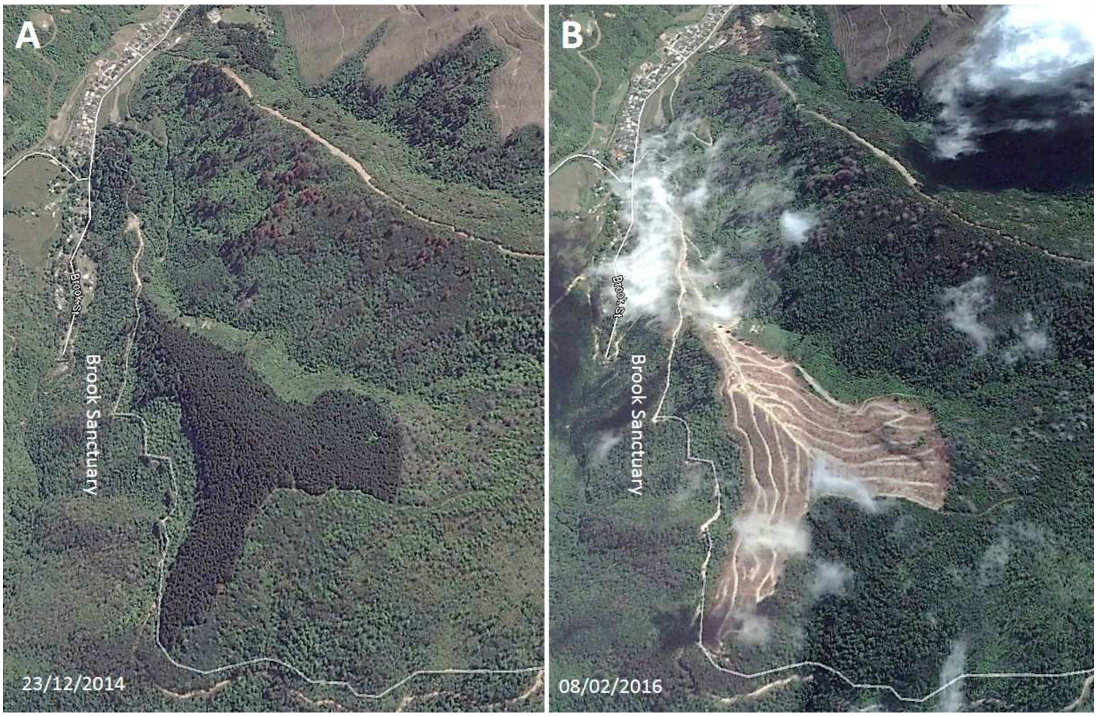

Figure 4-4: Google Earth images showing (A) pre-harvest and (B) post-harvest of the forestry block adjacent to the Brook Sanctuary near the head of Brook Stream. The area of exposed soil from construction of the Brook Sanctuary pest-proof fence is considerably less than the area of bare soil following harvesting. Dates are when the images were taken.

CSSI estimates of the soil source contributions immediately downstream of the Brook Stream confluence and at the lower Maitai River site near the Trafalgar Street Bridge (Ngaire Place) indicate similar land use proportions, although the soil source proportions at the lower Maitai River site include more pasture than the site immediately downstream of Brook Stream. While this difference is possible from local catchment inputs, it could also reflect a higher variability in the sediment deposited in the tidal reach of the Maitai River. Essentially, the sediment in the lower Maitai River comprises about 87% - 95% bank and deep subsoil. Based on the contribution of soil sources at the different sampling sites down the Maitai River, the bank sediment is likely to have been derived from soils that were previously from pine forest.

4.2 Answering Key questions:

1. *Is plantation forestry contributing a disproportionate percentage of sediment to the river compared to other land uses in the catchment?*

Probably. There is a large amount of native forest in the watershed (~46% (Table 1-1)), and yet native forest soils were never identified as a substantial sediment source at any site. The gorse and broom soil source was almost always associated with pine forest that had not been replanted following harvest or had been replanted but had yet to achieve canopy closure. This implies a secondary source of sediment associated with historical plantation forestry. With very little native forest sediment in the river, the relative proportion of plantation forestry sediment increases. Plantation forestry is estimated to produce on average about 36% more sediment than would be expected from its land use area.

In the Brook Stream sub-catchment, the bank erosion sediment had the same signature as the deep subsoil from the Tantragee pipeline earthworks, even upstream of Tantragee Creek. That suggests that the deep scarring of the harvested pine forest land near the head of the valley was the likely source of this sediment. The CSSI technique found that, at the time of sampling, the Brook Stream catchment contributed about 31% of the sediment to the Maitai River, which is more than twice the NZ River Maps estimate of 14.6% (Table 3-1) for the annual suspended sediment load, and about 58% more than would be expected from the catchment area alone, assuming uniform sediment yield per unit area.

2. *Is bank erosion contributing a disproportionate percentage of sediment to the river, and if so where are the hot spots?*

In specific locations, yes. The first indication of bank erosion was found around Neds Creek with more than 90% of the sediment at the upstream of Grooms Creek site being attributed to bank erosion (Table 3-2). This reach of the river has the first houses down the Maitai River as well as a camping ground bordering the river. Substantial river bank erosion occurs around the ~90-degree bend immediately upstream of the Kaka Hill Tributary confluence, where the river impacts directly on the bank. Elsewhere, undercutting of river banks provided measurable amounts of sediment to the river system. The Tantragee subsoil signature could not be separated from other bank erosion signatures in Brook Stream, and a single bank erosion estimate was derived for those sample sites.

3. *Is it possible to get an estimate of the proportion of sediment from urban runoff?*

Not from the data currently available – no storm water reference sediment sample was collected. Notwithstanding, missing local sediment sources within the urban catchment were not indicated, even though the LCDB estimates an urban area of 323 ha or 3.4% of the total watershed (Table 3-3) with a NZ River Maps estimated annual suspended sediment yield of about 1200 t y^{-1}. In the Brook Stream catchment there is an urban area of about 130 ha, which the NZ River Maps estimates is delivering an annual suspended sediment load of 57 t y^{-1}. Absence of an urban influence may reflect channelization of urban runoff through the storm water system that only occurs during rainfall events. At these times, storm water enters the river close to its discharge into the Haven and is unlikely to have sufficient time to settle in the river during the high flow.

5 Conclusions

This study shows the pattern of catchment sediment deposition down the Maitai River at the time of sampling in December 2016. This pattern reflects recent activities in the watershed, which have caused or exacerbated natural soil erosion. The relative proportions of each soil source in the deposited sediment associated with a specific location are likely to change over time as vegetative cover increases or decreases in response to land use management practices, or the bank erosion and mass wasting (landslides and earth flows) that occurs during heavy rain events.

Application of the CSSI technique to the Maitai River system demonstrates no relationship between the amount of sediment from a specific land use and the area of that land use in the catchment. Areas of mature production forest and native forest are unlikely to produce substantial amounts of sediment runoff during rainfall events due to protection of the soil surface from the erosive energy of the rain drops by an extensive leaf canopy, as well as enhancement of slope stability by root networks of trees and dense understory plants.

Sediment from native forest, which comprises 46 % of the land use in the watershed, was present in very low proportions. Conversely, sediment from plantation forestry, which comprises 26% of the land use, was a major source of fine sediment. However, because a mature pine forest also has an extensive protective leaf canopy, most of this sediment would come from recently harvested forest, which is likely to be only a small proportion of the total forest under a ~27 year rotation. There is a general expectation for three to five years of elevated sediment runoff following harvest, until canopy closure from replanting protects the soil from erosion once more.

In the Maitai River watershed, there are areas where forest replanting has not occurred or has been delayed, and the bare ground has been colonised by gorse and broom and other weed species. These plants provide some level of vegetative cover, but not as much as a closed forest canopy. Gorse and broom also colonise replanted forestry blocks before canopy closure. Consequently, the ‘gorse and broom’ soil fingerprint has been used as an indication of forestry activity and suggests that production forestry is contributing a substantial amount of sediment to the Maitai River as well as the tributaries draining into the river in the upper and middle reaches.

For example, harvesting of pine forest on the steep hill slopes in the Brook Stream sub-catchment and the associated scarring by access roads and hauler lines is estimated to have produced almost 20% of the sediment in the lower Maitai River.

Because bank material is often reworked with successive flood events, the distinctive pine signature and signatures of gorse and broom and pasture found in the sediment in the middle reaches of the Maitai River are likely to have been blended into an amorphous “bank” signature in the lower Maitai River. Distinctive bank source signatures were found elsewhere and obvious areas of bank erosion occur downstream of Groom Creek, with an extensive area of bank erosion immediately upstream Kaka Hill Tributary confluence. This latter source of bank erosion is probably due to the geometry of the river as it passes through a ~90-degree bend.

The apparently disproportionately large sediment contribution to the Maitai River from the Kaka Hill Tributary i.e., 18.6 % estimated from the CSSI technique versus 0.6% from the NZ River Map database using national estimates, is an example of where the NZ River Map database cannot account for changes in local conditions. In this case, the NZ River Map database was last updated in 2008 and the more recent extensive erosion of the pastoral river bank just upstream of the Kaka Hill Tributary confluence is likely to have affected this result.

Pastoral soil from the Kaka Hill Tributary catchment was distinctive as a black topsoil, potentially nutrient rich, especially in P, due to fertiliser application. Elevated P concentrations favour the growth of cyanobacteria (Havens et al. 2003) and the P in fine sediment has been shown to support and sustain the development of *Phormidium* blooms in several New Zealand rivers (Wood et al. 2014, 2015; Appendix E). Interestingly, the worst *Phormidium* blooms occur downstream of the Kaka confluence (Jo Martin, pers. comm, NCC).

Although the Maitai River flows through the urban area of Nelson City, there was no indication of a substantial change in the sediment source contribution through this reach. This may be due to reticulation of the stormwater through the city, or that the large amount of sediment from Brook Stream may have masked any change. It would require a more detailed evaluation of the variety of urban soil sources relative to the sediment in the lower Maitai River to answer the urban question.

6 Acknowledgements

We thank Greg Olsen, Ron Ovenden and the laboratory staff at NIWA Hamilton for assistance in sample preparation, and the laboratory staff at the NIWA stable isotope facility, Wellington, for the bulk carbon isotope analyses, and the UC Davis stable isotope facility, California, for the compound specific stable isotope analyses. We thank Sanjay Wadhwa (NIWA) for extracting the land use information from the LCDB and we also thank Jo Martin for guiding us around the catchment and finding some of the sampling sites. Valuable discussion with John Quinn (NIWA) improved the clarity of the report and the interpretation of the CSSI results.

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Appendix A Stream Samples

Samples were collected from the Maitai River upstream and downstream of the confluence with each tributary, well as from the tributary. The data listed includes the CSSI data used in the modelling.

Lab code	Site name	Land use	Lat	Long	%C	d13C	C14:0	C16:0	C16:1	C18:0	C18:1	C18:2	C20:0	C22:0	C24:0
OA194/5	Maitai Rd Dam	Stream	-41.290236	173.365261	0.45	-27.46	-30.68	-29.92	-29.07	-27.25	-30.46	-29.43	-31.60	-31.31	-33.69
OA194/7	U/S Neds Real	Stream	-41.294832	173.344461	0.87	-27.35	-29.74	-30.00	-27.20	-29.08	-29.85	-29.74	-31.35	-32.12	-32.50
OA194/8	Neds Crk	Tributary	-41.298669	173.338783	3.18	-28.74	-32.65	-31.06	-30.87	-30.26	-31.71	-32.43	-32.93	-32.08	-33.59
OA194/9	D/S Neds	Stream	-41.294192	173.335330	0.18	-27.05	2.14	-28.31	-27.68	-25.09	-29.81	-28.04	-30.01	-30.90	-32.17
OA194/10	Groom Crk	Tributary	-41.288338	173.325821	5.88	-29.03	-33.78	-31.86	-30.64	-29.49	-31.31	-31.43	-34.51	-34.75	-34.53
OA194/11	U/S Groom	Stream	-41.288516	173.324707	0.46	-27.00	-29.60	-28.52	-26.92	-28.74	-30.14	-29.25	-32.22	-31.99	-33.62
OA194/12	D/S Groom	Stream	-41.286803	173.329119	0.83	-27.85	-30.34	-29.30	-26.74	-29.00	-29.49	-29.09	-32.92	-32.48	-33.14
OA194/14	Sharland St @ road	Tributary	-41.275792	173.328315	2.13	-28.46	-33.67	-32.60	-32.14	-31.91	-32.25	-30.27	-33.87	-33.39	-33.55
OA194/15	U/S Sharland	Stream	-41.276425	173.329136	0.25	-27.27	-30.21	-28.88	-27.66	-26.79	-30.62	-29.14	-30.60	-31.48	-32.34
OA194/16	D/S Sharland	Stream	-41.276091	173.327299	0.84	-27.50	-32.67	-30.18	-29.91	-29.80	-30.09	-29.38	-32.68	-32.15	-32.47
OA194/18	Lower Maitai @ Ngaire Pl	Stream	-41.271746	173.290250	0.37	-28.04	-31.09	-29.76	-28.23	-28.66	-28.25	-32.94	-31.74	-32.90	-32.91
OA194/20	Kaka Hill Tributary	Tribtary	-41.270589	173.307937	8.93	-29.16	-34.57	-34.18	-33.51	-33.86	-32.17	-30.74	-35.56	-35.89	-35.81
OA194/22	Maitai D/S Kaka	Stream	-41.272156	173.307300	3.98	-28.74	-34.94	-30.43	-30.88	-32.12	-31.52	-31.42	-34.44	-34.31	-34.93
OA194/23	Maitai U/S Kaka	Stream	-41.271613	173.310540	1.26	-28.64	-31.49	-30.54	-31.00	-29.53	-30.40	-29.24	-33.00	-33.29	-33.85
OA194/25	Brook U/S confluence	Stream	-41.275701	173.294072	0.79	-27.90	-31.17	-31.19	-29.91	-28.43	-30.45	-29.22	-32.59	-33.10	-33.20
OA194/26	Maitai U/S of Brook	Stream	-41.276230	173.294762	1.15	-28.28	-30.88	-31.77	-29.31	-28.90	-30.38	-32.55	-32.08	-32.76	-33.67
OA194/27	Maitai D/S of Brook	Stream	-41.274778	173.293669	1.43	-28.87	-32.27	-31.60	-31.62	-30.11	-30.36	-28.90	-35.13	-34.11	-34.24
OA194/2	Brook at Tindle Rd	Tribtary	-41.300799	173.294963	0.19	-27.85	-30.57	-29.62	-29.82	-25.98	-27.41	-29.87	-30.15	-31.24	-31.67
OA194/31	Cummins Stream (Brook)	Tribtary	-41.305488	173.292572	0.31	-27.29	-29.21	-27.17	-25.67	1.67	-29.36	-28.02	-30.77	-30.55	-31.38
OA194/3	Tantragee Stream (Brook)	Tribtary	-41.292816	173.297080	7.39	-29.40	-32.81	-31.91	-30.54	-32.33	-31.00	-30.31	-35.17	-35.78	-35.94
OA194/33	Packer Creek	Tribtary	-41.264959	173.296451	4.94	-29.59	-32.89	-32.60	-34.66	-31.79	-31.88	-30.02	-34.21	-34.28	-30.29
OA194/34	Sharlands U/S Packer Crk	Tribtary	-41.272729	173.334297	0.21	-27.30	-29.65	-28.68	-28.23	-26.86	-29.62	-28.12	-31.39	-31.74	-35.41

Appendix B Land use samples

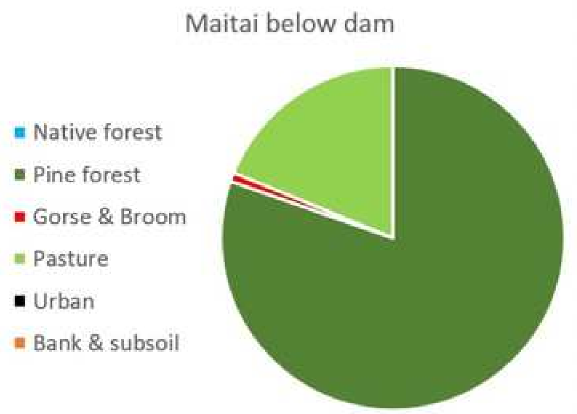
Soil samples for the reference library were collected from different land use types across the Maitai River catchment downstream of the Maitai dam. Because there was no access granted for collecting pine forest samples within the Maitai River catchment, these samples were collected from adjacent catchments. The data listed includes the CSSI data used in the modelling.

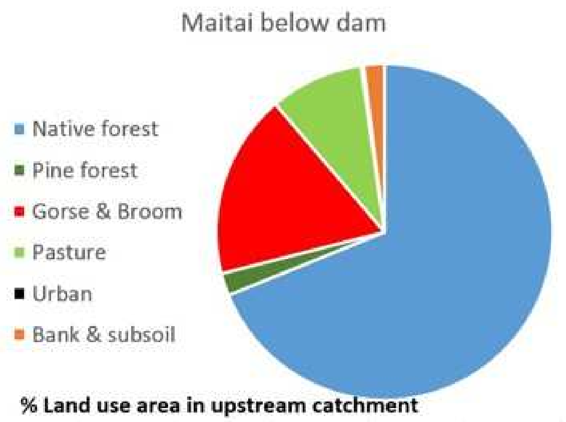
Lab code	Site name	Land use	Lat	Long	%C	d13C	C14:0	C16:0	C16:1	C18:0	C18:1	C18:2	C20:0	C22:0	C24:0
OA194/21	Pasture Kaka	Pasture	-41.270400	173.308198	6.71	-28.97	-32.47	-31.47	-33.16	-32.40	-32.26	-31.75	-35.39	-35.39	-35.63
OA194/36	Pasture sheep Maitai Dam	Pasture	-41.291057	173.372734	8.06	-29.24	-32.50	-31.04	-32.22	-33.02	-32.62	-30.69	-34.61	-34.72	-35.24
OA194/29	Codgers hill pasture	Pasture	-41.293172	173.299765	3.78	-26.72	-32.53	-31.12	-32.13	-31.78	-30.15	-30.86	-34.58	-34.77	-35.79
OA194/19	Bank @ Kaka Stream	Bank	-41.271093	173.307634	7.41	-28.61	-33.91	-33.11	-31.85	-31.87	-30.68	-32.41	-35.00	-33.99	-33.93
OA194/1	Upper Brook	Bank	-41.307011	173.292465	1.22	-27.33	-32.01	-31.05	-31.15	-31.12	-31.45	-31.43	-33.20	-32.91	-33.22
OA194/24	Maitai bank	Bank	-41.271917	173.310918	0.58	-24.53	-32.07	-29.22	-29.03	-28.29	-29.47	-28.81	-31.86	-32.78	-31.55
OA194/17	Bank at Sharland	Bank/subsoil	-41.276091	173.327299	4.43	-30.31	-34.41	1.88	-29.08	-34.70	-37.58	-32.90	-38.01	-37.45	-38.21
OA194/28	Codger's Hill gorse & broom	Gorse & broom	-41.292377	173.299286	3.15	-26.34	-32.68	-30.40	-31.48	-27.54	-30.85	-29.53	-32.41	-32.11	-32.91
OA194/35	Douglas Fir mature	Douglas fir	-41.274079	173.330298	17.46	-28.74	-35.26	-33.41	-29.20	-30.92	-31.52	-30.58	-34.02	-32.67	-33.82
OA194/32	Pine Mature (Teal Valley Rd)	P radiata mature	-41.243376	173.398682	4.39	-28.27	-37.35	-32.50	-33.88	-29.94	-28.85	-31.99	-30.88	-30.59	-31.60
OA 195 36	Pine clearcut (Serpentine area)	P radiata harvested	-41.398744	173.204232	4.39	-26.76	-30.93	-27.71	-29.32	-27.28	-28.48	-29.35	-30.74	-30.66	-30.85
OA194/30	Sanctuary Brook pine side cast	P radiata harvested	-41.309376	173.294619	5.40	-26.62	-31.51	-29.31	-31.15	-28.41	-33.54	-29.54	-29.87	-29.11	-29.31
OA 195 35	Pine subsoil (Serpentine area)	P radiata subsoil	-41.396376	173.205221	2.74	-27.99	-32.63	-31.01	-30.70	-28.35	-31.97	-27.64	-27.88	-26.94	-27.30
OA194/4	Tantragee pipeline	Subsoil (deep)	-41.292854	173.296038	0.48	-25.28	2.14	-28.97	-27.86	-26.63	-29.76	-27.53	-31.43	-32.60	-32.44
OA194/38	Pine clearcut P. muricata	P muricata harvested	-41.290548	173.321053	8.41	-28.31	-39.36	-33.22	-32.26	-30.15	-32.76	-33.14	-31.42	-31.22	-31.92
OA 195 26	Native (Wairoa gorge)	Native forest	-41.479646	173.078867	18.90	-28.45	-34.87	-31.31	-27.67	-31.16	-30.75	-30.06	-33.02	-33.33	-33.69
OA194/37	Road infrastructure	Road unsealed	-41.288862	173.368927	0.88	-28.65	-32.77	-31.93	-31.97	-31.44	-31.04	-32.04	-32.90	-32.17	-33.79

Appendix C Soil source proportions at stream sampling sites

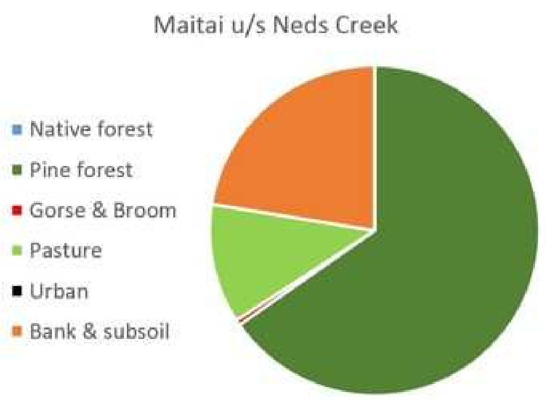
The pie charts show the relative proportions of specified soil sources at each site (left) compared with the % land use area in the upstream catchment (right) from the LCDB. The CSSI estimate of the percentage of total sediment in the river from each land use upstream of each site location is given.

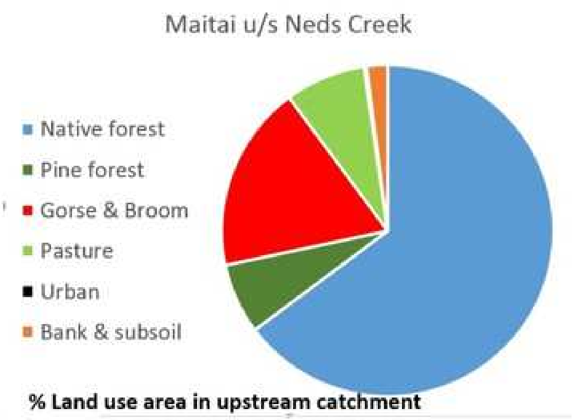
<u>Main Stem</u>



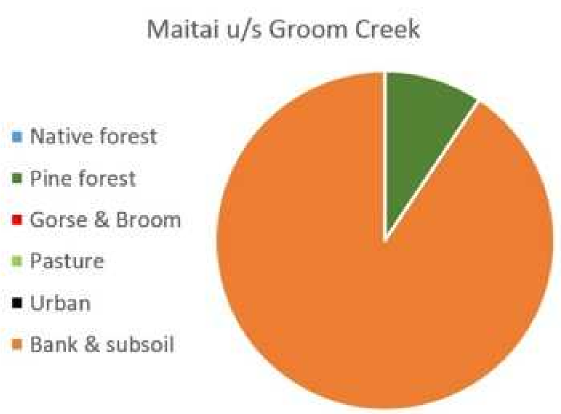


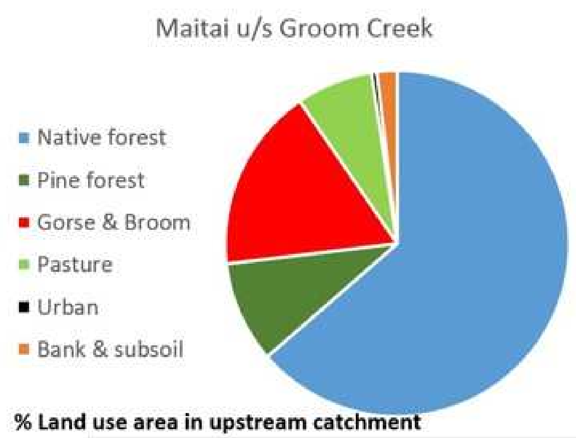
2.4% of total



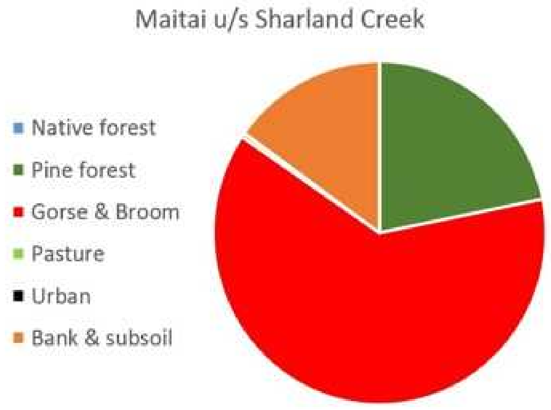


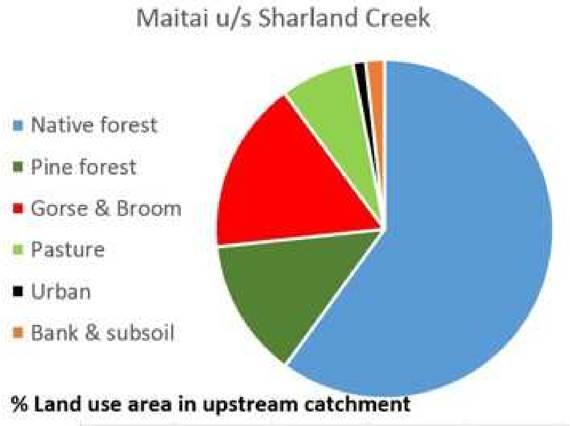
23% of total



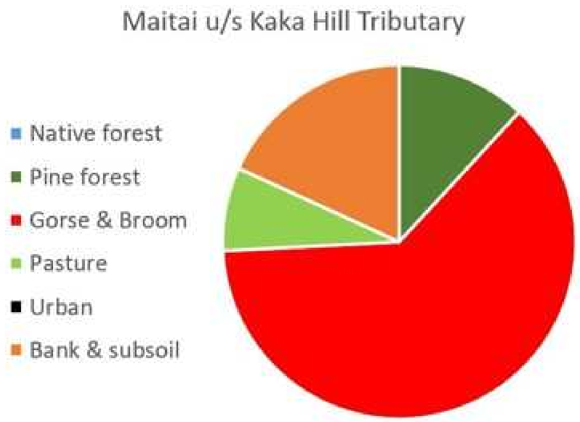


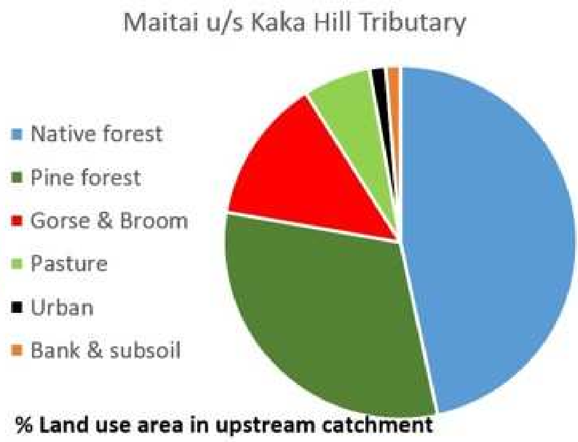
27% of total



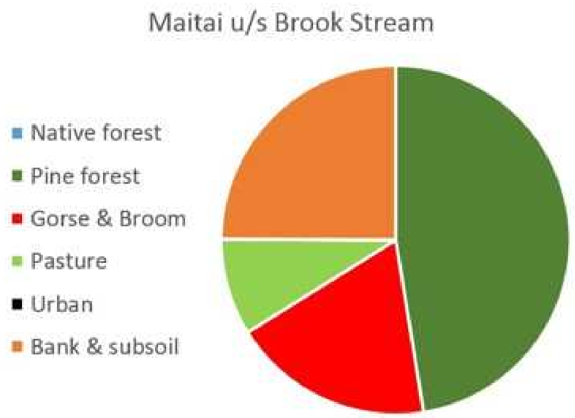


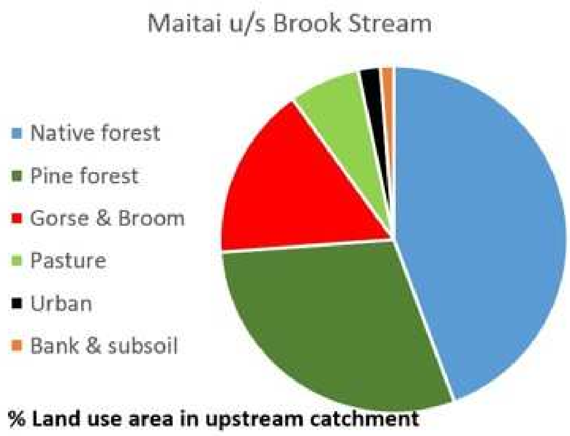
36% of total



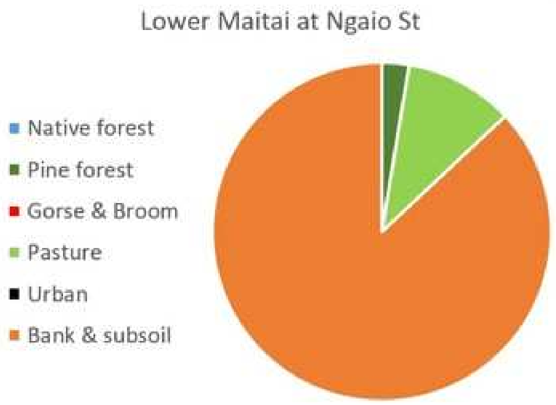


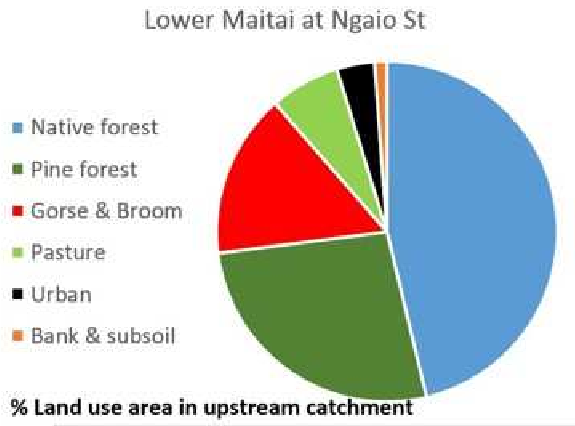
50% of total





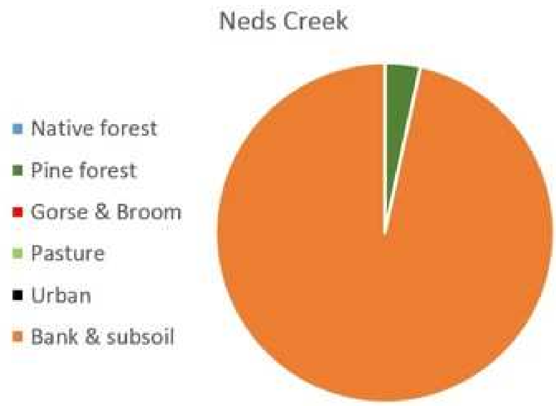
69% of total

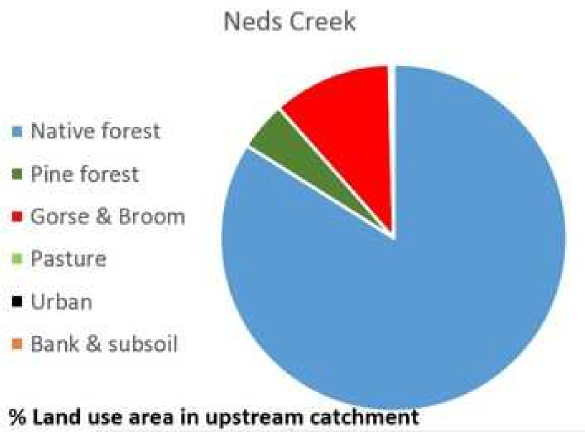




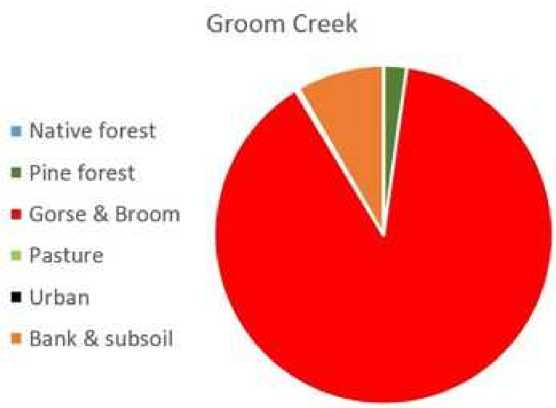
100% of total

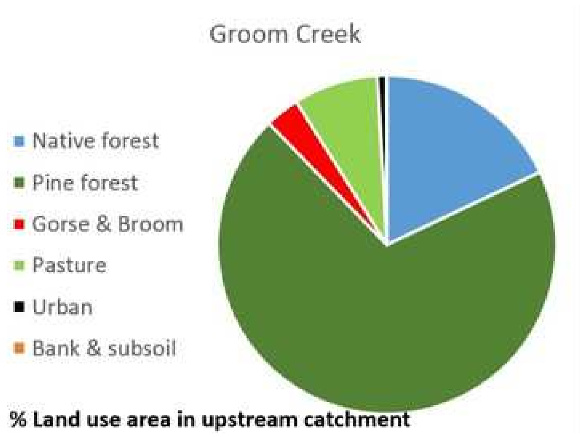
Tributaries



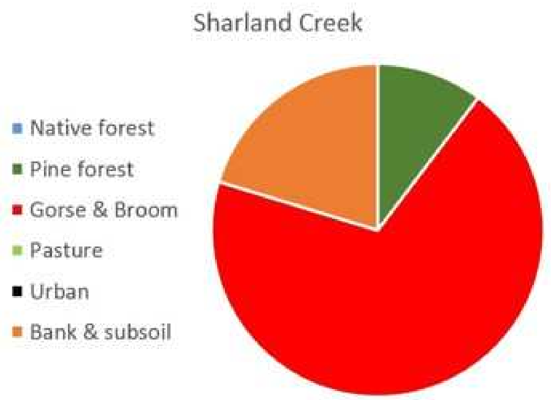


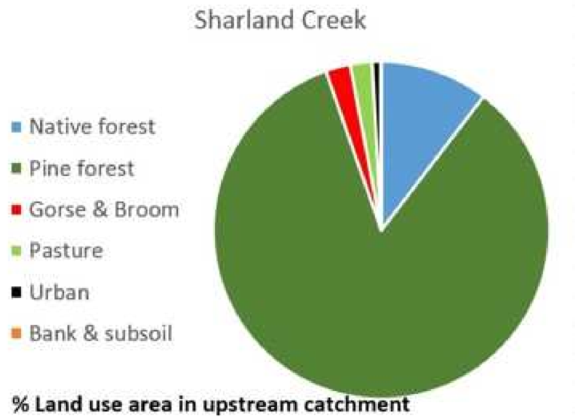
1.2% of total



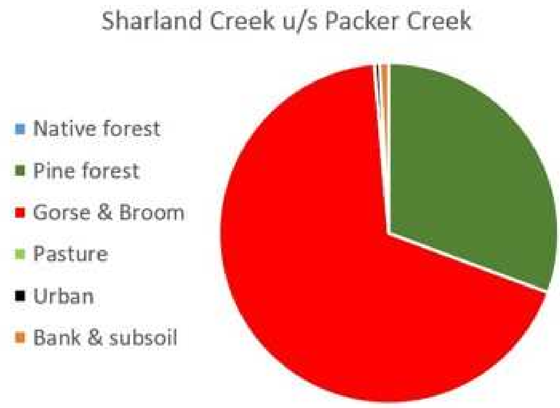


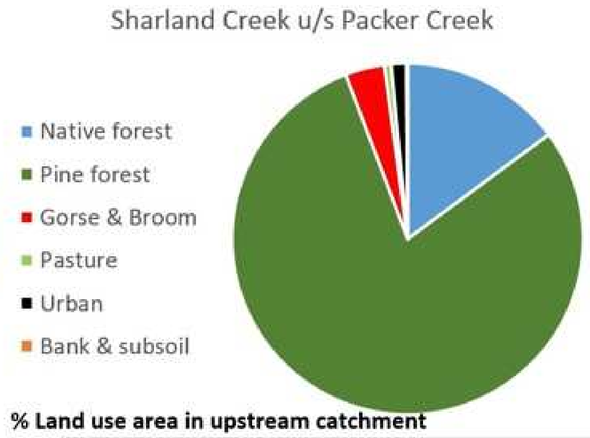
9% of total



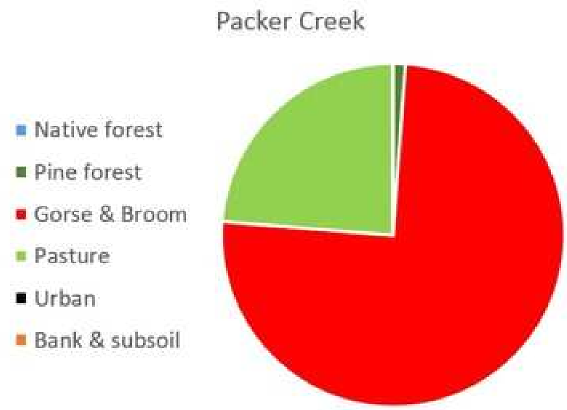


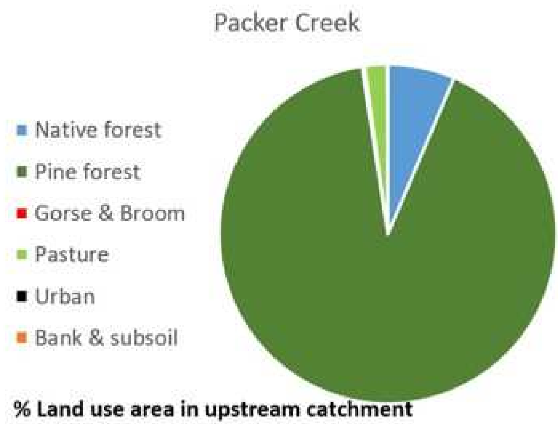
14% of total



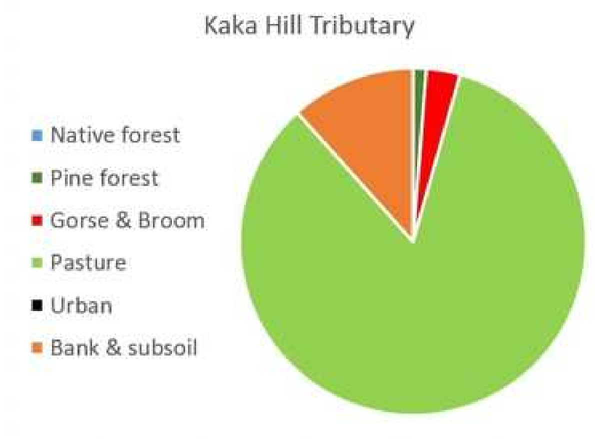


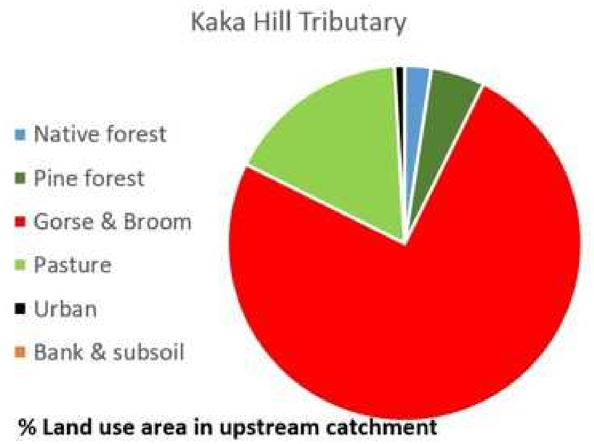
8% of total (at Sharland)



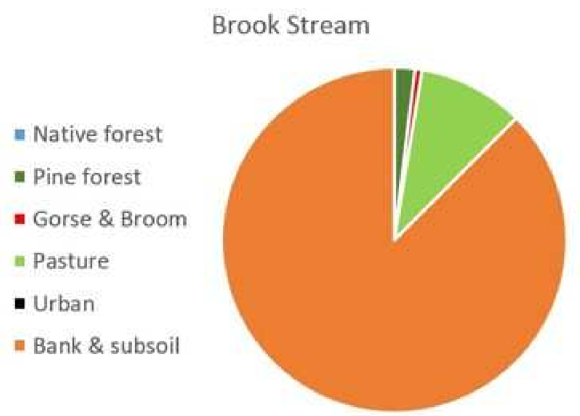


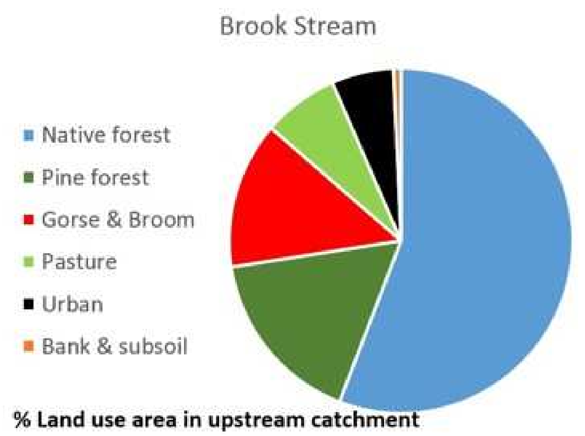
6% of total (at Sharland)



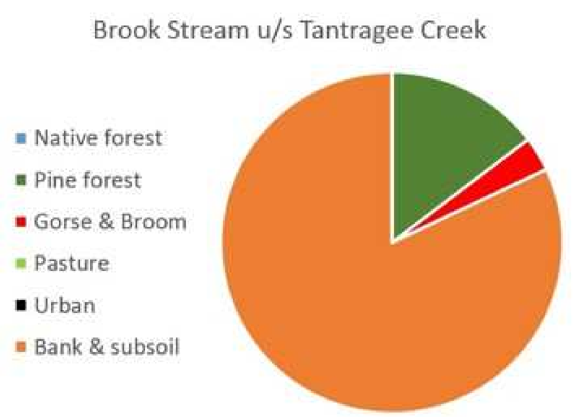


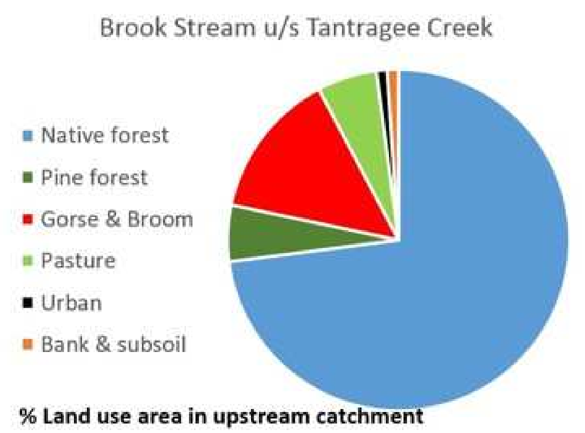
18.6% of total



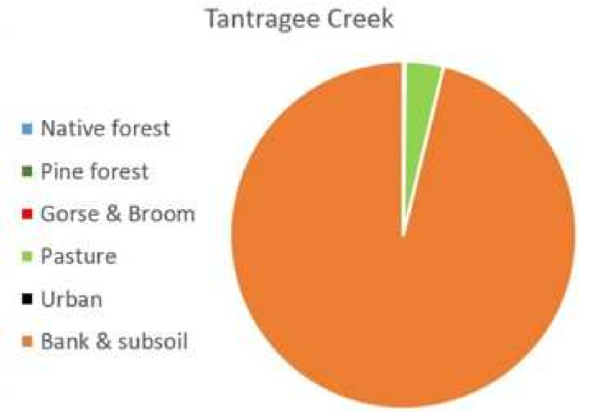


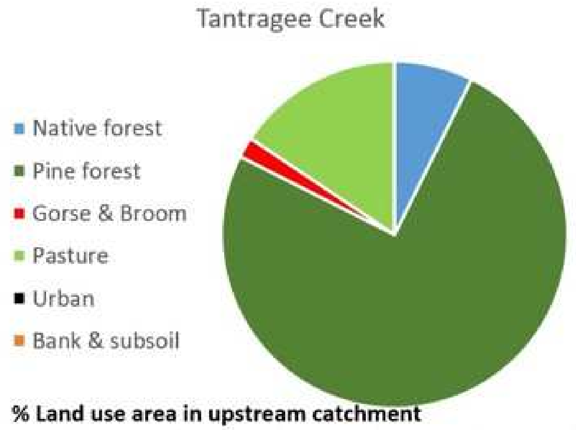
31% of total





20% of total (at Brook)





11% of total (at Brook)

Appendix D Sample site photos

Selected sampling site photos to illustrate the different soil sources.

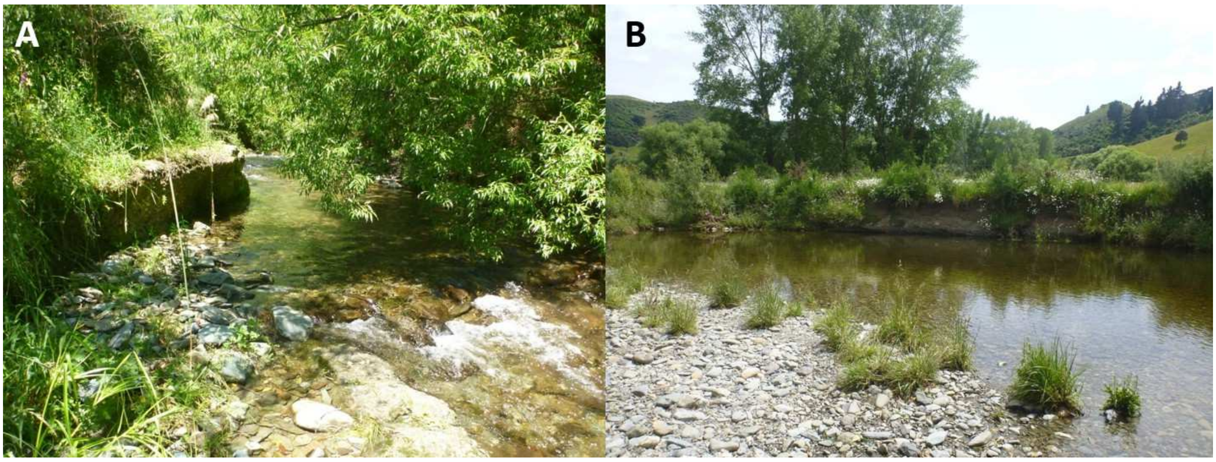


Figure D-1: Bank erosion A) upper Maitai River below dam, B) near Kaka Hill Tributary.

Figure D-2: Pasture A) hill country above Maitai Dam, B) flat country at Kaka Hill Tributary.

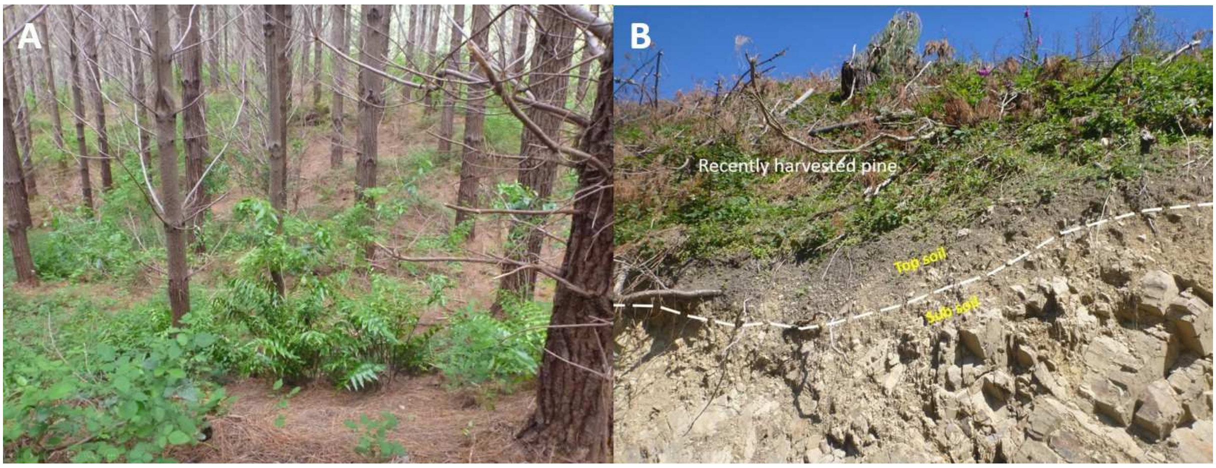


Figure D-3: Pine forest A) mature with dense needle litter and understory plants, B) harvested showing the top soil layer taken to represent harvested pine and the subsoil beneath as exposed by roading.

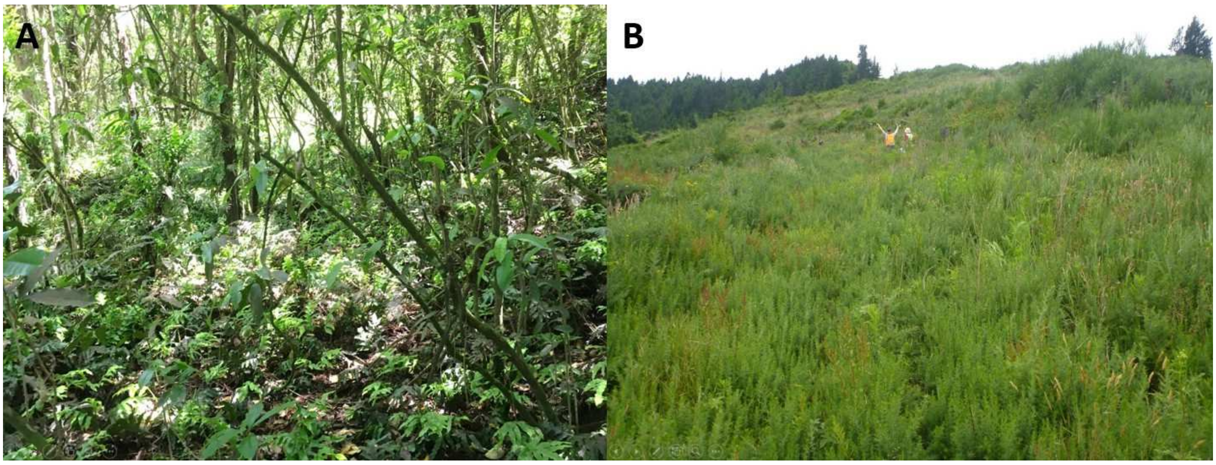


Figure D-4: A) Native forest with thick understory of ferns, and B) typical gorse and broom on harvested pine forest land.

Figure D-5: Tantragee A) subsoil on the pipeline, B) earth moving vehicle moving up Tantragee Creek to work site.

Figure D-6: A) Brook Stream looking upstream from Tindle Place and B) Cummins Creek at the culvert above the confluence with Brook Stream. Both sites are upstream from Tantragee Creek.

Appendix E Nelson Mail article by Sara Meij, 4 December 2016

Fine sediment in rivers promotes toxic algae growth, says Nelson scientist

Sara Meij

Cawthron Institute research scientist Dr Susie Wood in front of the experiment with in the background South Eastern University of Norway aquatic ecology student Nina Meijer.

Fine sediment run-off in rivers could promote toxic algae blooms a Nelson scientist says.

Cawthron research scientist Dr Susie Wood recently observed from working in rivers that fine sediment that came from the land encouraged toxic algae growth in rivers.

"We were mimicking what might happen when we have a rainfall event and it flushes sediment into the river off the land, particularly where land has just been forested for example."

She said the experiment ran for five weeks and the first three weeks clearly showed a growth in toxic blooms due to an increase in fine sediment.

The experiment set-up included four different "streams" made out of plastic and filled with running water and rocks, mimicking a flowing river.

Wood said they added a type of toxic algae, Phormidium, to every rock in all four channels and different amounts of fine sediment to three channels, leaving one channel the control group.

She said the increase in sediment was one of the reasons toxic algae was growing in rivers.

The growth was also influenced by the right balance of nitrogen and phosphorus in the water.

Wood said the experiment showed the use of land around rivers needed to be carefully considered.

She said corridors alongside rivers that were not logged or farmed on would be beneficial to rivers.

"I mean that's just not something that's going to help reduce Phormidium, it's also going to improve water quality for a variety of other reasons."

Wood said the amount of fine sediment on the river bottom increased at the lower end of a river.

"We can see in the Maitai River that up above the reservoir there's very little sediment deposited and what's deposited doesn't actually have much nutrients bound to it.

"But down here on Avon Tce there's a lot more fine sediment and it got a lot more biologically available nutrients.

"You can associate places with blooms with large amounts of sediment and the settlement with high nutrients."

She said planting the river banks with native bush, and keeping livestock away from rivers would help reduce the amount of sediment running off.

"Wetlands are another great way to capture sediment that's coming off the land before it enters the river."

Wood said the next step in the research included looking at the effect of fine sediment on Phormidium blooms in comparison to nitrogen and phosphorus.

She said this time of year, with warmer weather and less rain, means toxic algae blooms can be expected in the Maitai River.

The Nelson City Council monitors the river weekly throughout summer.

The council and community group Project Maitai are also working on planting more native plants along waterways to reduce erosion and sediment run off, provide shade to cool the water, and increase habitat for other native plants and animals.

For more information on toxic algae, visit nelson.govt.nz/environment/water-3/toxic-algae.