Waimea and Moutere Sediment Sources by Land Use

Prepared for Tasman District Council

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Executive summary

Tasman District Council (TDC) asked the National Institute of Water and Atmospheric Research Ltd (NIWA) to identify the catchment sources of sediment being deposited in the Waimea and Moutere estuaries, using NIWA's compound specific stable isotope (CSSI) technique. The study was jointly funded by Envirolink contract, CO1X1632 1749-7SDC130, with a top-up contract from Tasman District Council. This report covers the sampling and analysis under the Envirolink contract and provides a preliminary evaluation of the data giving an estimation of sediment production by sub-catchment using a two end-member mixing model coupled with predicted annual sediment loads from a national model presented in the NZ River Maps database. Sediment source estimates by land use used data from the Land Cover Database (LCDB), which was last updated in 2012-13.

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 Waimea and Moutere Rivers from all sources at that time. These samples represent an integration of the soil sources deposited at each location over the previous one or two years, or longer. While the national model prediction of mean annual sediment load is the best estimate based on the data available during construction and updating of the model. Conversely, predictions of contemporary land use source contribution proportions may be significantly different from the LCDB land use proportions due to land use changes, as well as the extent of denudation of the steep hills during forest harvesting, since the LCDB predictions were last updated.

The NZ River Maps database sediment predictions from the national model indicate that about 50% more sediment comes from the Waimea River system than the Moutere River with mean specific sediment yields of 156 t/km^2/y and 100 t/km^2/y, respectively. This may be due to the difference in land slope, with large areas of steep land in the headwaters of the Waimea River system.

The proportion of soil from these two catchments contributed by various land uses to the deposited sediment in the rivers determined by the CSSI technique agreed within 10 % with similar estimates at the same locations using the NZ River Maps sediment database, with two exceptions. First, the CSSI technique estimates of sediment proportions from Hacket Stream into the Roding were substantially greater than similar estimates from a national sediment model displayed in NZ River Maps. Trucks observed working in the Hacket Stream catchment may have been a local source of high sediment yield at the time of sampling. Forest harvesting around this confluence may also have had a local effect. Second, the CSSI technique estimates of sediment proportions from the 88-Valley Stream into the Wai-iti River were substantially greater than predicted in NZ River Maps. While there was forest harvesting in the catchment at the time of sampling, the CSSI results indicate that majority of the sediment was derived from bank erosion.

Application of the CSSI technique to the Waimea River system indicated that the land use sources of sediment changed moving downstream along the Wai-iti and Wairoa Rivers. Headwater tributaries, such as the Roding, Lee, and Wairoa, all produced elevated proportions of sediment attributable to pine forest. This is consistent with these catchments having extensive areas of recently harvested production pine forest. In contrast, CSSI indicates that the Wai-iti, 88-Valley and Pidgeon Valley Streams produced elevated proportions of sediment attributable to legacy sediment[1] from bank

[1] Legacy sediment is sediment that has accumulated at a location from previous erosion events. It is the material that forms the stream banks and then erodes during subsequent events. It will have the original land use isotopic signatures plus additional signatures from plants growing on it over time.

erosion. Pidgeon Valley stream also produced a high proportion of pine sediment, consistent with recent harvesting in that sub-catchment at the time of sampling.

In the Moutere catchment, CSSI indicates the headwater streams of Gardner Valley and upper Moutere both mostly produced sediment identified as 'bank erosion' although there was a large area of mature pine forest. Conversion from pine to pasture about 2007-08 may have been the origin of this sediment. While this sediment is labelled as "bank erosion", it could be from any sub-soil source. Given the amount of erosion of sub-soil off slopes in this catchment as a result of removing tree root boles and recontouring for conversion to pasture, it is conceivable that a large amount of this "bank erosion" is from hill-slope erosion slowly moving through the river channels. The main sources of fine sediment below the Moutere / Gardner Valley confluence were recently[2] harvested pine forest, with only a small amount of pasture contribution. Almost 90 % of the sediment at the Moutere River mouth was identified as being of pine forest origin.

Sediment with CSSI signatures of mature production forest and native forest were only minor components in all sediment samples. This is consistent with the extensive leaf canopy protecting the soil from the direct erosive energy of the rain drops during rainstorm events.

Key findings from this study included:

1. Native forest and mature pine forest plantations were found to produce very little sediment.
2. A substantial proportion of fine sediment was found to originate from forest harvesting, although loads could not be calculated without additional mass transport data.
3. Areas of harvested production forest can become colonised by gorse, broom and other weed species if not replanted in pine or before canopy closure by replanted pines. These weedy species are less efficient at protecting the soil from rainfall than a closed canopy forest and provide a distinctive sediment CSSI signature.
4. Bank erosion is a major source of fine sediment.
5. The Waimea Estuary is receiving a high proportion of legacy sediment from bank erosion but is also receiving sediment from harvested pine forest at various locations down the river, particularly the Wairoa, Lee and Roding catchments.
6. Moutere Estuary is receiving a high proportion of sediment directly attributable to pine forest harvesting. This sediment may be travelling through the Moutere River system rapidly and being flocced out at the river mouth when it contacts the more saline sea water. Some of this sediment may be derived from recent harvesting in the Central Road tributary.

[2] Recently harvested pine has isotopically different signatures than mature pine and older harvested pine with replanting or weed invasion.

1 Introduction

Tasman District Council (TDC) asked the National Institute of Water and Atmospheric Research Ltd (NIWA) to conduct a catchment study of the Waimea and Moutere River systems, using NIWA's compound specific stable isotope (CSSI) technique, in order to identify the sources of sediment being deposited in the Waimea and Moutere estuaries. The CSSI technique is a forensic sediment source tracing technique for identifying and apportioning sediment sources contributing to deposited sediment in a downstream environment (Gibbs 2008). The investigation was jointly funded by Envirolink contract, CO1X1632 1749-7STDC130, and a top-up contract from Tasman District Council. This report covers the sampling and analysis, and provides an evaluation of the data giving an estimation of fine sediment production (defined as particle sizes less than 2mm) by sub-catchment using a two end-member mixing model coupled with output from a national sediment load model (Hicks et al. 2011) presented in the NZ River Maps database[3] (see Section 2.6; Appendix A). These data are further interpreted using the CSSI technique to estimate the proportions of different land uses and land use practices contributing soil to the sediment load in these two rivers.

1.1 Objective

The aim of this study is to identify and apportion the contemporary sources of catchment sediment accumulating in the Waimea and Moutere estuaries by sub-catchment and then by land use.

1.2 Background

The Waimea and Moutere estuaries are highly valued environments for their aesthetics, biodiversity and uses for fishing, shell fish gathering and boating activities. Waimea Inlet in particular is regarded as a site of international importance for wading birds. The Lee, Roding and Wairoa catchments are some of the most heavily used rivers for recreational swimming in New Zealand. Therefore, these areas can be viewed as strategic assets for cultural and social wellbeing. Because of this importance, Tasman District Council has developed the Waimea Inlet Strategy which aims to create a sustainable future for these estuaries. The strategy brings together the communities of Tasman and Nelson and the many groups who have an interest in, and a commitment to, the Waimea Inlet in order improve the management of these areas.

Excessive fine sediment adversely effects rivers, estuaries and the coast. It affects rivers by smothering habitat within the bed that would otherwise be home to many invertebrates and fish. Deposition of sediment (Thrush et al. 2004) sourced from erosion in the catchment of the Waimea and Moutere Rivers is a major problem (Stevens and Robertson 2010, 2011 and 2014). Fine sediment reduces water clarity, interferes with feeding of filter feeding bivalves and crustacea and may smother benthic communities changing the biodiversity within the estuary (Norrko et al. 2002; Thrush et al. 2003a, 2003b). To reduce these inputs of sediment it is first necessary to understand what the sources of sediment are within the catchment so that management can be targeted. The information from this study will feed directly into this process and enable Council to develop a robust strategy for the management of the estuary and its catchment.

The Waimea catchment is also a Freshwater Management Unit and the focus of a collaborative governance group (a Freshwater and Land Advisory Group) set up under the National Policy

[3] NZ River Maps web site: https://shiny.niwa.co.nz/nzrivermaps/ See Appendix for more details

Statement for Freshwater Management (NPS-FWM 2014). Such a collaborative process will be set up for the Moutere catchment as outlined in the Progressive Implementation Plan under this NPS.

National scale sediment load model of Hicks et al. (2011) used in NZ River Maps predicts the long-term average sediment based on fundamental characteristics of catchments (excluding land use per se) and does not account for shorter term variations within and between sub-catchments due to cyclical events such as harvesting, cultivation and planting activities. The CSSI technique provides a means of evaluating contemporary differences in loads from sub-catchments and by source type from the contemporary source soil proportions in the deposited sediment at different locations down the river channel.

An example of the effect of land use change on sediment yield is provided from the Pakuratahi Land Use Study (Eyles and Fahey 2006), which included a comparison of sediment yield from paired forestry and pasture catchments over a 12-year period. The results indicated that the farmed catchment produced almost four times more suspended sediment than the catchment in mature forest. This suggests there will be low sediment export from undisturbed native forest and mature pine forest plantations. However, the Pakuratahi Land Use Study also found that during harvesting, sediment yields from the forested catchment were about three times more than the farmed catchment, and therefore up to 12 times higher than before harvesting.

The Mahurangi Harbour study (Gibbs 2006a) estimated the sediment yield to be up to 20 times higher than before harvesting, but that was a special case where harvesting drag lines inadvertently crossed a stream. Elevated sediment yield from harvested forest was expected to reduce to pre-harvest levels over a period of 2 to 3 years after replanting as canopy closure from the trees and their root systems once more protect the soil from erosion by rainfall (Eyles and Fahey 2006)[4]. During this period the erosion will decrease as weeds, native plants and the replanted pines revegetate the bare land. 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.

A review of more recent studies by Quinn and Phillips (2016) indicate that forestry practices may have improved. They say “Forest sediment yields at harvesting time can increase 5 fold over preharvest levels declining to preharvest levels often within 2-3 years of replanting.” Basher et al. (2011) also found that forest harvesting was an important influence at small catchment scale, producing a five-fold increase in storm event sediment yield in the adjacent Motueka River catchment.

Changes in the level of sediment production are also likely to occur during the clearance of native forest, during cultivation of cropping land and clearance of land for urban development (Figure 1-1).

[4] The Pakuratahi Land Use Study was undertaken on the east coast of the North Island of New Zealand, which is a dry region where droughts are common. Erosion increases after forest harvesting may be higher in wetter regions with more frequent rain events.

Figure 1-1: Production forest land clearance and development for cropping, pastoral farming and urban land use in the catchment adjacent to the Waimea and Moutere catchments.

1.3 Sources of sediment

Whenever bare soil is exposed to the weather (e.g., by earthworks, grazing or earthquakes) there is risk of erosion and sediment discharge to waterways. Common earthworks include: forest harvesting, land clearance for conversion of forest to pasture, cultivation for cropping, road construction, land recontouring and subdivision development. Stock trampling pugging the soil or breaking river banks can also be a significant source of sediment. Factors that influence the amount of erosion from any land use are 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.

The Moutere River watershed is very different from the Waimea River watershed, in that it is largely hilly to rolling pastoral country with cropping on the alluvial plains. There are also large areas of pine forest in the upper parts of the catchment and on the steeper hills throughout the Moutere catchment. In contrast, the Waimea River watershed includes steep forested hill slopes in the headwaters before the river crosses the lowland plains dominated by pasture and cropping closer to the estuary.

With such large catchments (Waimea 770 km^2; Moutere 148 km^2), localised rainfall events can also affect the sources of soil contributing to downstream deposition zones. The gradient change from steep headwater streams to low slope rivers across the plains provides an opportunity for course sediment particles to settle along the sides of the low slope river channel and subsequently be moved further downstream with successive flood events. Because of this gradual progression downstream, this material develops an amorphous isotopic tracer signature, which we have called ‘bank’, and is used to estimate the proportion of bank erosion. Bank erosion becomes a proportionally larger sediment source closer to the river mouth because runoff from land adjacent to the river during rainfall events is relatively low due to the gentler slopes in this area of the catchment and the high power of flood water caused by hydraulic head of water moving from higher in the catchments decreases. In combination, these factors cause river bed and channel bank erosion to be relatively higher in areas lower in the catchment.

An important question then relates to the connectivity between the sediment sources in the steep forested sub-catchments and the sediment in the lower river. If most of the sediment in the steep forested sub-catchments is retained in those catchments by modern forestry management practices, those sources should be reduced in importance relative to other land use sources from elsewhere in those sub-catchments, i.e., there is low connectivity between steep forestry land and the lower river.

Another important question is how many different land uses occur in the sub-catchment. If the land use in a sub-catchment is a monoculture, i.e., a single land use, the CSSI technique will only find the monoculture signature and report a 100% contribution of that soil source to the downstream deposition zone. The CSSI technique was designed to estimate the proportional contribution of each land use source in the sub-catchment to the deposited sediment. It does not estimate sediment loads. Sediment loads have to be determined by different techniques, such as multi-rain event sediment sampling using continuous flow, sediment sampling and turbidity measurements at flow rated hydrological stations or flow-weighted auto-samplers (e.g., Phillips et al. 2005; Hughes et al. 2012; Hughes and Hoyle 2014).

The CSSI technique has been applied across New Zealand at many sites including Bay of Islands (Gibbs and Olsen 2010), Whangarei Harbour (Swales et al. 2013), Mahurangi Harbour (Gibbs 2006a), Kaipara Harbour (Gibbs et al. 2012), Wharekawa Estuary (Gibbs and Bremner 2007), Whangapoua Harbour (Gibbs 2006b), Whangamarino wetland (Gibbs 2009; Reeve et al. 2011; Gibbs 2016), Pelorus Sounds (Handley et al. 2017), Maitai River, Nelson (Gibbs and Woodward 2017), New River Estuary, Invercargill (Gibbs et al. 2015) and Jacobs River Estuary, Southland (Gibbs et al. 2014). In all of these studies the sediment came from a range of different sources, but not necessarily sources that occupied the greatest area within the catchment. Forestry signatures were dominant in several studies (Mahurangi, Whangapoua, Maitai and Pelorus Sound after early 1900s) and native forest in others (Wharekawa). Pasture contributed most sediment in the Southland studies and land development from the city was a major source of sediment to the Whangarei Harbour.

2 Methods

2.1 Overview of the CSSI technique

The catchment sources of fine sediment deposited in the Waimea and Moutere Rivers were identified using the CSSI techniques developed by NIWA (Gibbs 2008). This is a forensic method that uses the stable isotopic signatures of fatty acids (FA), which are produced by plants growing on the land. The FAs with carbon chain lengths in the range 12 to 26 (i.e., C12:0 to C26:0) are slightly water soluble, allowing them to disperse from plant roots to the adjacent soil during rainfall infiltration. Because they are polar, the fatty acids bind to the soil particles and become biomarkers or labels for that soil and thereby provide a way to identify the land use that generated sediment deposited downstream; i.e., these FA become permanently bound to the soils as biomarkers (fingerprints).

For the CSSI technique, 'land use' is defined by the plant community growing on the land. Different land uses have different plant communities that produce the same range of fatty acids but with different isotopic signatures. This unique land use isotopic signature enables soil and sediment found in rivers and estuaries to be traced back to particular land use sources. Furthermore, as the stable isotopic signatures of fatty acids are conservative they are not affected by decomposition processes that produce changes in concentration through time.

The CSSI technique concept relies on the fact that all plants produce the same specific range of FAs from their root systems. 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. There are 12 different fatty acids produced by plants, which provides a range of potential tracers or combination of tracers that are unique to a particular plant community and associated land use.

Table 2-1 shows an example of the numerical difference between different isotopic signatures for some different land uses, while Figure 2-1 shows the spectral difference in chromatogram trace fingerprints from three different common land use source soils and a sediment mixture. Differences between the three pine sources in Table 2-1 are caused by differences in the understory plant community i.e., these sources represent the whole plant community, not just the pine trees.

Table 2-1: Example of the differences in isotopic signatures of bulk soil carbon and three different fatty acid tracers that allow differentiation between different land use types.

Land-use / Sources	Bulk isotopes	CSSI (Fatty acids)		
	$\delta^{13}C$ (‰)	Myristic (C14:0) (‰)	Palmitic (C16:0) (‰)	Oleic (C18:1) (‰)
Pasture	-22.2	-27.0	-24.0	-21.6
Native Forest (Nikau)	-27.7	-34.9	-30.4	-28.2
Native Forest (Kauri)	-25.1	-28.9	-25.6	-27.8
Pine forest (Mature)	-26.2	-40.7	-32.4	-29.5
Pine forest (Clear-felled)	-26.5	-32.7	-28.7	-28.2
Pine forest (sub-soil)	-26.2	-37.0	-29.1	-25.0
Seagrass (estuary)	-8.0	-11.7	-10.9	-16.9

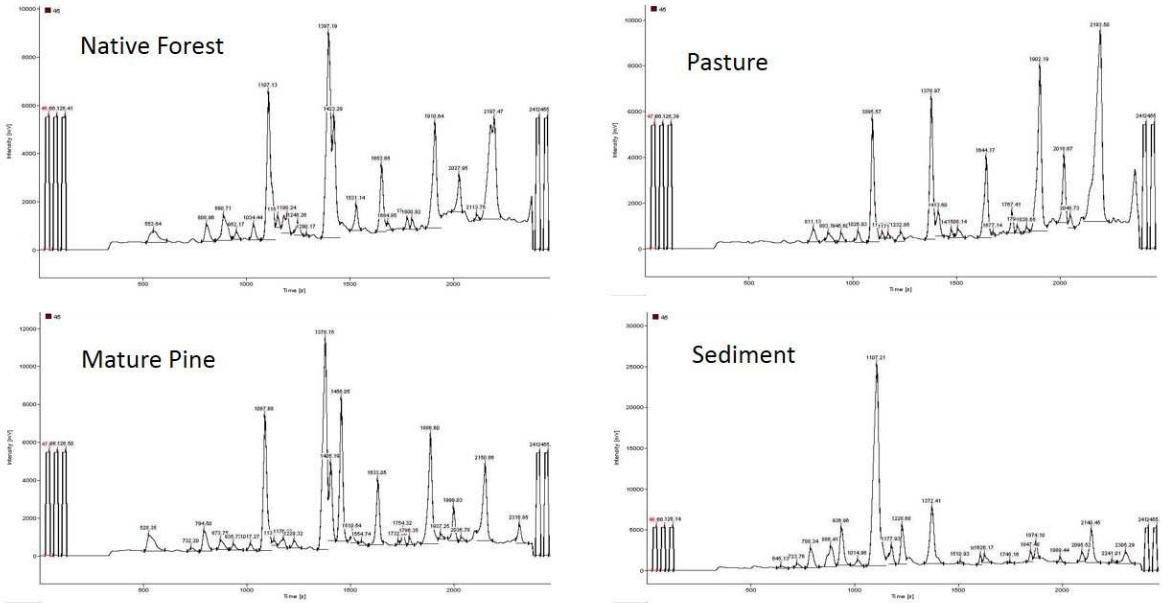


Figure 2-1: Chromatogram fingerprints of saturated fatty acids produced by three different land use plant species and an example of the fatty acid content of a deposited sediment. These are fatty acid concentrations as extracted from the soil. Each peak has an isotopic signature specific to the specified plant community. 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 in the deposition zone downstream 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, including river banks, 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 have a very low proportional contribution to the downstream sediment mixture, or none at all.

Studies elsewhere (e.g., Hoare 1982) have demonstrated that rivers are likely to be at base-flow conditions with low suspended solids for most of the time. Hoare (1982) also found that, for the Ngongotaha Stream at Rotorua, 42% of the annual sediment load was carried on just three days and that 25% of the annual load was carried in a period of 16 hours at the peak of the flood event. Different river systems will behave differently but the general pattern is likely to be similar.

Importantly, very fine sediment particles (e.g., <64 micron) may not settle in the river channel while the river is in flood and therefore will not be present in the deposited sediment. Fine sediment will settle in back eddies along the river or where there has been over-bank flow that allows fine sediment to be trapped in the grass on the river bank. To allow for this “winnowing” effect, the CSSI technique uses all particle size fractions less than 2 mm from the deposited sediment and does not use concentration, just the stable isotopic signatures, which are conservative.

The approach taken in this study was to 1) assess the proportional contribution from each sub-catchment to the downstream deposited fine sediment below each major tributary confluence using a linear two end-member mixing model applied to data using 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 using the CSSI technique, and 3) sum the land use proportions to provide an estimate of the relative proportions of each land use contributing sediment being discharged to the estuaries.

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. Taking a single sample may not be representative of the land use being sampled because of natural variability across that land use.

To reduce sampling errors for the reference library, a set of 10 or more uniform sized small soil samples (divots) were collected from an area of about 100 m^2 in each land use type and combined into a single bulk composite sample. Each sample divot in the composite must be the same size to avoid bias in the case where natural variability is large. Under natural conditions, it is assumed that erosion from the land use site will be relatively even during a rainfall event and therefore a composite sample from across a large area is more likely to produce a representative sample of the land use than a sample from a single point.

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

A river confluence technique was used to identify and apportion sediment contributions from different catchments down the Waimea and the Moutere Rivers. This technique requires collection of three sediment samples at each site – 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 flow and channel morphometry - a bend in the river or a riffle usually being sufficient to induce complete mixing. Note that base flow conditions might not reflect the sediment loads carried during an event and samples may need to be collected on the flood plain on the river banks.

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 28 confluence sites down the Waimea and the Moutere Rivers (Figure 2-2) and (Figure 2-3). 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.

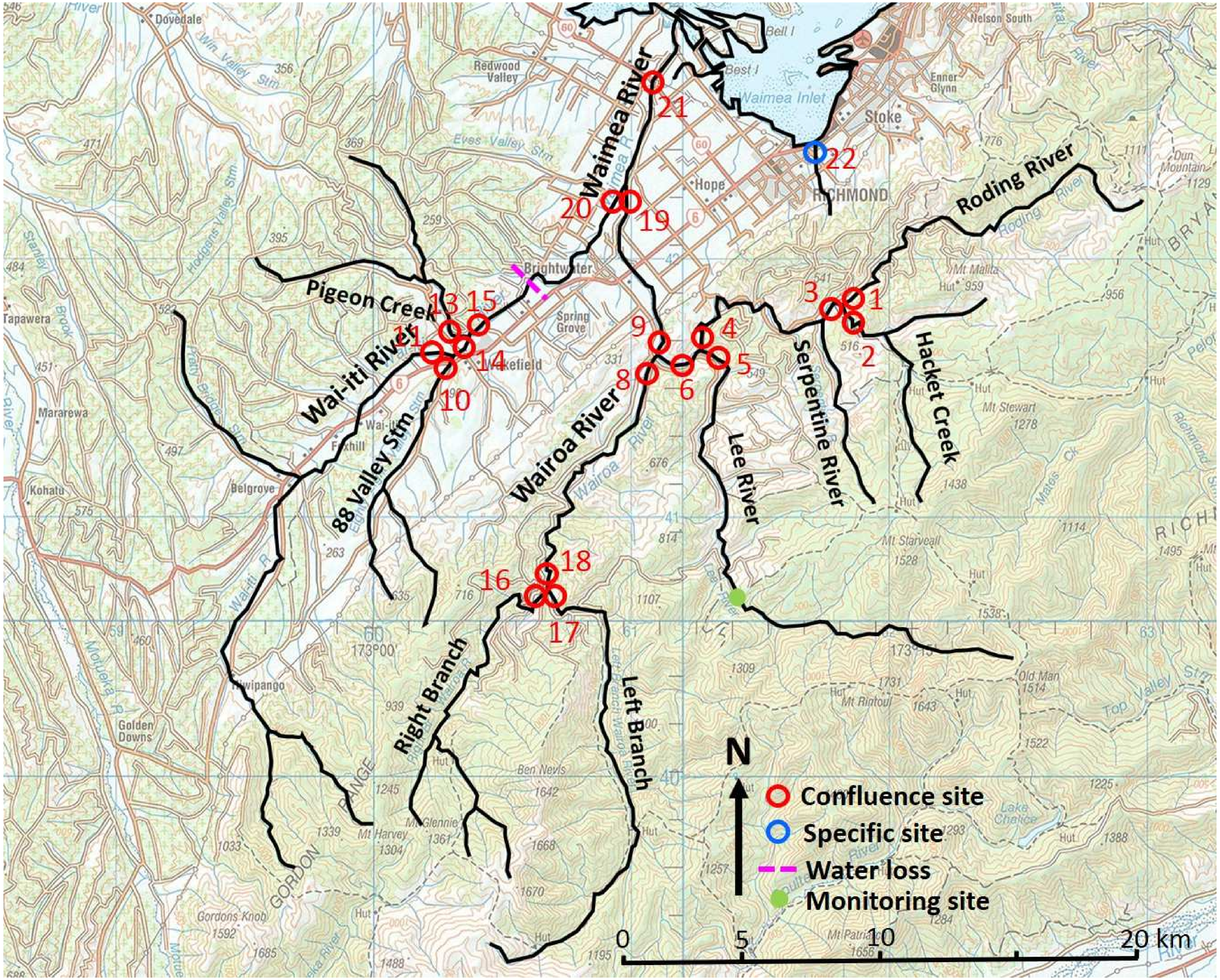


Figure 2-2: Sampling sites at river confluences in the Waimea watershed. Site numbers refer to Table 2-3. (Water loss and monitoring site – see Section 4.1).

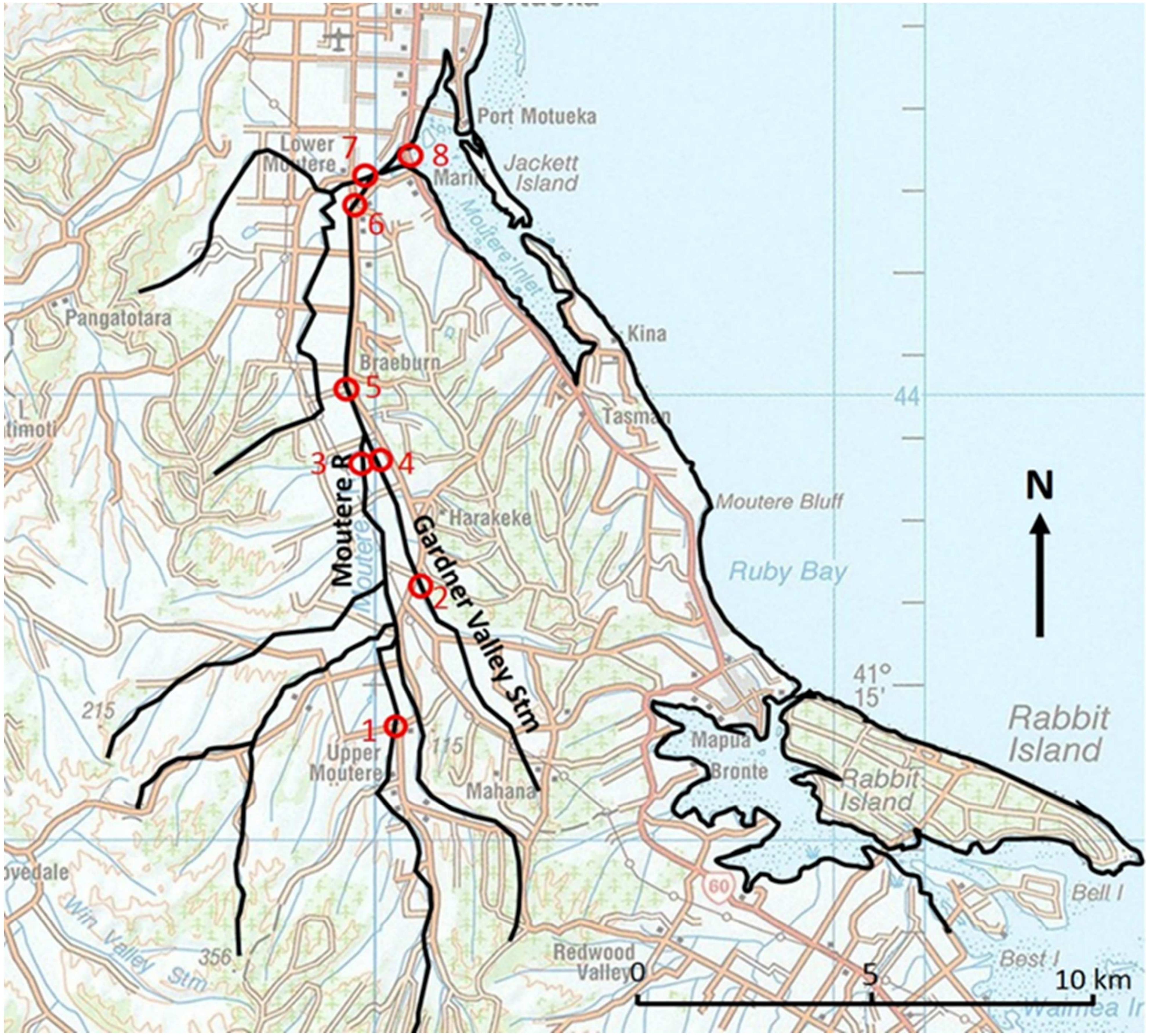


Figure 2-3: Sampling sites at river confluences in the Moutere watershed. Site numbers refer to Table 2-2. Site numbers 1 and 2 are sub-catchments, not confluence samples

Table 2-2: Location of confluence sediment samples collected in the Moutere River watershed. Samples are listed in the order used in the two end-member mixing model.

Sample Code	Site No	Longitude	Latitude	Site description
OA 195 2	1	173.004081	-41.258553	Moutere u/s at Kelling Bridge
OA 195 3	2	173.010857	-41.229187	Gardner Valley u/s at Davey Rd
OA 195 4	3	172.995046	-41.201723	Moutere u/s Gardner Valley at Wilson Rd
OA 195 5	4	172.998266	-41.200778	Gardner Valley u/s Moutere at Wilson Rd
OA 195 6	5	172.991932	-41.189870	Moutere d/s Gardner Valley at Drummond Rd
OA 195 7	6	172.993615	-41.152307	Moutere u/s Central Road Tributary
OA 195 8	7	172.993547	-41.148990	Central Road Tributary
OA 195 33	8	173.003882	-41.145201	Moutere d/s of Central Road Trib confluence

Table 2-3: Location of confluence sediment samples collected in the Waimea River watershed. Samples are listed in the order used in the two end-member mixing model. Samples 14 and 17 were used as downstream sites for one confluence and then the upstream sites for next downstream confluence.

Sample Code	Site No	Longitude	Latitude	Site description
OA 195 9	1	173.214200	-41.388204	Roding u/s Hacket
OA 195 10	2	173.215200	-41.389504	Hacket u/s Roding
OA 195 11	3	173.209813	-41.386104	Roding d/s Hacket
OA 195 13	5	173.159045	-41.407700	Lee u/s Roding
OA 195 12	4	173.149857	-41.403077	Roding u/s Lee
OA 195 14	6	173.146401	-41.408741	Lee d/s/ Roding
OA 195 15	8	173.127142	-41.408402	Wairoa u/s Lee
OA 195 14	6	173.146401	-41.408741	Lee u/s Wairoa
OA 195 16	9	173.131083	-41.394839	Wairoa d/s Lee
OA 195 23	17	173.083012	-41.487824	Wairoa u/s Left Branch
OA 195 22	16	173.078953	-41.486505	Wairoa u/s Right Branch
OA 195 24	18	173.081101	-41.481380	Wairoa d/s confluence
OA 195 20	11	173.016186	-41.406157	Wai-iti u/s 88 Valley
OA 195 19	10	173.029173	-41.413778	88 Valley u/s Wai-iti
OA 195 17	14	173.040292	-41.404587	Wai-iti d/s 88 Valley
OA 195 17	14	173.040292	-41.404587	Wai-iti u/s Pidgeon
OA 195 18	13	173.039083	-41.399147	Pidgeon u/s Wai-iti
OA 195 21	15	173.067128	-41.385590	Wai-iti d/s Pidgeon
OA 195 29	19	173.113023	-41.361146	Wairoa u/s Wai-iti
OA 195 30	20	173.116402	-41.345714	Wai-iti u/s Wairoa
OA 195 31	21	173.128910	-41.308981	Waimea d/s confluence
OA 195 32	22	173.202707	-41.337269	Reservoir Creek (Richmond)

Shading in the tables links the three sites used in each confluence modelling step. These comprise an upstream site and a downstream site on the main stem of the river, and a site on the tributary entering the river between these two sites. Because some tributaries were close together, e.g., 88 Valley and Pidgeon Valley on the Wai-iti River (Figure 2-2), the downstream site for the upstream tributary was used as the upstream site for the next tributary downstream. Consequently, sites OA 195 14 and OA195 17 are listed twice in Table 2-3.

2.4 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[5] 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 (10 FAs and %C). 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.

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

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

$$1 = fA + fB \qquad (2)$$

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

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

and for fB, the equation is rewritten as:

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

The caveat for the two-end member 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 2-4). 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

[5] Linear mixing models with n tracers can be solved for up to n + 1 sources.

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 2-4). The sediment characteristics tested in the two end-member mixing model were percent organic carbon (%C), the bulk carbon-13 (^{13}C) signature of the sediment and the isotopic signatures of the FA biomarkers. In Table 2-4, 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.

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.

Table 2-4: 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

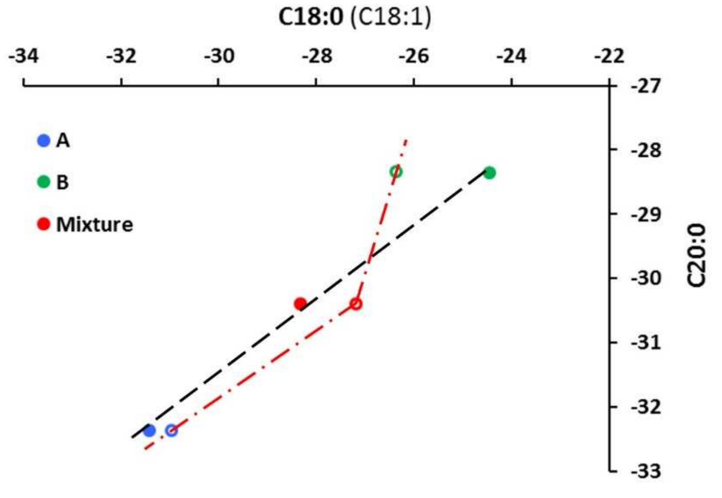


Figure 2-4: Linearity test used to confirm valid data for the two end-member mixing model. Solid dots are valid data (C18:0 vs C20:0). Open circles are invalid data (C18:1 vs C20:0). (See text). (Diagram by M. Gibbs).

2.5 Soil source modelling

Soil samples were collected (10 replicates) from representative land uses to produce data for a library. Soils from urban land uses were not sampled for the library as they make up such a small percentage of the land uses in both catchments (<0.5%). Soils from cropping could have been included given the prevalence of that activity on the Waimea plains and Moutere valley floors. However, given that this land use was a small part of the whole Waimea (1.6%) and Moutere (12.7%) River catchments and generally occupies very flat ground the risk of erosion is low, these were not included in this study. Soil library samples were collected locally in the two river catchments but included some from the adjacent Maitai River catchment. Wherever possible, however, the Land use samples from within the Waimea and Moutere catchments were used in preference to those from outside these catchments.

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 land use sources and the sediment mixture, using the isotopic values of pairs of FAs. These are the isotopic tracers. In the example (Figure 2-5), the bulk soil $\delta^{13}C$ and oleic acid (C18:1) were used. All sources are plotted individually to allow appropriate source selection or grouping.

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. The polygon is drawn through the source points closest to the mixture. In this example, all sources were selected because the polygon produced using this pair of isotopes enclosed all sources and the mixture.

The polygon test can also be used to identify valid isotopes to be used in the modelling. The eight sources selected include three different pine sources (recently harvested, mature and sub-soil from earthworks), native forest, scrub (gorse & broom), pasture (sheep), bank erosion, and an unsealed road. Because all sources are enclosed by the polygon, they all have the potential to contribute soil the sediment mixture. At other sites, one or more source soil isotopic values plotted outside the polygon. While these sources may still be valid, they would be less likely to contribute substantial proportions of soil to the mixture.

Of special interest in the example (Figure 2-5) is the grouping of the five sources enclosed by the elipse. These sources are related as sub-soils (Pine sub-soil, bank erosion and unsealed road) with linkage to native forest and pasture, i.e., all of these sources have had native forest soil as their origin and it is likely that the native forest signature remains as a dwindling legacy signature / fingerprint. The mature pine, harvested pine and scrub are likely to have very different and stronger isotopic signatures from pine overwriting the native forest legacy signature. Current studies on transition times for the isotopic signatures from an original land use to be replaced by the new land use isotopic signatures suggest that this is essentially complete within about 5 years from the change (NIWA, unpublished data).

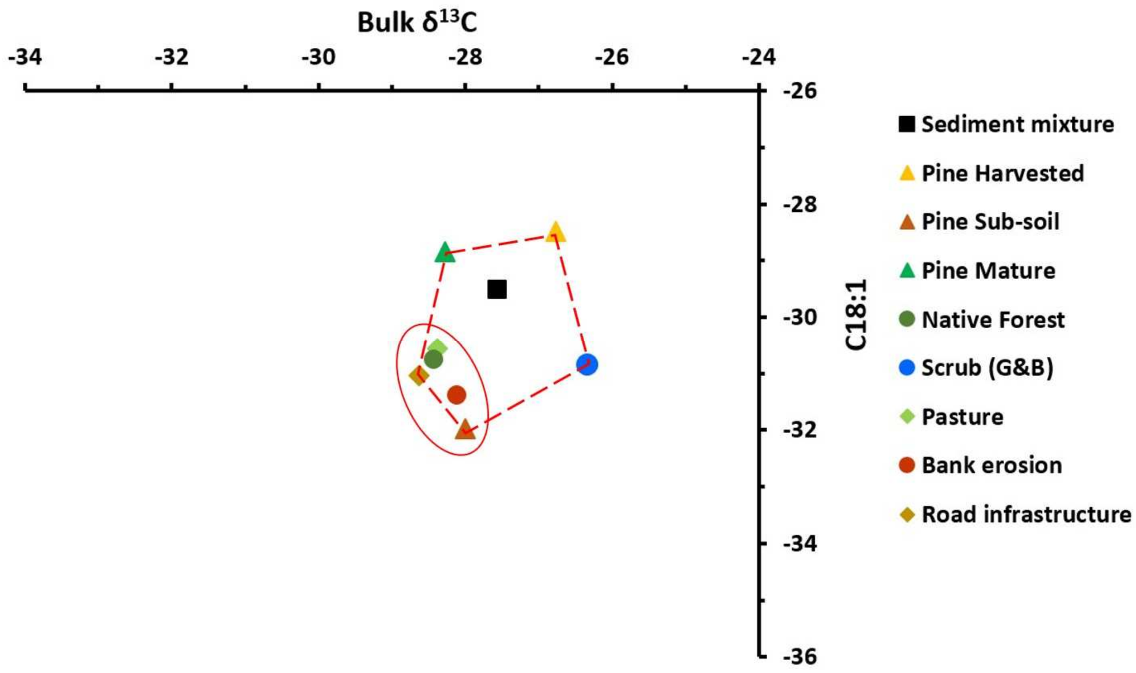


Figure 2-5: Example of a polygon analysis on a fatty acid (FA) biplot of the potential sources that could contribute to sediment at the site downstream of Hacket Stream confluence. The red dashed line is the polygon that links the sources contributing to the mixture. (See text).

When used in the biplot, other combinations of FA tracers produced polygons with slightly different relationships between the sources and the mixture. Polygon analysis of all samples showed that best results for this site were obtained using bulk soil $\delta^{13}C$, C16:0 and C18:1. Outside this range, the results were mostly invalid.

All modelling used the best FA tracers determined for the eight land use sources. It should be noted that just because these eight 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 stable isotopic mixing model (SIMM), four tracers can accommodate 5 sources. In this example there are 8 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 of 3000 model iterations are used to provide estimates of uncertainty. The data in Figure 2-5 shows substantial differences in the isotopic signatures from the three pine land uses classes, but a close grouping of sources which are likely to have a native forest legacy isotopic tracer. The differences in the pine source signatures are likely to reflect the plant community growing with the main land use plant i.e., the understory beneath pine forest. These differences are too large to be combined in a single land use and can to be used as unique fingerprints to discriminate between these land use classes. If there were too many sources for modelling, source reduction can be achieved by using only those sources from sites closest to the mixture site i.e., a geographical constraint.

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 outputs 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. 2018). This gives confidence in reporting the mean ± SD from the IsoSource model results.

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).

As the SIMM program was written, the number of sources and FA isotope tracers used in IsoSource is limited to nine and five, respectively. The model is slow to run with this number of sources and tracers, and is more efficient (faster) 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 a value "n", which is the actual number of feasible solutions found that could produce the isotopic balance matching the isotopic values in the sediment mixture. 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 of the feasible solutions indicates whether there is 'coupling' between some sources. This effect will appear as low broad peaks that can extend over more than 50% of the feasible solutions and the value of n is likely to >> 1000. 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 for the other and a substantial 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.

Since sediment cores were not collected from the estuaries, the proportional contribution of catchment sources at the downstream river sample sites will be used as the input sources to the estuaries.

2.6 Database information

Two national databases were used for assessing the potential sediment loads in the river and tributaries. These were predictions from the annual average suspended sediment yield national model of Hicks et al. (2011) as presented in NZ River Maps[6] and the land use cover in each sub-catchment in the Waimea and Moutere River watersheds from the Land Cover Database (LCDB[7]). Theoretical sediment yields by land use from the catchments can be calculated from the land use cover and the national sediment load model data and assuming that sediment loss by land use is proportional to catchment area of land uses. Both the national sediment model and the LCDB provide information for the whole catchment upstream of each node point on the river. The sediment yield for each land use in the upstream catchment was estimated as a proportion of the total sediment yield at that node by multiplying the total suspended sediment yield at a node by the proportional land cover area from the LCDB for that land use at that node. This estimate will be correct when the LCDB areas were first loaded but will become different as the land use areas change due to different land management strategies e.g., rotational harvesting of forests, conversion of forests to pasture. Periodically the LCDB is revised to give the most up-to-date estimates of vegetation cover. The most recent update was 2012.

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 Waimea River for annual suspended solids load are shown in Figure 2-6.

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

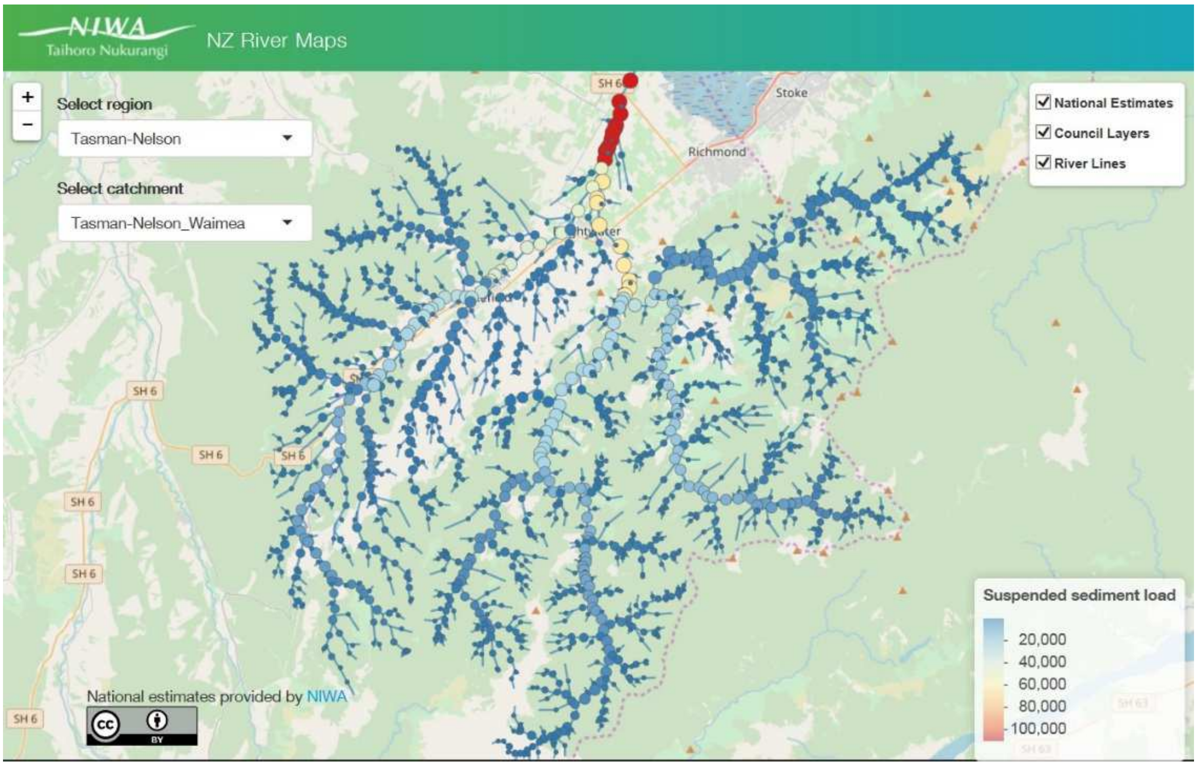


Figure 2-6: Example of the River Environment Classification (REC) for predicted Suspended Sediment load in the Waimea River from NZ River Map. Nodes are defined by round dots - clicking on any of them will produce a tab (example shown for the last node on the river) representing the cumulative information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

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.

Cautionary notes:

The REC sediment load information in NZ River Maps are modelled estimates from a national scale model (Hicks et al. 2011) and are not expected to be as accurate as site-specific studies, i.e., the predicted REC values in NZ River Maps may differ from the observations made in the field.

Time series changes in land cover from Google Earth Timelapse[8] show the progression of forest harvesting in the Waimea River catchment from 1984 to 2016, so that the NZ River Maps predictions based on 2012 land cover data do not match the contemporary situation perfectly.

[8] https://earthengine.google.com/timelapse/

3 Results

A linear two end-member mixing model was applied to sediment isotopic data at the confluence of each tributary entering the Waimea and Moutere Rivers (see section 2.4) (Table 3 1; Table 3-2). There results were subsequently used with the soil source identification model (IsoSource) to determine the proportional contribution of soil from each land use class at each site.

3.1 Catchment sediment loads

3.1.1 Waimea River catchment modelling output

In most cases in the Waimea River, the two end-member mixing model result was the average of 3 valid calculations, giving the results relatively high certainty. Where the modelling produced only a single valid result, these results have a higher level of uncertainty. The cause of just a single valid result can be low organic content resulting in missing isotopic data, which was below analytical detection level for the sample size extracted. For example, at the Roding / Hacket confluence (Sites 1 – 3) the organic content was very low and several key fatty acid biomarkers present at other sites were not detected.

A comparison of the CSSI estimate with the proportional contributions based on the annual sediment load estimate from the NZ River Map database (Table 3-1) shows that the CSSI results are generally in agreement with the proportions estimated from the NZ River Map sediment data. The Wairoa left Branch (Site 17) contribution to the downstream confluence at 65.5% from River Map data is essentially the same as the 65.3% estimate by the CSSI data, as is the Wairoa upstream of Wai-iti (Site 19) contribution to the downstream confluence at 57.2% from River Map data compared with the 59.4% estimate from the CSSI data.

Proportional contributions by the CSSI techniques were similar to the estimates obtained using the NZ River Map sediment data at Wairoa upstream of Lee (Site 8), Wai-iti upstream of Pidgeon Valley (Site 14) and Roding upstream of Lee (Site 4) with 57.8% vs 46.3%, 93.5% vs 87.0% and 62.9% vs 73.7%, respectively. However, there were substantial differences between the results at Wai-iti upstream of 88 Valley collected at Baigent Rd (Site 11) and Roding upstream of Hacket (Site 1) with 39.5% vs 88.3% and 4.4% vs 40.4%, respectively.

The differences between the CSSI proportional sediment contribution estimates and the NZ River Map model sediment predictions at Sites 10 and 11 are likely to be associated with land use or land disturbance. A disproportionately higher sediment contribution is coming down the 88-Valley Stream (above site 10). This stream drains land that has been largely pastoral for many years and should have comparable sediment yields between years. This change in sediment source proportions identified by the CSSI technique indicates an increase in the area of bare exposed soil that is now eroding. This may be from cultivation or roading. It is also possible that flood events have eroded banks, and there was some evidence of forest harvesting in parts of the 88-Valley catchment. Any of these factors could exacerbate sediment loads in the stream.

Table 3-1: Estimated contributions from the upstream branches at each confluence using catchment area, mean flow, annual suspended sediment loads and CSSI values. The catchment area, mean flow, annual suspended sediment load values were from the NZ River Maps database at each confluence sampling point. The CSSI estimate was based on applying the two end-member mixing model to the CSSI values from the fatty acid biomarkers extracted from the deposited sediment samples at each confluence sampling point. Map Site numbers refer to Figure 2-2 and Table 2 3. Shading indicates the grouping of data used in the two end-member mixing model. (* See text).

River confluence analyses		NZ River Map data				Estimated contribution from u/s branches at confluence			
Map (site No)	Site description	Area (km^2)	Mean Flow ($m^3 s^{-1}$)	Sediment (SS t y^{-1})	Sediment Yield ($t/km^2/y$)	Area (%)	Mean Flow (%)	Sediment (%)	CSSI estimate (%)
1	Roding u/s Hacket	56.0	2.48	2908	51.9	59.4	63.8	40.2	*4.4
2	Hacket u/s Roding	37.5	1.36	4330	115.5	39.8	35.0	59.9	*95.6
3	Roding d/s Hacket	94.3	3.89	7230	76.7				
5	Lee u/s Roding	114.0	5.27	24469	214.6	46.5	54.8	73.7	62.9 (8.5)
4	Roding u/s Lee	131.0	4.15	8710	66.5	53.5	43.1	26.2	37.1 (8.5)
6	Lee d/s/ Roding	245.0	9.62	33200	135.5				
8	Wairoa u/s Lee	204.0	7.41	28631	140.3	45.0	44.4	46.3	*57.8 (10)
6	Lee u/s Wairoa	245.0	9.62	33200	135.5	54.1	57.6	53.6	*42.2 (10)
9	Wairoa d/s Lee	453.0	16.70	61890	136.6				
17	Wairoa u/s Left Branch	96.9	3.59	18065	186.4	61.7	64.2	65.5	65.3 (10)
16	Wairoa u/s Right Branch	58.7	2.06	9494	161.7	37.4	36.9	34.4	34.7 (10)
18	Wairoa d/s confluence	157.0	5.59	27588	175.7				
11	Wai-iti u/s 88 Valley	167.0	4.71	31902	191.0	81.9	84.0	88.3	39.5 (5.5)
10	88 Valley u/s Wai-iti	35.1	0.73	3998	113.9	17.2	13.0	11.1	60.5 (5.5)
14	Wai-iti d/s 88 Valley	204.0	5.61	36147	177.2				
14	Wai-iti u/s Pidgeon	204.0	5.61	36147	177.2	84.3	99.1	87.0	93.5 (5.9)
13	Pidgeon u/s Wai-iti	37.8	0.50	5333	141.1	15.6	8.8	12.8	6.5 (5.9)
15	Wai-iti d/s Pidgeon	242.0	5.66	41569	171.8				
19	Wairoa u/s Wai-iti	467.0	17.30	62702	134.3	60.6	62.9	57.2	59.4 (8.9)
20	Wai-iti u/s Wairoa	291.0	5.19	46312	159.1	37.8	18.9	42.3	40.6 (8.9)
21	Waimea d/s confluence	770.0	27.50	109556	142.3				
22	Reservoir Creek (Richmond)	3.4	0.05	249	73.2				

Bank erosion and forest harvesting may also be driving the difference between the CSSI estimate and the NZ River Map estimate at Roding upstream of Hacket (Site 1). In this case the Roding River upstream of the Hacket Stream has very little organic sediment but shows evidence of inorganic sediment deposition mainly of ultramafic origin (Figure 3-1). While sampling this confluence, earth moving trucks were fording the river downstream of Site 1 to move up Hacket Stream. This activity is likely to have mobilised stream bed sediment in the Hacket Stream catchment, thereby enhancing the proportional contribution of sediment from the Hacket Stream tributary (Site 2) to the downstream confluence at Site 3. The high pine signature at downstream confluence, Site 3, could have come from forest harvesting upstream of that site but downstream of Site 1.

Figure 3-1: Deposited sediment on the side of the Roding River at Site 1. The layers indicate deposition at different water levels. The layers contained very little organic matter, being mainly of ultramafic rock origin. [Photo by M. Gibbs]

3.1.2 Moutere River catchment modelling output

For the main confluences in the Moutere River system, the difference between the CSSI estimates and NZ River Map estimates of sediment contributions from the different sub-catchments were about 10% (Table 3-2). CSSI estimates indicate higher proportional sediment loads upstream of Gardner Valley (Site 3) and in the Central Road tributary (Site 7) than the predictions from the national sediment model in NZ River Maps.

Table 3-2: Estimated contributions from the upstream branches at each confluence in the Moutere Catchment using catchment area, mean flow, annual suspended sediment loads and CSSI values. The catchment area, mean flow, annual suspended sediment load values were from the NZ River Maps database at each confluence sampling point. The CSSI estimate was based on applying a two end-member mixing model to the CSSI values from the fatty acid biomarkers extracted from the deposited sediment samples at each confluence sampling point. Map Site numbers refer to Figure 2-3.

	River confluence analysies	NZ River Map data				Estimated contribution from u/s branches			
Map (site No)	Site description	Area (km^2)	Mean Flow (m^3 s^{-1})	Sediment (SS t y^{-1})	Sediment Yield (t/km^2/y)	Area (%)	Mean Flow (%)	Sediment (%)	CSSI estimate (%)
1	Moutere at Kelling Rd Bridge	39.5	0.46	3557	90.1				
2	Gardner Valley Stream at Davey Rd Bridge	15.3	0.18	1286	84.1				
3	Moutere u/s Gardner Valley at Wilson Rd	87.4	1.05	8509	97.4	79.5	80.2	82.4	90.4 (7.5)
4	Gardner Valley u/s Moutere at Wilson Rd	22.3	0.26	1886	84.6	20.3	19.6	17.6	9.6 (7.5)
5	Moutere d/s Gardner Valley at Drummond Rd	110.0	1.31	10686	97.1				
6	Moutere u/s Central Road Tributary	126.0	1.48	11890	94.4	84.7	81.8	80.5	69.4 (10)
7	Central Road Tributary	22.2	0.24	2849	128.3	15.0	13.0	19.2	30.6 (10)
8	Moutere d/s of Central Road Trib confluence	148.8	1.81	14769	99.3				

3.2 Land use source modelling

Because land uses can change over time, the results obtained for land use proportions in this study represent a snapshot of the land use sources of sediment at the time of sampling, i.e., December 2016.

3.2.1 Waimea River catchment

The isotopic mixing model results used to identify land use sources were corrected for carbon content differences and then expressed in terms of % of total sediment in the river, normalised to the load at the Waimea River mouth (Site 21) (Table 3-3) (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 (mass transport data is available for the upper Lee River, Trevor James TDC, pers. comm.). For example, if it were known that a storm event produced a sediment load of X t d^{-1} this 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. This assumes uniform erosion across the catchment.

The land use soil sources tested using the CSSI technique for contribution of sediment to the Waimea River down its length were native forest, pine forest, pasture, gorse and broom, and bank erosion (Table 3-3). The LCDB classes included crops and urban (Table 3-4) but neither of these sources were included in the reference library. Based on the LCDB proportions, crops occupied 1.6% of the catchment with most of that occurring on the flat land close to the Waimea Estuary. Because the cropland has low slope it will have a low sediment runoff unless there is rainfall soon after cultivation and planting. Urban occupied 0.5% of the catchment. The omission of these potential sources from the modelling constitutes a minor error of less than 2.1% of the total catchment area in the overall model output.

The sediment proportions by land use area estimated from the LCDB and the sediment proportions by land use estimated by the CSSI technique are very different (Table 3-5). The LCDB estimate gives the areal proportions of the land use in the catchment and would only be correct as a sediment source estimate if the whole catchment eroded at the same rate per unit area. This does not happen as illustrated by the differences in specific sediment yield for the sub-catchments upstream of each confluence (Table 3-1). The CSSI estimate only "sees" the sediment that enters and settles in the river and is more likely to represent the actual land use proportions contributing to sediment entering the estuary. If a land use is not producing sediment, that land use will not be present in the model results.

Table 3-3: Soil source contributions to the fine deposited sediment of the Waimea River system at each of the confluence sampling points. The column "% of total catchment" shows the relative proportion of catchment upstream at each location normalised to 100% at the mouth of the Waimea River (Site 21). The land use columns show the estimated source contributions by land use in the % of total at each site. The land use class "Gorse & Broom" is mostly associated with harvested forest land that has yet to achieve canopy closure after replanting. The column 'n' is the number of feasible solutions found by the IsoSource model (See Section 2.5).

	Waimea River system		**Land use proportion at site (%)**					
Site No	**Site name at confluence**	**% of total catchment**	**Native Forest**	**Pine Forest**	**Pasture**	**Gorse & Broom**	**Bank erosion**	**n**
1	Roding U/S Hacket	7.4	0.12	26.21	0.20	0.00	73.47	180
2	Hacket U/S of Roding	4.9	0.04	4.32	0.00	20.07	75.58	799
3	Roding D/S Hacket	12.6	10.59	89.41	0.00	0.00	0.00	1
5	Lee U/S Roding	14.6	13.00	83.69	0.00	3.31	0.00	1
4	Roding U/S Lee	17.0	0.90	56.86	3.31	38.94	0.00	8
6	Lee D/S Roding	31.9	0.96	43.24	0.00	40.57	15.23	25
8	Wairoa U/S Lee	26.6	0.00	45.47	0.00	18.26	36.27	3
9	Wairoa D/S Lee (Max's bush)	59.2	51.63	12.55	7.48	2.13	26.21	734
17	Wairoa - Left Branch	12.5	0.21	24.79	1.87	59.69	13.44	68
16	Wairoa - Right Branch	7.7	0.41	53.64	0.91	15.16	29.88	286
18	Wairoa D/S Left/Right Confluence	20.4	4.64	89.95	1.03	4.39	0.00	1
11	Wai-iti U/S 88 Valley at Baigent Rd	21.3	1.32	4.69	23.44	0.43	70.12	41
10	88 Valley U/S Wai-iti	4.4	0.17	4.12	4.22	0.00	91.48	1
14	Wai-iti U/S Pidgeon Valley	26.4	2.43	5.26	0.26	68.28	23.77	3
13	Pidgeon Valley U/S Wai-iti	4.8	0.00	25.17	0.57	32.95	41.31	14
15	Wai-iti D/S Pidgeon at Barton Rd	32.0	1.66	0.00	0.90	0.00	97.44	4
19	Wairoa U/S Wai-iti at Clover Rd West	59.7	0.26	57.43	15.99	0.00	26.33	65
20	Wai-iti U/S Waimea at confluence	38.0	4.68	12.06	20.50	0.00	62.76	19
21	Waimea mouth D/S Applby Bridge	100.0	0.21	17.65	0.36	13.58	68.21	51
22	The Reservoir Creek	100.0	0.00	12.41	2.52	6.23	78.84	4

Table 3-4: Land use areas in the Waimea River system upstream of each confluence sampling point. The column "Catchment area" shows the total area of catchment upstream at each confluence. The land use area columns show the area of each land use in the catchment upstream of each confluence. (Data from Land Cover Database updated as at 2012).

	Waimea River system		Land use area at site (km²)						
Site No	Site name at confluence	Catchment Area (km^2)	Native Forest	Pine Forest	Pasture	Gorse & Broom	Crop	Bank erosion	Urban
1	Roding U/S Hacket	56.74	31.01	11.20	7.15	6.20	0.00	1.06	0.11
2	Hacket U/S of Roding	37.54	23.32	2.71	3.86	7.53	0.00	0.13	0.00
3	Roding D/S Hacket	96.66	54.46	15.85	11.27	13.76	0.00	1.22	0.11
5	Lee U/S Roding	112.06	70.33	32.71	4.07	3.86	0.00	1.09	0.00
4	Roding U/S Lee	130.79	60.61	35.98	15.12	17.35	0.00	1.56	0.18
6	Lee D/S Roding	245.45	131.00	70.53	19.52	21.47	0.00	2.75	0.18
8	Wairoa U/S Lee	204.67	125.79	45.94	21.54	10.12	0.03	1.26	0.00
9	Wairoa D/S Lee (Max's bush)	455.87	257.11	118.73	43.53	32.02	0.09	4.22	0.18
17	Wairoa - Left Branch	96.51	74.84	8.86	6.96	5.17	0.00	0.68	0.00
16	Wairoa - Right Branch	59.31	43.52	11.32	2.75	1.40	0.00	0.32	0.00
18	Wairoa D/S Left/Right Confluence	156.81	118.36	21.03	9.77	6.65	0.00	1.00	0.00
11	Wai-iti U/S 88 Valley at Baigent Rd	164.10	32.35	93.15	30.68	6.48	0.62	0.40	0.43
10	88 Valley U/S Wai-iti	33.61	7.44	3.36	22.04	0.30	0.00	0.03	0.45
14	Wai-iti U/S Pidgeon Valley	203.20	39.95	98.18	55.74	6.92	0.73	0.56	1.10
13	Pidgeon Valley U/S Wai-iti	36.72	0.84	31.38	4.06	0.15	0.00	0.00	0.28
15	Wai-iti D/S Pidgeon at Barton Rd	246.63	41.12	131.67	62.83	7.18	0.84	0.74	2.25
19	Wairoa U/S Wai-iti at Clover Rd West	459.62	257.17	118.82	45.46	32.04	1.41	4.45	0.27
20	Wai-iti U/S Waimea at confluence	292.81	42.04	140.58	94.46	7.37	4.55	1.06	2.74
21	Waimea mouth D/S Applby Bridge	769.94	299.64	259.64	147.70	39.49	12.74	6.76	3.97
22	The Reservoir Creek	3.52	0.23	0.74	0.41	0.37	-	0.01	1.77

Table 3-5: Proportional contributions of source soils to the Waimea Estuary estimated from the Land Cover Database (LCDB) and the compound-specific stable isotope (CSSI) technique modelling. (- = not modelled, see text).

Sediment Source estimated from	Native forest	Pine forest	Pasture	Crop	Gorse & Broom	Urban	Bank erosion
LCDB data	38.92	33.72	19.18	1.65	5.13	0.52	0.88
CSSI modelling	0.21	17.65	0.36	-	13.58	-	68.21

3.2.2 Moutere River catchment

In a similar process for the Moutere River catchment, the isotopic mixing model results as 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 Moutere River mouth (Site 8) (Table 3-7), as calculated for Table 3-2.

The land use soil sources tested using the CSSI technique for contribution of sediment to the Waimea River down its length were native forest, pine forest, pasture, gorse and broom, and bank erosion (Table 3-7). The LCDB classes included crops and urban (Table 3-8) but neither of these sources were included in the reference library. Based on the LCDB proportions, crops occupied 12.65% of the catchment with most of that occurring on the flat land close to the Moutere River and Estuary. Because the cropland has low slope it is likely to have a low sediment runoff unless there is rainfall soon after cultivation and planting. Urban occupied 0.4% of the catchment. The omission of the potential crop sources from the modelling was an oversight during sampling and introduces a potentially significant error of up to 13% of the total catchment in the overall model output. However, the error is likely to be much less than 13% because most of the cropland is behind flood protection stop banks designed to reduce soil erosion.

The sediment proportions by land use area estimated from the LCDB and the sediment proportions by land use estimated by the CSSI technique are very different (Table 3-6). The CSSI results suggest that most of the sediment entering the Moutere estuary is associated with plantation forestry whereas the LCDB proportions suggest that, if the erosion was at the same rate across the whole catchment, there should be a higher proportion of sediment from pasture and crops. The CSSI results indicate pine forest harvesting and clearance of native forest has been occurring recently in the catchment. Evidence of this is apparent in the Google Earth image of the headwater catchment of the Moutere River (Figure 3-2).

Table 3-6: Proportional contributions of source soils to the Moutere Estuary estimated from the Land Cover Database (LCDB) and the compound-specific stable isotope (CSSI) technique modelling. (- = not modelled, see text).

Sediment Source estimated from	Native Forest	Pine Forest	Pasture	Crop	Gorse & Broom	Urban	Bank erosion
LCDB data	2.93	25.97	54.94	12.65	2.67	0.40	0.44
CSSI modelling	10.82	87.28	0.40	0.00	1.50	-	0.00

Table 3-7: Soil source contributions to the fine deposited sediment of the Moutere River system at each of the confluence sampling points. The column "% of total sediment" shows the relative proportion of catchment upstream at each location normalised to 100% at the mouth of the Moutere River (Site 8). The land use columns show the estimated source contributions by land use in the % of total at each site. The column 'n' is the number of feasible solutions found by the IsoSource model (See Section 2.5).

	Moutere River System		Land use proportion at site (%)						
Site No	Sitename at confluence	% of Total Catchment	Native Forest	Pine Forest	Pasture	Crop	Gorse & Broom	Bank erosion	n
1	Moutere at Kelling Rd Bridge	19.5	8.30	11.70	9.03	0.00	0.92	70.04	62
2	Gardner Valley Stream at Davey Rd Bridge	10.3	1.21	4.58	1.43	0.00	0.00	92.78	20
3	Moutere u/s Gardner Valley at Wilson Rd	58.7	0.00	82.29	10.55	0.00	0.00	7.16	10
4	Gardner Valley u/s Moutere at Wilson Rd	15.1	0.00	32.06	0.18	0.00	0.00	67.76	1
5	Moutere d/s Gardner Valley at Drummond Rd	80.6	2.94	6.64	0.00	0.00	9.17	81.25	5
6	Moutere u/s Central Road Tributary	84.3	0.33	9.89	5.36	0.00	0.76	83.66	57
7	Central Road Tributary	13.5	6.40	50.21	0.96	0.00	42.43	0.00	1
8	Moutere d/s of Central Road Trib confluence	100.0	10.82	87.28	0.40	0.00	1.50	0.00	63

Table 3-8: Land use areas in the Moutere River system upstream of each confluence sampling point. The column "Catchment area" shows the total area of catchment upstream at each confluence. The land use area columns show the area of each land use in the catchment upstream of each confluence. (Data from Land Cover Database updated as at 2012).

	Moutere River System		Land use area at site (km^2)						
Site No	Sitename at confluence	Catchment Area (km^2)	Native Forest	Pine Forest	Pasture	Crop	Gorse & Broom	Bank erosion	Urban
1	Moutere at Kelling Rd Bridge	29.08	0.95	15.32	10.37	1.88	0.26	0.12	0.18
2	Gardner Valley Stream at Davey Rd Bridge	15.3	0.04	2.60	9.56	2.76	0.15	0.11	0.08
3	Moutere u/s Gardner Valley at Wilson Rd	87.4	2.84	28.38	46.98	5.95	2.48	0.23	0.43
4	Gardner Valley u/s Moutere at Wilson Rd	22.3	0.11	4.35	13.11	4.29	0.28	0.17	0.09
5	Moutere d/s Gardner Valley at Drummond Rd	110.0	2.97	35.02	65.93	12.05	3.05	0.41	0.52
6	Moutere u/s Central Road Tributary	126.0	2.99	35.33	70.31	12.71	3.17	0.43	0.53
7	Central Road Tributary	22.2	1.29	3.15	10.04	4.84	0.73	0.06	0.03
8	Moutere d/s of Central Road Trib confluence	148.8	4.35	38.64	81.74	18.82	3.97	0.65	0.60

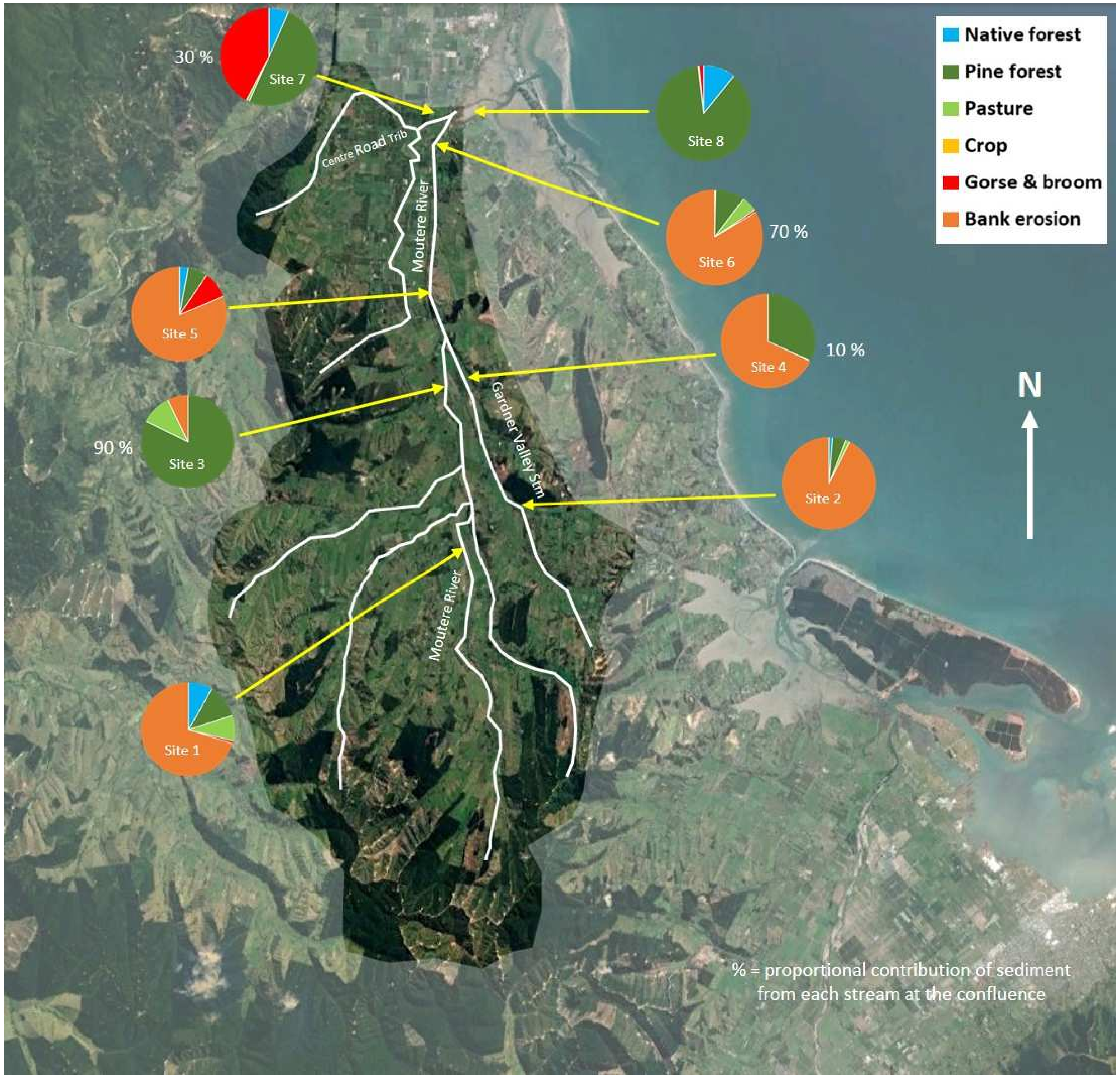


Figure 3-2: Land use soil contributions to the Moutere River system at each river confluence. Data is presented in pie-chart format where the pie chart includes all land use sources modelled. River channels are marked in white and the yellow arrow tips indicate the relative position of the sample. Values are not absolute and are best estimates from the data modelled. Comparison of CSSI results with LCDB pie charts are presented in Appendix B.

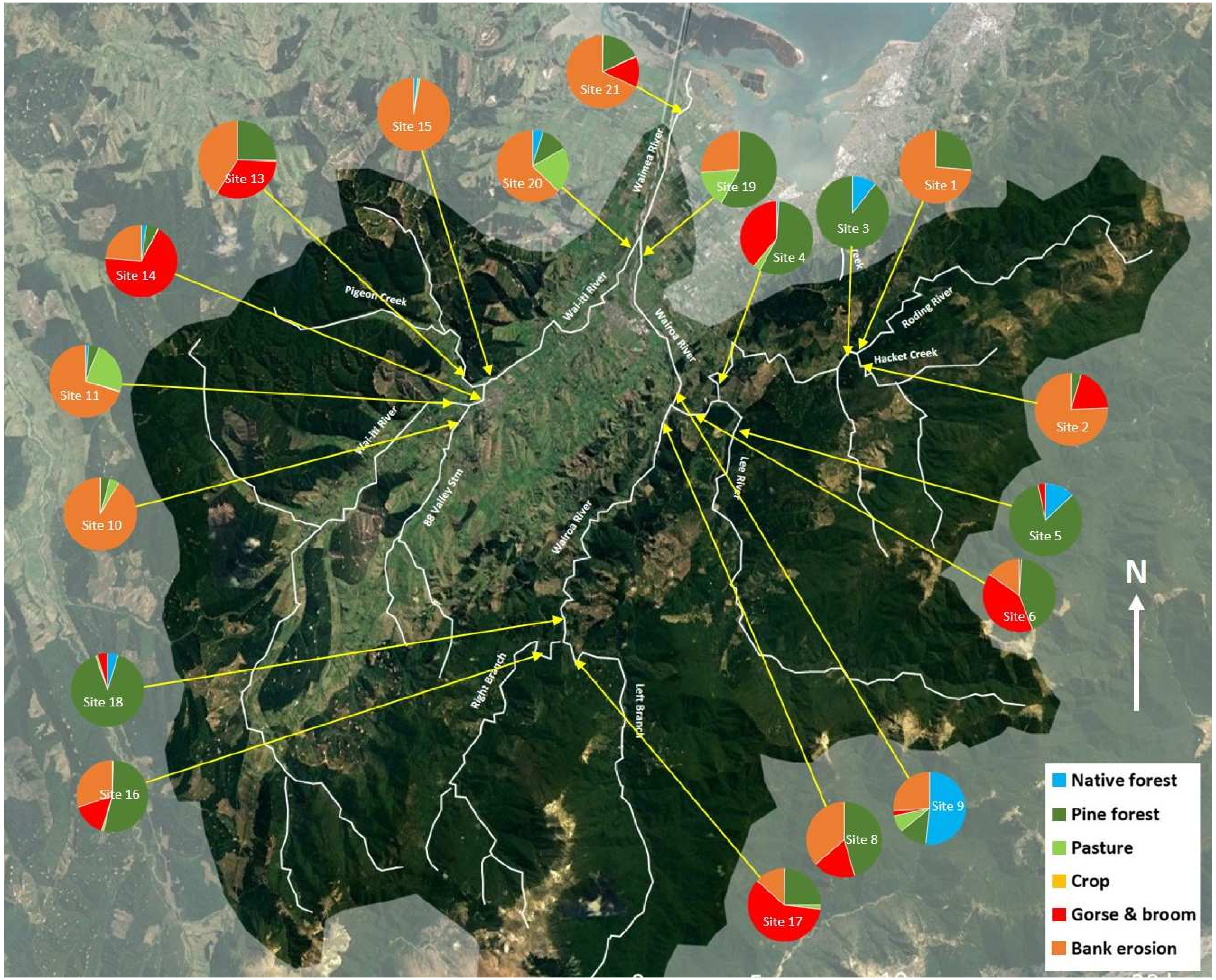


Figure 3-3: Land use soil contributions to the Waimea River system at each river confluence. Data is presented in pie-chart format where the pie chart includes all land use sources modelled. River channels are marked in white and the yellow arrow tips indicate the relative position of the sample. Values are not absolute and are best estimates from the data modelled. Comparison of CSSI results with LCDB pie charts are presented in Appendix B.

4 Discussion

4.1 Sediment proportions by sub-catchments

The CSSI estimates of sediment contributions from the tributaries at each confluence in the Waimea and Moutere River catchments were generally consistent with the contributions estimated from the NZ River Map sediment data, with two major exceptions outlined in Section 3.1. This was expected and the differences observed are likely to be due to changes in the amount of bare soil in the sub-catchments, which influences the CSSI estimates. Both estimates rely on modelling. The CSSI technique uses only the stable isotopic signature of the fatty acids extracted from the sediment to estimate sediment proportions, without reference to rainfall, catchment area, land slope or vegetation cover. In contrast, NZ River Map displays the predictions from the national sediment model, which estimates mean annual suspended loads from each tributary down the river system.

The NZ River Map data are from a predictive model that gives a best estimate based on algorithms developed from national estimates of sediment runoff. The caveat for using the NZ River Maps data is that the sediment load estimates predicted should be checked against local measurements.

For example, in a study by Hicks (2009), 2.2 years of monitoring data from a site on the upper Lee River near Waterfall Creek[9] were used to establish the mean annual sediment load from the 65 km^2 forested catchment. An event yield rating estimate for that site agreed with direct measurement to within 2% giving a mean annual sediment load of 2900 t/y and a specific sediment yield of 45 $t/km^2/y$. The monitoring catchment on the upper Lee River was of similar size to the Roding above Site 1 (57 km^2) for which the NZ River Map database gives a mean annual sediment load of 2908 t/y and a specific sediment yield of 51 $t/km^2/y$. The consistency in sediment loads and specific sediment yields between these two forested catchments at similar elevations on the Richmond Range gives confidence in the data produced from NZ River Maps.

Not all studies produce consistent sediment outputs over time and these can change with the frequency and magnitudes of storm events. For example, a study of the Motueka River in the same region (Basher et al. 2011) found very large inter-annual variations in sediment yield depending on storm events, with annual sediment yields at the coast ranging from 49,000 t to 1,700,00 t.

Sediment yield in the upper Lee River also changes dramatically between the upper Lee monitoring site and Site 5. The NZ River Map mean annual sediment load estimate increases from the measured 2900 t/y to an estimated 24469 t/y from a total catchment area of 131 km^2. The resultant specific sediment yield of 187 $t/km^2/y$ is a 4-fold increase over the sediment yield in the upper river catchment. This suggests a change in geological formation from ultramafic rock above the upper Lee monitoring station to more erodible soils below that site.

From the data in Table 3-1 and Table 3-2, the mean average specific sediment yield in the Waimea River is 156 $t/km^2/y$, which is 56 $t/km^2/y$ greater than the mean average specific sediment yield in the Moutere River. This is likely to be a function of larger areas of steeper land and more erodible soils in headwater catchments of the Waimea River.

[9] The monitoring data provides information useful for the design of a future Waimea Community Dam at this location.

Land use will affect sediment runoff but this is not captured in the national sediment model, which does not use land use to estimate sediment loads. For example, it is only coincidental that the increase in sediment load between the upper Lee monitoring site and Site 5 from this report on the Lee River coincides with an area of extensive forest harvesting on steep sloping land beside the middle reaches of the Lee (Figure 4-1). Because there is a sediment yield increase, this suggests that the soils may be more erodible in that area.

Figure 4-1: Lee River sampling Site 4 at Mead Road-Lucy Road junction at the bridge. A) View of the extent forest harvest upstream of this site; B) level of flood debris beneath the bridge; C) view upstream from the bridge showing the cobbled and rocky nature of the Lee River bed. Sediment samples were collected from the deposition zone on the true right bank. [Photos by M. Gibbs].

Figure 4-2: Wind-rowing pine slash down the slope can exacerbate soil erosion. This practice enhances the runoff velocity and thus erosive energy down the slope during rain events. Wind-rowing across the slope causes the water to slow as it passes through each wind-row reducing velocity and erosive energy. [Photo by M. Gibbs]The effect of land use/management is captured by the CSSI technique, and the results

indicate that this level of change in land use cover can dramatically affect the sediment runoff into the rivers. Some enhancement of sediment runoff may occur where pine slash has been wind-rowed down the slope instead of across (Figure 4-2).

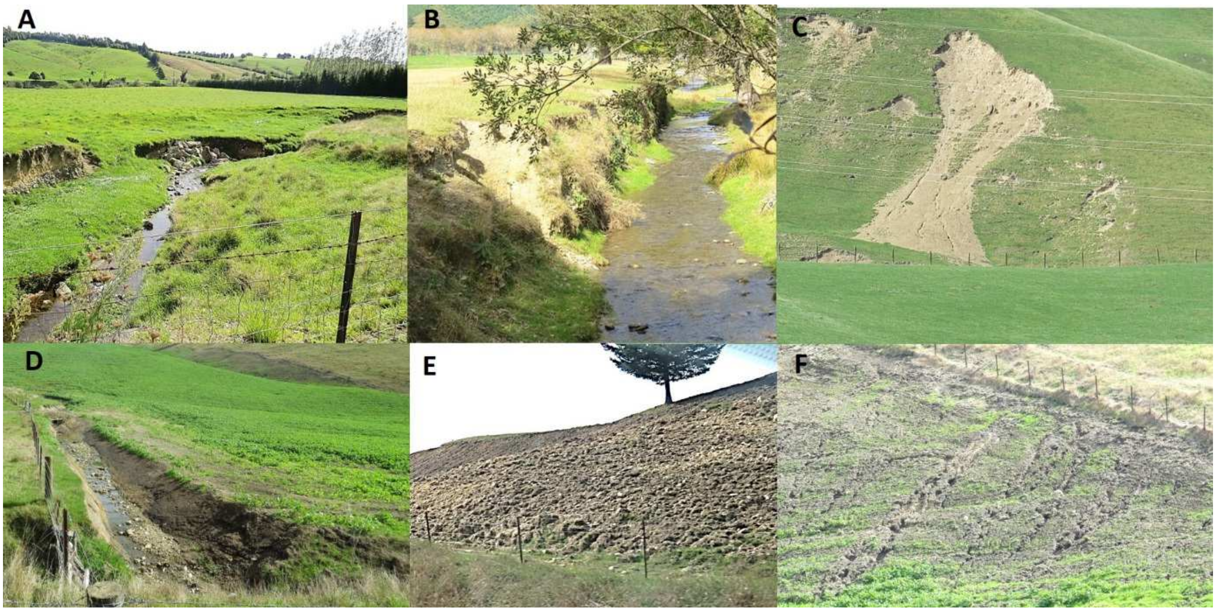


Figure 4-3: Common sources of sediment associated with soil erosion in the Waimea River catchment, not related to forestry. A) Stream bank collapse through undercutting; B) Stream bank erosion due to stock access; C) Earth flows and landslides on steep pasture; D) drain clearance leaving extensive bare soil exposed; E) Cultivation of steep hill sides leaving bare vulnerable exposed; F) Rilling of crop land on sloping land. [Photos by M. Gibbs]This type of erosion is not confined to harvested pine forests and will occur wherever there is cultivation or disturbance of sloping land that allows un-controlled runoff to free flow across bare land. Examples of vulnerable landscapes in the Waimea catchment that could affect sediment runoff into the streams and rivers include tillage on steep slopes causing rilling, earth flows on steep farm land, clearance of drains and bank erosion due to stock access to streams (Figure 4-3).

4.2 CSSI land use proportions compared with LCDB area information

The changes in soil source composition down the Waimea and Moutere Rivers reflect natural erosion processes, land use and the land use practices in the catchment upstream of the locations sampled and in the tributaries. The differences between the CSSI land use predictions and the areas occupied by land uses (LCDB information) are illustrated in a series of pie charts for each sampling location (Appendix B), 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.

While the CSSI land use predictions represent the contemporary land use source proportions at the time of sampling, the LCDB information represents GIS information which is periodically updated. The LCDB information for the Waimea and Moutere watersheds were updated in 2012. Consequently, the LCDB cannot account for recent changes in land cover - since 2012, which, along with effects of land cultivation, forest harvesting, and bank erosion, will be captured in the contemporary samples collected for CSSI based study.

CSSI results represent the proportions of 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 and different land uses are typically associated with areas with different inherent erodibility: pine forests are typically on steeper, more erodible parts of catchments than pasture and cropping land uses. 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 3-4; Table 3-8).

This is demonstrated in the Pakuratahi Land Use Study (Eyles and Fahey 2006), where the sheep and beef farm catchment produced four times more suspended sediment than the catchment in mature pine forest averaged over a 12-year period. However, the forested catchment, when harvested, produced a sediment yield that was 2.5 times higher than the farmed catchment and 6 times higher than the preharvest forest yield. Sediment yields returned to mature forest levels within 2-3-years of replanting. A study by Gibbs (2006; 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.

The Pakuratahi study findings indicate that, over the long term (25 to 27 year) forest rotation, the average sediment yield from production forest will be less than for pasture. However, the pulse of sediment input on estuaries during and shortly after each forest harvest phase can be damaging through the deposition of thin clay layers across the estuary that can exceed the threshold for biota tolerance (Cummings et al. 2001; Norkko et al. 2002; Thrush et al. 2003a; - 2003b; - 2004). Thin layers of fine clay sediment ranging from 3-7 mm thick adversely impact benthic communities with the negative effects increasing with increasing depth of the clay layer (Berkenbusch et al. 2002). Berkenbusch et al.'s study also found that chronic effects were exacerbated by repeat exposure to clay deposition. The frequency of disturbance and thus the time available for recovery between disturbance events was found to be critical in assessing whether the deposition of thin layers of terrigenous clay posed a threat of broad-scale degradation in the estuary.

Moreover, at the scale of a large catchment with significant proportions of forest, harvesting impacts are not a 'one off' process because parts of the forest may be felled in any year. Consequently, once forest harvesting begins, there is likely to be a succession of freshly harvested blocks each year producing high sediment yields. Each harvested block is likely to produce elevated sediment yields for up to 5 years (depending on stem density) until canopy closure. However, on a catchment scale, low sediment yields from "stable", mature or closed canopy replanted parts of the forest, will smooth out the peaks from recently harvested areas to some extent. Notwithstanding this, estuarine communities may experience chronic exposure to elevated concentrations of fine sediment from ongoing harvest over several years.

Consequently, the greatest effect on sediment load in the Waimea and Moutere Rivers is likely to be from land management practices that change vegetation cover. Of primary importance is the substantial increase in sediment erosion during pine forest harvesting and for the 3 to 5-year period after replanting and until canopy closure protects the soil once more. During the period before canopy closure, it is common for weed species such as gorse and broom to colonise the harvested areas, imparting that land use community CSSI signature to the soil. This is a useful identifier for the stage in the rotation of the plantation forest. The land use proportions determined by the CSSI technique at each site are presented as pie chart overlays on the Google Earth images (Figure 3-2; Figure 3-3) show how the soil sources change down each river system.

In large river systems, such as the Waimea River, some of the sediment eroded from the upper catchments during each high flow event accumulates along the banks further downstream as legacy sediment when flood flows overtop the banks and spill onto the flood plains. This streambank sediment becomes overgrown with grasses and other plants that can impart a new plant community CSSI signature. Consequently, further downstream this bank material can be discriminated as a source in its own right, i.e., as bank erosion. This effect is seen at the Waimea River mouth (Table 3-5) where about 68% of the sediment is identified as bank erosion.

In contrast, in smaller river systems such as the Moutere River, where flood protection schemes have been implemented and the rivers are shorter, it is more likely for an event to pass through the whole river system during that event. Consequently, there is less chance for legacy sediment accumulating along the river bank, although there will be some. This means that the fine sediment component of the eroded soil is likely to disperse directly into the estuary where it will floc and settle on the sea bed, retaining its source signature rather than becoming an amorphous 'bank' sediment. This effect is seen at the Moutere River Mouth (Table 3-6) were 87% of the deposited sediment is of pine forest origin and bank erosion is less than 1%.

4.3 CSSI land use proportion estimates

The CSSI estimates of land use source soil proportions at each sampling site were generally consistent with local observations of potential land use soil sources. However, there are differences between the expected land use proportions based on the LCDB information and what has been estimated from the CSSI technique (as demonstrated in the following sections).

4.3.1 Waimea River Catchment

Land use proportions in the various Waimea River sub-catchments have changed in recent years with large areas of production forest being harvested since the LCDB information was updated in 2012. While the harvested land is still nominally plantation forestry, the plant communities are better classified as "Gorse & Broom" (Table 3-3). In the Maitai River catchment, this class was found to reflect harvested pine forest land that had not been replanted, or that had been replanted but had yet to achieve pine canopy closure (Gibbs and Woodward 2017).

For example, at the Lee downstream of Roding site, (Site 6, Table 3-3), there is a prevalent local source of gorse and broom on the north bank right to the top of the ridgeline. This block was logged in about 2010-12 and became dominated by gorse and broom prior to replanting the pines, which were only starting to become visible at the time of our sampling. Furthermore, there were a lot of forestry blocks in the Left Branch of the Wairoa River that were harvested, on average, about 10 years ago, which probably contribute to the high gorse a broom component (Trevor James, TDC, pers. comm.). The gorse and broom land use class will be producing a higher sediment load than mature pine forest but is expected to have a diminishing sediment yield with canopy closure.

CSSI evidence for high bank erosion in the Roding River catchment upstream of Hacket (Site 1; Table 3-3) may reflect erosion on the bare rock slopes in ultramafic geology. This geology is rich in iron, chromium and nickel and this makes it inhospitable for forest vegetation. Natural erosion is evident around Mt Meares, with a relatively large slip on the north slopes, and Jackson Creek (observations from the 2015 aerial photos, Trevor James, TDC, pers. comm.). Another explanation for high bank erosion at Site 1 is that Nelson City Council could release sediment from the Roding Dam when sediment is removed (Trevor James, TDC, pers. comm.), although this will be an intermittent event rather than semi-continuous as occurs with rainfall driven processes.

Elevated native forest sediment in the Lee upstream of Roding site (Site5; Table 3-3) may be associated with the corridor of mature riparian native forest along the river in the upstream catchment (Trevor James, TDC, pers. comm.). Conversely, the high native forest influence at Max's Bush (Site 9; Table 3-3) appears to be an anomaly considering that both the tributaries feeding this site having low native forest proportions. Although there is some local native bush reserve on the northern banks of the river (Figure 4-4), the most likely explanation is that the sampling site was on the side of the river at the swimming hole upstream of the Waimea East Irrigation weir (Figure 4-4). The weir would act as a sediment trap for some of the fine organic sediment from native forest that would otherwise not settle in the river and be carried out into the estuary. Heavier sediment particles would tend to settle closer to the head of this pool, potentially distorting the relative proportional contributions of the different source soils at this site. Consequently, the data from this site should be used with caution.

Figure 4-4: Waimea East Irrigation weir on the Wairoa River downstream of the Lee River (Site 9). The pool behind the weir acts as a sediment trap enabling fine sediment from further upstream to settle along the banks. There is also an area of native forest regrowth on the steep, northern banks, which may be a local source of the high proportion of native forest sediment class found at this site.

The trapping effect of the weir can be seen in the sediment proportions at the Clover Rd site (Site 19, Table 3-3) where there is no trapping. These two sites would be expected to have very similar sediment source proportions as they are not far apart and no substantial tributaries enter the Wairoa River between them. The high pine source proportion at the Clover Rd site reflects the settling ability of the pine soil compared with native forest soil. It also indicates that there were probably low native forest soil contributions and these would only be seen where a sediment trapping effect was present and they could accumulate over time.

In explanation, it is the nature of surficial native forest soil to be very light, organic material (~20% carbon), which is buoyant and tends to float, compared with mature pine forest soils (~5% carbon), which are denser and tend to sink quickly. The other factor to consider is that the dense canopy of the undisturbed native forest will protect the soil from direct impact of rain drops and there will be very low erosion from native forest or mature pine forest. Disturbance of any forest will allow erosion to increase with the concomitant exacerbation of sediment run off.

These effects can also be seen in the upstream catchments of the Wairoa River where the catchment upstream of the Wairoa Left Branch site (17) has over three times as much native forest as pine and the catchment upstream of the Wairoa Right Branch site (Site 16) has 50% more native forest than plantation forest. At both sites the native forest soil contribution is very low but the pine soil proportions in the catchments are consistent with the difference in the pine sediment contributions between the left and right branches (Table 3-3) i.e. 24.8% pine sediment from 8.8 km^2 of pine forest in the left branch and 53.6% pine sediment from 11.3 km^2 of pine forest in the right branch.

Reservoir Creek (Site 22; Table 3-5) has a high proportional contribution of bank erosion sediment (79%). This is consistent with long term earthworks around this creek and soft banks that are very erodible. Earthworks activity includes subdivisions (about 30ha over the last 15 years), reconstruction of the old Reservoir in 2013 and forestry (road and landing construction), from Autumn 2008, that caused a lot of erosion and sub-soil discharge to the creek (Trevor James, TDC, pers. comm.). In 2005 about 10-15m^3 of fine sediment was discharged to the creek upstream of the sampling site during the construction of the underpass under Salisbury Road (Trevor James, TDC, pers. comm.).

4.3.2 Moutere River catchment

The disproportionately high native forest source soil contribution measured in the Moutere River at Kelling Road bridge (Site 1; Table 3-7) may be due to a wide mature beach forest riparian corridor upstream of this site. The high proportions of bank erosion sediment at this site and in the Gardner River upstream of Davey Road (Site 2; Table 3-7), as well as at Sites 4 and 5 further downstream, can be attributable to substantial land use changes in these catchments over the past decade. For example, 90 ha of plantation forest was removed from the upper Gardner Valley stream catchment in 2008. This involved major earthworks (removing root wads deep in the soil profile) and recontouring the landscape on a similar scale to the development shown in Figure 1-1. Rilling erosion over the following few years was extensive (Trevor James, TDC, pers. comm.).

The high pine forest sediment contribution to the Moutere River measured at the Mills Road (Site 3; Table 3-6) is attributable to the 150 ha of recent plantation harvesting upstream of this site in Blackbird Valley and Upper Wills Road catchments. There was also about 50 ha of recent pine harvesting in the Flaxmore Valley that is the likely source of pine sediment at the Gardner Valley site, Site 4 (Table 3-6) (Trevor James, TDC, pers. comm.).

The sediment proportions at the Centre Road Tributary site (Site 7; Table 3-6) are consistent with there being over 100ha recent pine harvesting and about 50ha of gorse and broom in this catchment (Trevor James, TDC. Pers. comm.).

Localised sources of sediment could be market gardens, which were in various stages of cultivation from bare land to mature vegetables, an obvious source of erodible soil. Some 'bank erosion' may be a function of stock having direct access to the stream at a location (Figure 4-5). There were also several areas of pine forest harvesting near the Moutere and Gardner Valley Rivers (e.g., Figure 4-6).

Figure 4-5: Bank erosion and stream bed disturbance occurs where stock have direct access to the stream. Gardner Valley Stream (Site 2) at Davey Road. [Photo M. Gibbs, 14 Dec. 2016].

Figure 4-6: Pine forest harvesting in the Gardner Valley catchment. [Photo by M. Gibbs, 14 Dec. 2016].

4.4 Catchment to estuary connectivity

Sediment from harvested pine forest, bank erosion, pasture and cropping is entering both the Waimea Estuary and the Moutere Inlet during flood events (Figure 4-7). How long it takes for fine sediment and debris from any source to reach the estuaries and settle out on the seabed will depend on the size of the flood event and the connectivity of the eroding land to the streams and rivers. Observations from the wharf at Mapua on the Waimea Estuary during a heavy rainfall event on 13 April 2017 showed highly turbid water with large drifts of pine slash flowing out to sea (Figure 4-7) on the same day as an event. In smaller events, there may be insufficient water to mobilise pine slash and it may be two or three days for fine sediment to reach the estuary, with some of that sediment recharging the bank storage along the river banks. Bank storage can also be recharged during very large events, which overtop the banks depositing sediment on the floodplain.

Figure 4-7: Observations of the flood event 15 April 2017 from Mapua Wharf. A) General view back up the estuary with an ebb tide showing highly turbid water and drifting pine woody debris; B) Closer view of the woody debris passing the wharf. [Photos by M. Gibbs, 13 April 2017].

5 Conclusions

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. For example, estimating the sediment yield for a specific land use based on the sediment yield for the whole catchment (national sediment model data) and the proportional area of the specific land use defined by plant community cover (LCDB data), assumes all erosion rates are the same across the catchment. Pasture and mature forest (native or pine) have very different erodibility factors, and these can change dramatically during harvest or cultivation. More GIS information is required to obtain a reliable estimate of land use sediment yield.

2. Native forest and mature pine forest plantations produce very little sediment. Preservation of native forest is an important way to control sediment yield.

3. Harvesting forests produces substantial pulses of sediment. Evidence from NZ studies indicate that elevated sediment loads after harvest persist for two to three years after replanting until canopy closure protects the soil again. Pine forest is estimated to occupy 33 % and 26 % of the Waimea and Moutere watersheds, respectively. Although only a small proportion of that forest is harvested at any time the sediment yield during harvesting may be 6 fold higher than from mature forest and remain elevated for 2-3 years after replanting. This suggests the need for an appropriate management strategy to reduce sediment yield during harvesting.

4. Areas of harvested production forest can become colonised by gorse and broom, as well as other weed species before replanted pines grow large enough to shade these weedy species out. These plants do not provide the canopy cover of mature pine or native forest, and these catchments may continue to bleed considerable amounts of sediment into the Waimea and Moutere Rivers during rainfall events. Mitigation of fine sediment requires a management strategy that highlights the requirement for rapid replanting of harvested pine forest land.

5. Bank erosion is a major source of sediment. This material progressively moves downstream depositing and being reworked by the river along the river banks as a legacy source. Because this deposited sediment is rapidly colonised by different plant communities, the isotopic signature of the original source merges with isotopic signatures of the plants colonising it to produce a new isotopic signature for this amorphous sediment source in the lower reaches of the rivers. CSSI analysis may be able to discriminate between land use sources in this material to allow management strategies for sediment reduction to target the sources of this sediment.

6. The Waimea Estuary is receiving a high proportion of legacy sediment as bank erosion but is also receiving sediment from harvested pine forest at various locations down the river. Gorse and broom signatures indicate sediment from older harvested pine forest or where replanted pines are yet to reach canopy closure, are also present in the river mouth sediments.

7. Moutere Estuary is receiving a high proportion of sediment directly attributable to pine forest harvesting and little legacy streambank sediment. This sediment may be travelling through the Moutere River system rapidly and being flocked out at the river mouth when it contacts the more saline sea water. Some of this sediment may be derived from recent harvesting in the Central Road tributary.

6 Recommendations

1. Quantification of sediment yield by land use. The CSSI technique only provides a qualitative snapshot in time from the deposited sediment. Quantification of sediment yields requires an estimate of sediment mass transport from at least one site down the river system to enable back-calculation of the yields by land use at all other sites on that river.

2. Determine the amount of fine sediment that doesn't settle in the river, especially native forest sediment. This would use an array of Phillips Time Integrated Suspended Sediment samplers (Phillips et al. 2000) to collect suspended sediment samples at the confluence sites for CSSI analysis.

3. Improve yield assessments in smaller sub-catchments dominated by recently-harvested land and others dominated by mature plantation forest. This would include collection of on-the-ground information on land use practices in the sub-catchment.

4. Assess the sediment runoff from cropping and the magnitude of crop sediment contribution to sediment production.

5. Assess urban sediment runoff via stormwater.

6. Use aerial photos or forestry company records to determine the proportion of catchment upstream of each sampling site that was harvested in the last 3 years vs mature forest.

7. Investigate specific sites where high erosion potential has been identified in this study to get some basic yield information.

8. Collect and date an exploratory core in the Waimea Estuary to determine whether it is feasible to determine changes in land use over time, as has been done in Pelorus Sound (Handley et al. 2017).

7 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 also thank Trevor James (TDC) for guiding us around the catchment and finding the sampling sites.

8 References

Basher, L.R., Hicks, D.M., Clapp, C., Hewitt, T. (2011) Sediment yield response to large storm events and forest harvesting, Motueka River, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 45:3, 333-356. DOI: 10.1080/00288330.2011.570350

Berkenbusch, K., Thrush, S., Hewitt, J., Ahrens, M., Gibbs, M., Cummings, V. (2001) Impact of thin deposits of terrigenous clay on benthic communities. *NIWA Client Report* ARC01269. NIWA Hamilton: 56.

Cummings, V.J., Funnell, G.F., Schultz, D., Thrush, S.F., Berkenbusch, K., Nicholls, P. (2001) Mahurangi estuary ecological monitoring programme – report on data collected from July 1994 to January 2001. *NIWA client Report* ARC01207. NIWA Hamilton.

Eyles, G., Fahey, B. (eds) (2006) Pakuratahi land use study. *Hawkes Bay Regional Council report HBRC plan number,* 3861. June: 128. www.hbrc.govt.nz/Land/PakuratahiLandUseStudy/ tabid/299/Default.aspx

Fahey B.D., Marden M., Phillips C.J. (2003) Sediment yields from plantation forestry and pastoral farming, coastal Hawke's Bay, North Island, New Zealand. *Journal of Hydrology (NZ)*, 42: 27-38.

Gibbs, M. (2006a) Source Mapping in Mahurangi Harbour. *Auckland Regional Council Technical Publication*, TP321.

Gibbs, M. (2006b) Whangapoua Harbour sediment sources. *Environment Waikato Technical Report*, No. 2006/42: 49.

Gibbs, M. (2008) Identifying source soils in contemporary estuarine sediments: a new compound specific isotope method. *Estuaries and Coasts,* 31: 344–359.

Gibbs, M. (2009) Whangamarino Wetland pilot study: sediment sources. *NIWA Report* No. HAM2009-033, to the Department of Conservation. Project code DOC08205: 33.

Gibbs M. (2016) Sediment source analysis using the CSSI technique - Whangamarino Wetland. *NIWA client report* HAM2016-078, prepared for Department of Conservation. Project code DOC16203: 21.

Gibbs, M., Bremner, D. (2007) Wharekawa Estuary sediment sources. *NIWA Client Report* HAM2007-111 to Environment Waikato. Project code EVW07217.

Gibbs, M., Olsen, G. (2010) Determining sediment sources and dispersion in the Bay of Islands. Chapter 5. In: *Bay of Islands OS20/20 survey report for LINZ*. NIWA project LIN09305 / CSI.

Gibbs, M., Olsen, G., Swales, A., He, S. (2012) Kaipara Harbour Sediment Tracing: Sediment dispersion across the harbour. *NIWA client report number* HAM2011-091, prepared for the Integrated Kaipara Harbour Management Group: 58. http://www.kaiparaharbour.net.nz/Content/Publications/Gibbsetal2012KaiparaHarbourSedimentTracingFinal.pdf

Gibbs M., Olsen G., Stewart M. (2015) New River Estuary sediment sources tracking pilot study. *NIWA client report* HAM2014-002, prepared for Southland Regional Council. Project code ENS13203: 39.

Gibbs M., Olsen G., Stewart M. (2014). Jacobs River Estuary sediment sources assessment. *NIWA client report* HAM2014-003, prepared for DairyNZ. Project code DNZ1320: 32.

Gibbs, M., Woodward, B. (2017) CSSI-based sediment source tracking study for the Maitai River, Nelson. *NIWA Client Report* 2017256HN, to Nelson City Council. Project code NCC17201: 46.

Handley, S., Gibbs, M., Swales, A., Olsen, G., Ovenden, R., Bradley, A. (2017) A 1,000 year seabed history Pelorus Sound/Te Hoiere, Marlborough. *NIWA Client report* prepared for Marlborough District Council, Ministry of Primary Industries and the Marine Farming Association. No. 2016119NE, MDC15401. No.: 117.

Hicks, D.M. (2009) Analysis of suspended sediment data from Upper Lee River, Nelson. *NIWA client report* CHC2009-179 to Tasman District Council: 24.

Hicks, D.M., Shankar, U., McKerchar, A.I., Basher, L., Lynn, I., Page, M., Jessen, M. (2011) Suspended Sediment Yields from New Zealand Rivers. *Journal of Hydrology (New Zealand)*, 50: 81-142.

Hoare, R.A. (1982) Nitrogen and phosphorus in the Ngongotaha Stream. *New Zealand Journal of Marine and Freshwater Research*, 16: 339-349.

Hughes, A., Hoyle, J. (2014) The importance of bank erosion as a source of suspended sediment within the Kopurererua catchment. *NIWA client report* HAM2014-064 to Bay of Plenty Regional Council: 74.

Hughes, A.O., Quinn, J.M., McKergow, L.A. (2012) Land use influences on suspended sediment yields and event sediment dynamics within two headwater catchments, Waikato, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 46:3, 315-333. DOI: 10.1080/00288330.2012.661745

Mabit, L., Gibbs, M., Mbaye, M., Meusburger, K., Toloza, A., Resch, C., Klik, A., Swales, A., Alewell, C. (2018) Novel application of a Compound Specific Stable Isotope (CSSI) technique to investigate on-site sediment origins across arable fields. *Geoderma,* 316: 19–26.

Norkko, A., Thrush, S.F., Hewitt, J.E., Cummings, V.J. et al. (2002) Smothering of estuarine sandflats by terrigenous clay: the role of wind-wave disturbance and bioturbation in site-dependent macrofaunal recovery. *Marine Ecology–Progress Series,* 234: 23–41.

Phillips, C.J., Marden, J.W., Rowan, D. (2005) Sediment yields following plantation harvesting, Coromandel Peninsula, North Island, New Zealand. *Journal of Hydrology (NZ),* 44: 29-44.

Phillips, D.L., Gregg, J.W. (2003) Source partitioning using stable isotopes: Coping with too many sources. *Oecologia,* 136: 261–269. www.epa.gov/wed/pages/models/stableIsotopes/isotopes.htm

Phillips, J.M., Russell, M.A., Walling, D.E. (2000) Time-integrated sampling of fluvial suspended sediment: a simple methodology for small catchments. *Hydrological Processes,* 14: 2589–2602.

Quinn, J., Phillips, C. (2016) Production forestry. *In* Jellyman, P.G., Davie, T.J.A., Pearson, C.P., Harding, J.S. (Eds) *Advances in New Zealand Freshwater Science.* New Zealand Freshwater Sciences Society & New Zealand Hydrological Society.

Reeve, G., Gibbs, M., Swales, A. (2011) Recent Sedimentation in the Whangamarino Wetland. *NIWA client report* HAM2010-080, to Department of Conservation. Project code DOC10202: 40.

Stevens, L., Robertson, B. (2010) *Waimea Inlet: Vulnerability Assessment and Monitoring Recommendations.* Prepared for TDC: 58.

Stevens L., Robertson B. (2011) *Waimea Inlet Historical Sediment Coring 2011*. Prepared for TDC: 41.

Stevens, L., Robertson, B. (2014) *Waimea Inlet Broad-Scale Habitat Mapping*. Prepared for TDC: 46.

Stock, B.C., Semmens, B.X. (2015) *MixSIAR User Manual,* Version 3.0. https://github.com/brianstock/MixSIAR/

Swales, A., Gibbs, M., Pritchard, M., Budd, R., Olsen, G., Ovenden, R., Costley, K., Hermanspahn, N., Griffiths, R. (2013) Whangarei Harbour sedimentation: Sediment accumulation rates and present-day sediment sources. *NIWA Client report* HAM2013-143, prepared for Northland Regional Council. May: 83.

Thrush, S.F., Hewitt, J.E., Norkko, A., Nicholls, P.E., Funnell, G.A., Ellis, J.I. (2003a) Habitat change in estuaries: Predicting broadscale responses of intertidal macrofauna to sediment mud content. *Marine Ecology-Progress Series*, 263: 101–112.

Thrush, S.F., Hewitt, J.E., Norkko, A., Cummings, V.J., Funnell, G.A. (2003b) Macrobenthic recovery processes following catastrophic sedimentation on estuarine sandflats. *Ecological Applications,* 13: 1433–1455.

Thrush, S.F., Hewitt, J.E., Cummings, V., Ellis, J.I., Hatton, C., Lohrer, A., Norkko, A. (2004) Muddy waters: Elevating sediment input to coastal and estuarine habitats. *Frontiers in Ecology and the Environment,* 2: 299–306.

Appendix A NZ River Maps by NIWA

Basic information on the river and tributary systems encompassing the Waimea and Moutere Rivers was extracted from the NIWA River Maps database which incorporates GIS data from National Estimates and Council layers.

NZ River Maps © 2016 NIWA, Version 1.0.0

This web tool was developed by Dr Doug Booker and Dr Amy Whitehead, with funding from NIWA's Sustainable Water Allocation Programme (SWAP). It is publicly available at https://shiny.niwa.co.nz/nzrivermaps/

Categories used in this report include:

Catchment area (square kilometres)

It provides the catchment area upstream of each location (km^2). Higher numbers mean rainfall is being captured from a larger area. For more information read:

Snelder, T.H., Biggs, B.J.F. (2002) Multiscale River Environment Classification for Water Resources Management. *Journal of the American Water Resources Association,* 38: 1225-1239.

Landcover class (category)

Classification of landcover as derived using proportions of each land cover category in the upstream catchment. See Table 2 in Snelder & Biggs (2002) for more details about the categories.

B = Bare ground; EF = Exotic forest; IF = Indigenous forest; P = Pasture; S = Scrub; T = Tussock; U = Urban; W = Wetland. Watershed land cover controls surface interception of rainfall as well as potential evapotranspiration. When joined with climate, topography and geology, this constitutes the fourth River Environment Classification (REC) level.

Snelder, T.H., Biggs, B.J.F. (2002) Multiscale River Environment Classification for Water Resources Management. *Journal of the American Water Resources Association,* 38: 1225-1239.

Mean Flow (cumecs)

This category provides the mean flow over all time ($m^3 s^{-1}$) at the location based on national estimates and Council data. Lower values mean less flow.

Booker, D.J., Woods, R.A. (2014) Comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments. *Journal of Hydrology*, 508: 227-239.

Suspended sediment load (tonnes/year)

Estimates of suspended sediment load (tonnes/year) include the influence of lakes. Higher numbers are rivers transporting larger quantities of sediment suspended in the water column. Estimates represent the long-term average. Lake sediment trapping efficiency was estimated from the ratio of lake volume to mean annual water outflow using median curve of Brune (1953) as approximated by Gill (1979).

Brune, G.M. (1953) Trap efficiency of reservoirs. *Trans. Am. Geophysical Union*, 34: 407-418.

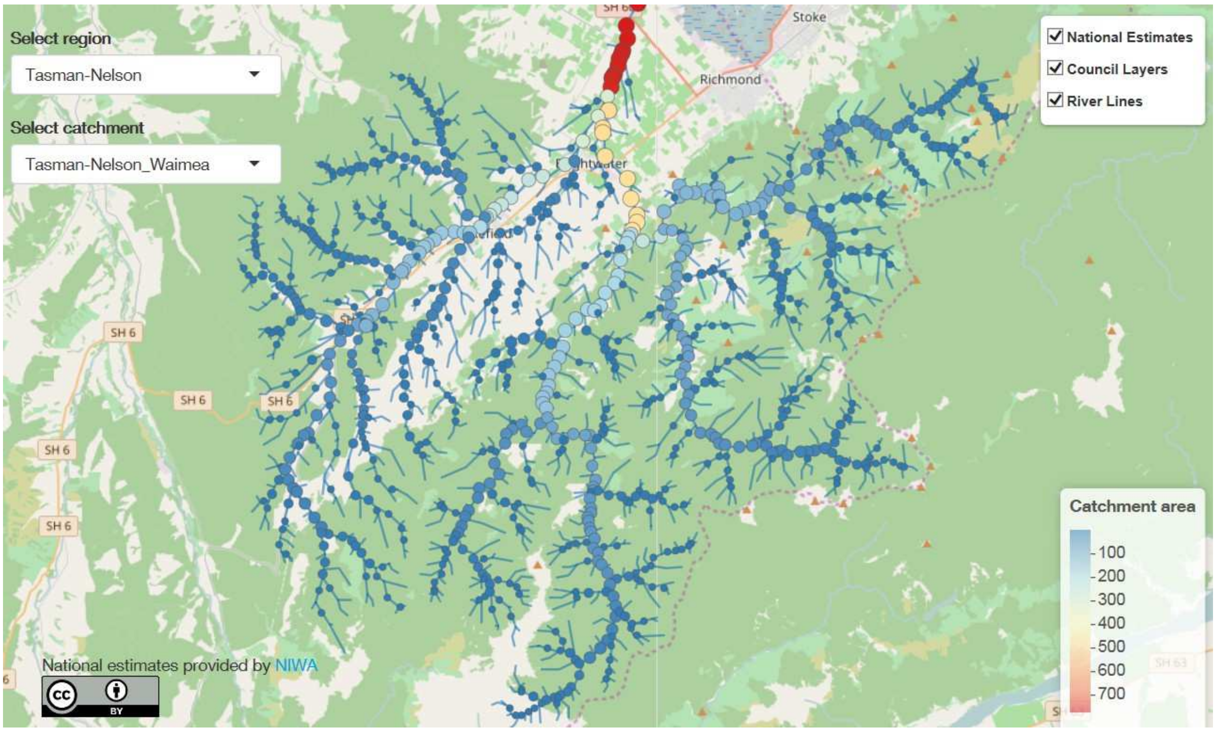
Gill, M.A. (1979) Sedimentation and useful life of reservoirs. *Journal of Hydrology,* 44: 89-95.

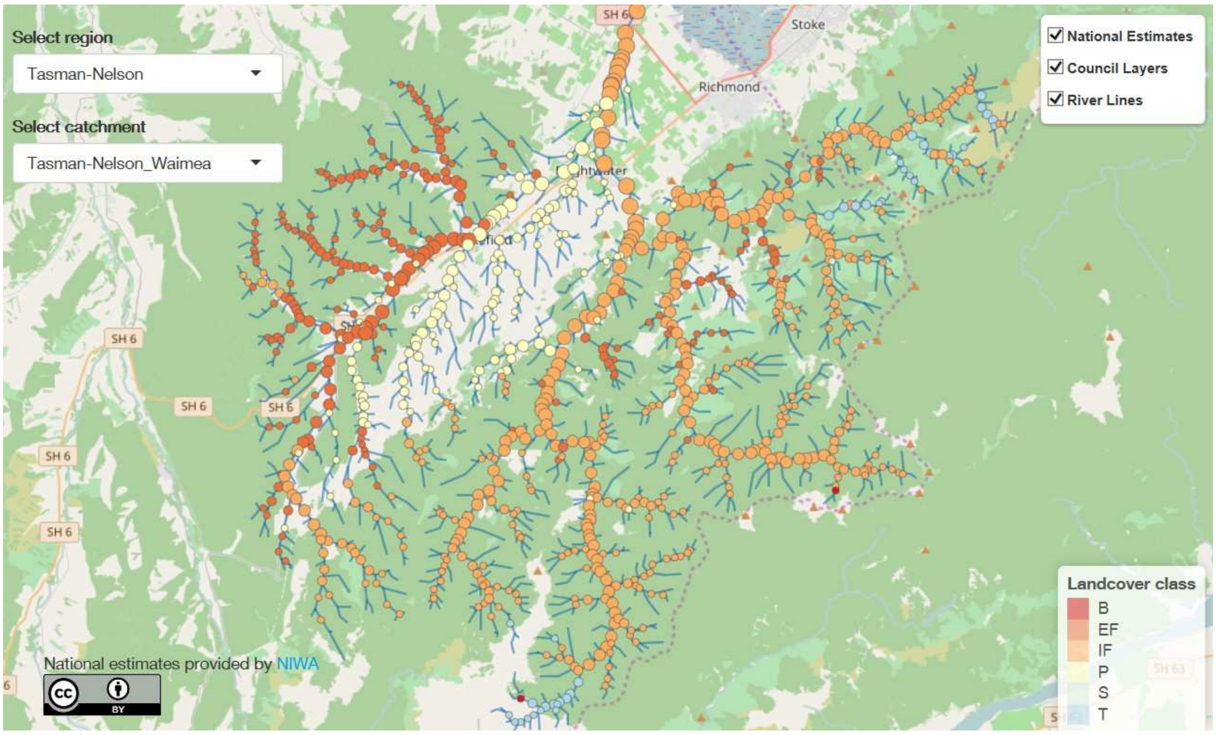
Hicks, D.M., Shankar, U., McKerchar, A.I., Basher, L., Lynn, I., Page, M., Jessen, M. (2011) Suspended Sediment Yields from New Zealand Rivers. *Journal of Hydrology (New Zealand),* 50: 81-142.

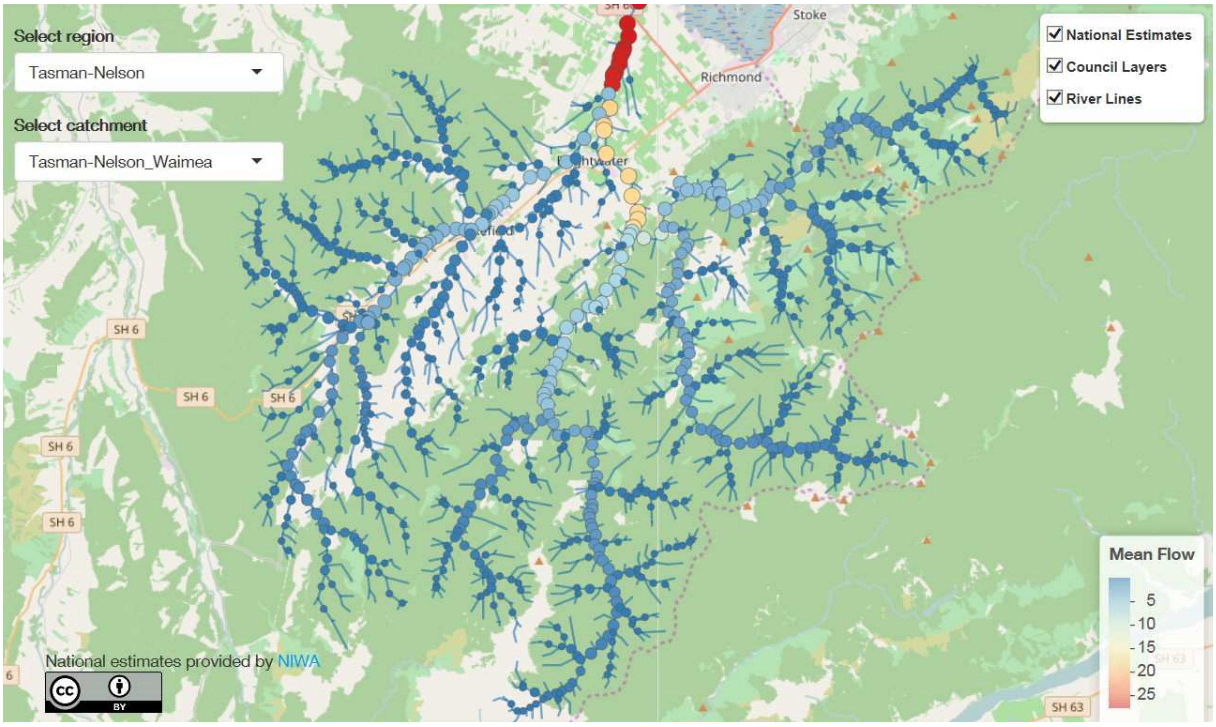
Plots of NZ River Maps for each parameter by river system

The data in these maps are best estimates based on GIS data as well as comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments.

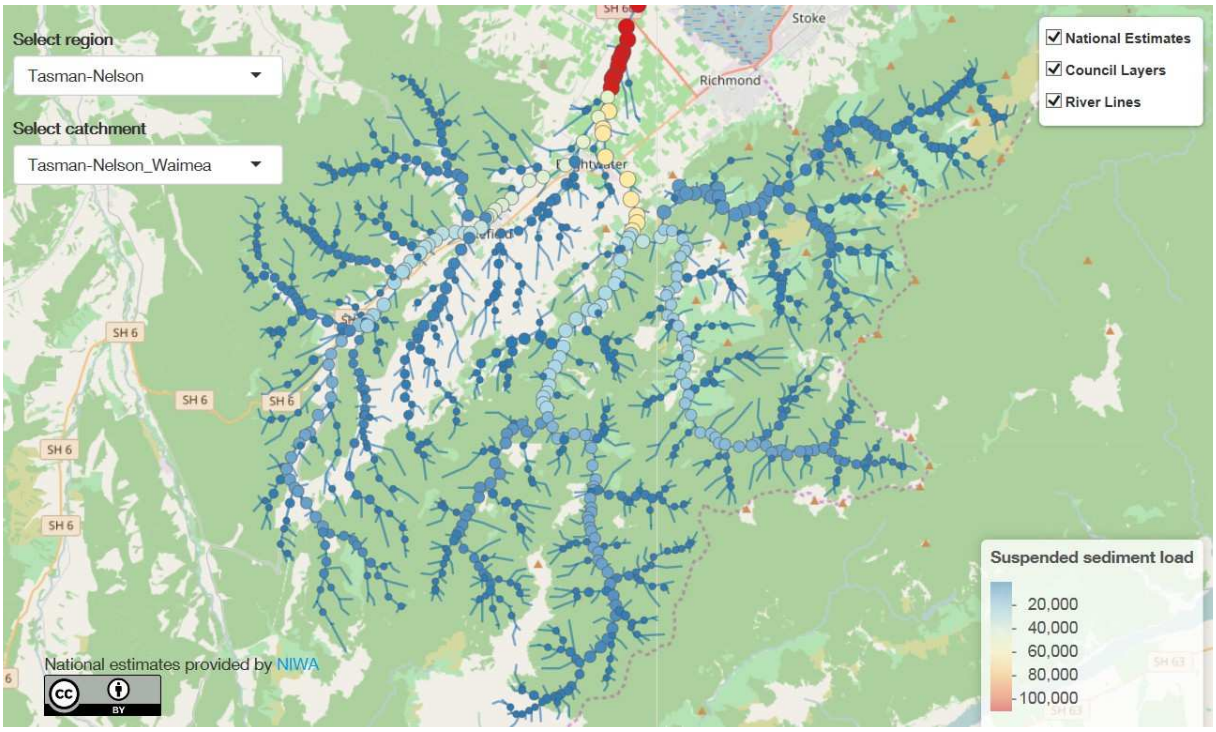
Waimea River





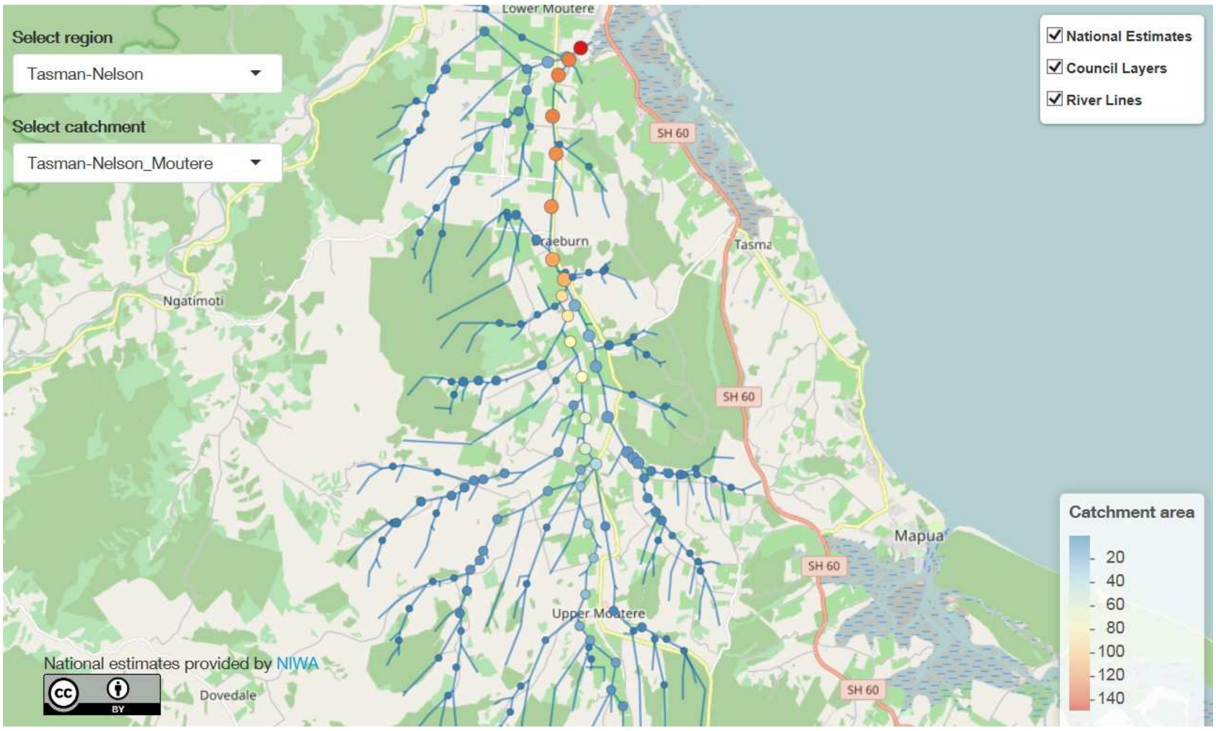


Mean flow data in $m^3 s^{-1}$

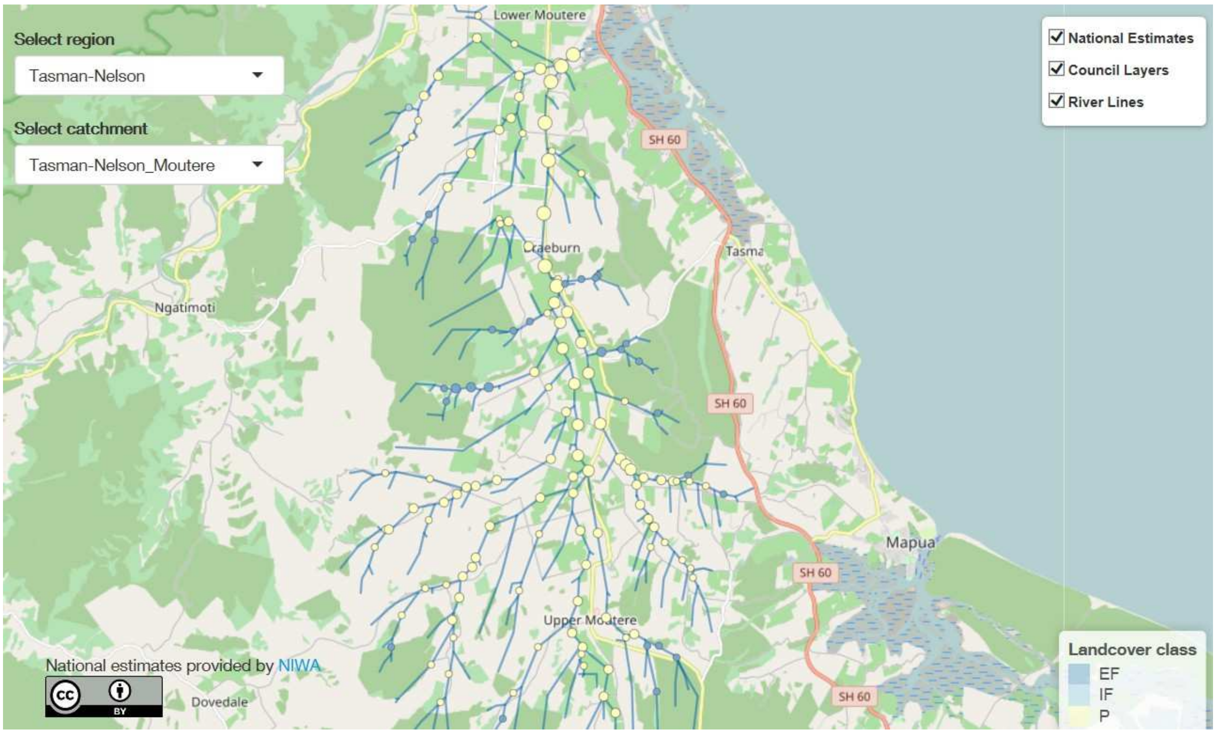


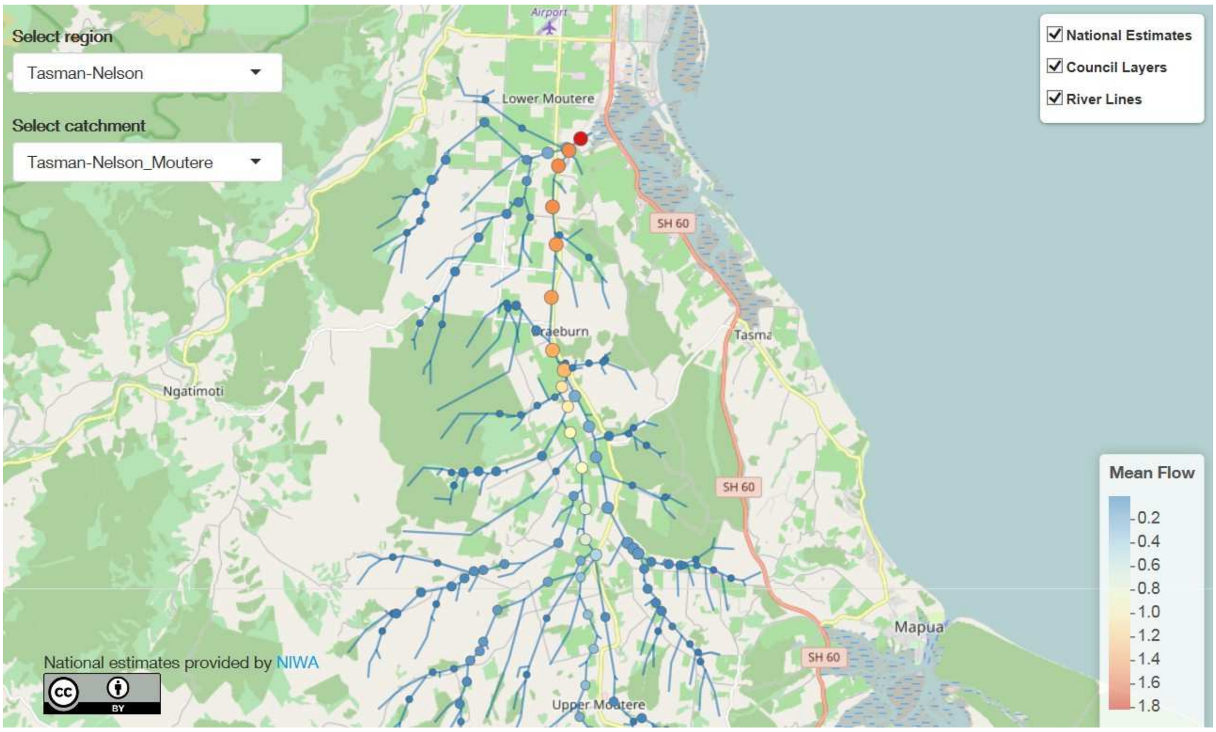
Suspended sediment (SS) estimated in t y^{-1}. Note that these SS estimates will be affected locally by land use management practices of tilling, engineering works and forest harvesting. They will also be affected by adverse weather conditions that cause bank erosion and slips.

Moutere

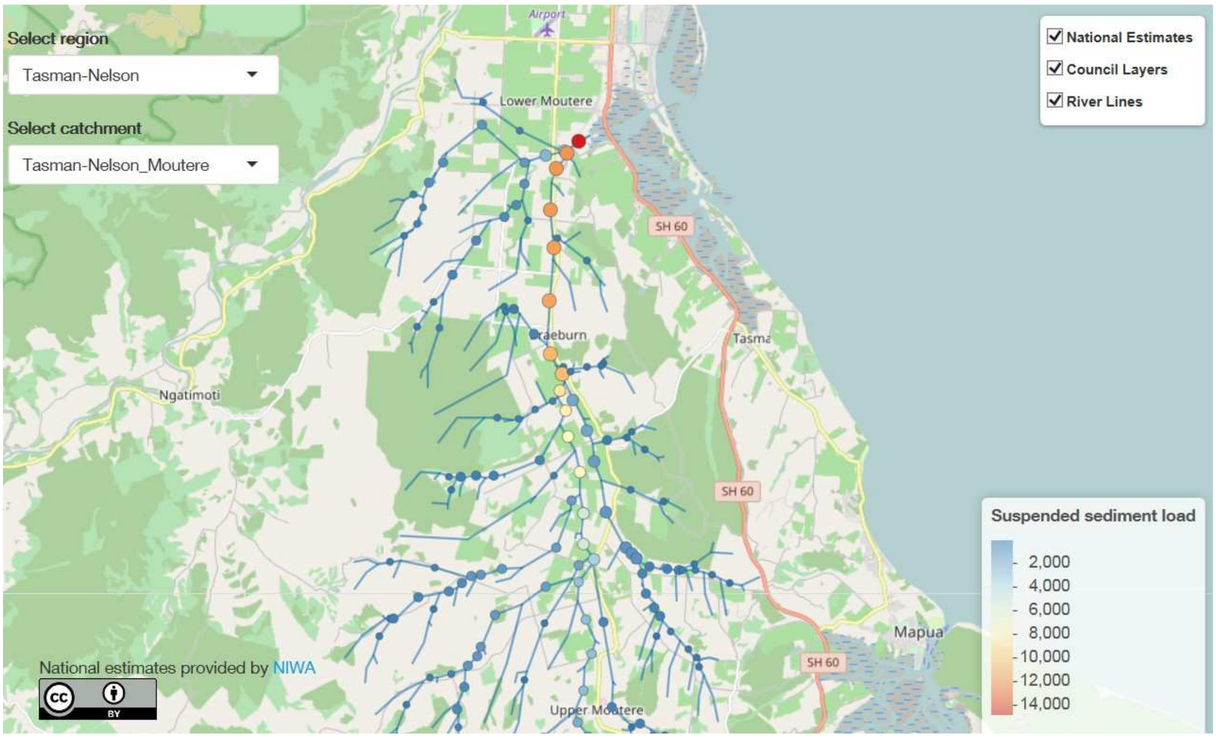


Catchment area in km^2.





Mean flow data in $m^3\ s^{-1}$

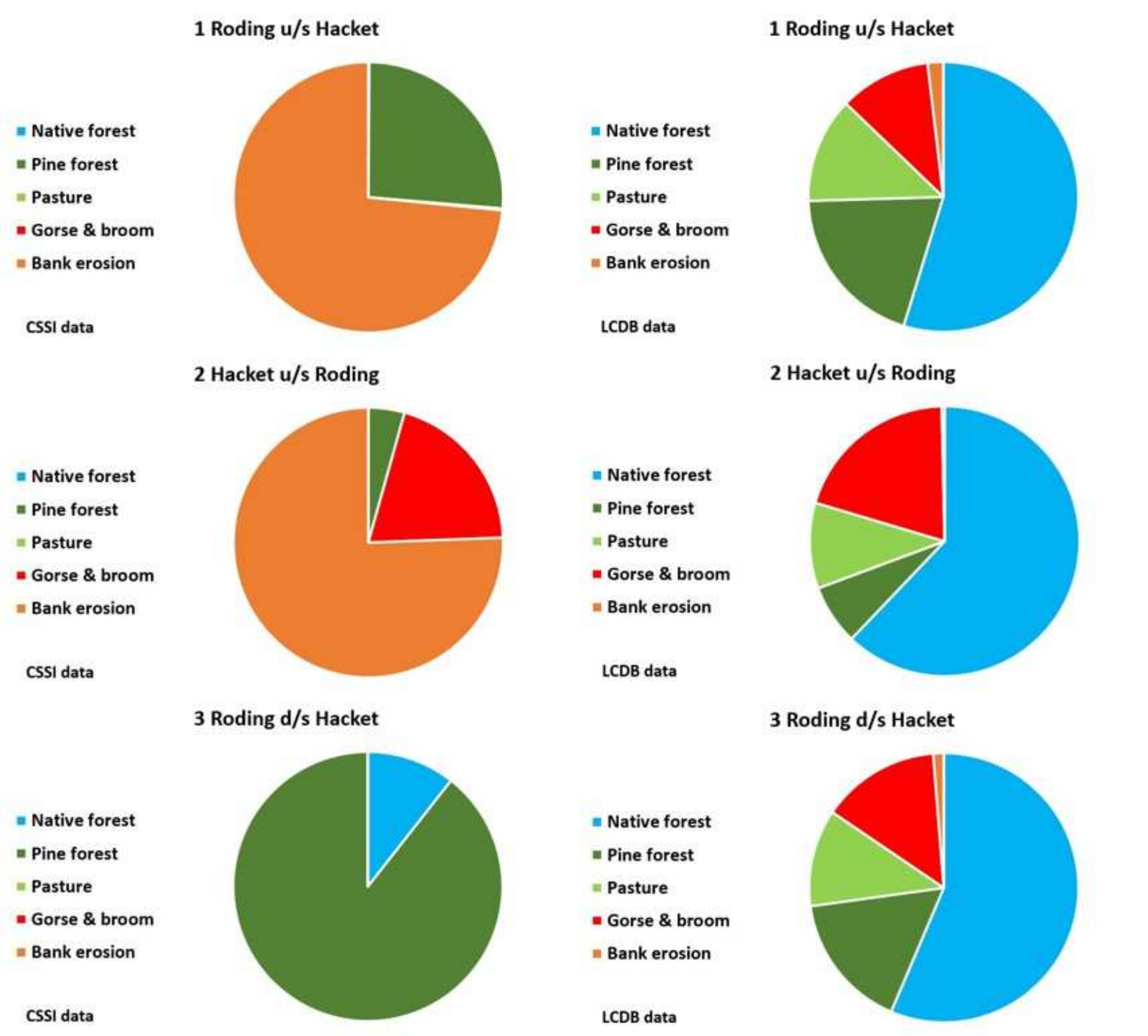


Suspended sediment (SS) estimated in t y^{-1}. Note that these SS estimates will be affected locally by land use management practices of tilling, engineering works and forest harvesting. They will also be affected by adverse weather conditions that cause bank erosion and slips.

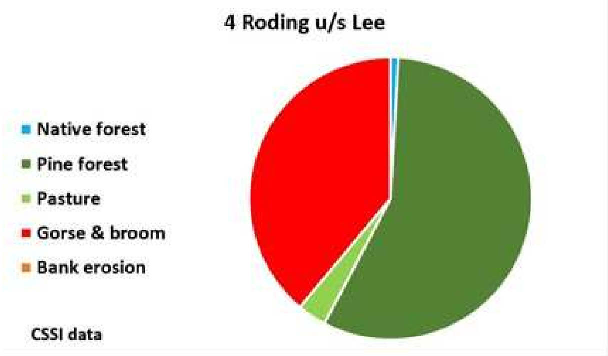
Appendix B Soil source proportions at river sampling sites

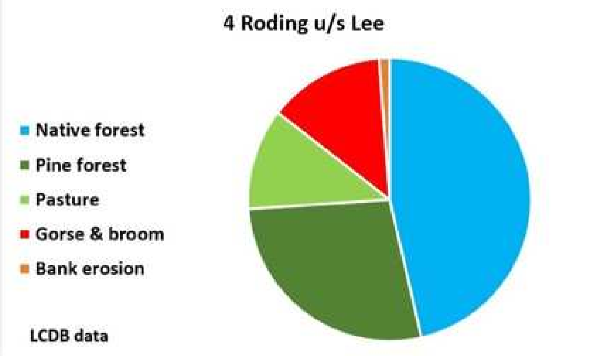
The pie charts show the relative proportions of specified soil sources at each site (left) from the CSSI technique compared with the % land use area in the upstream catchment (right) from the LCDB. The CSSI estimate of the percentage of total sediment in the river from each land use upstream of each site location is given. Note that sediment labelled "bank erosion" could include any sub-soil source.

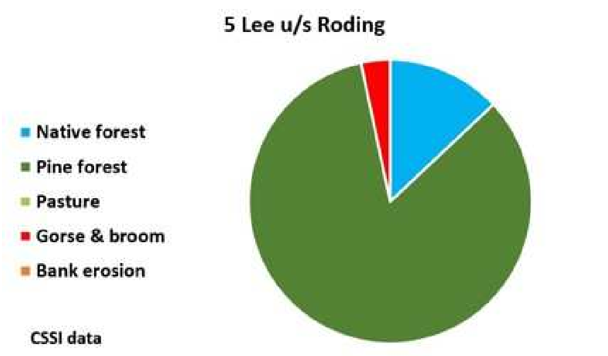
Waimea River system

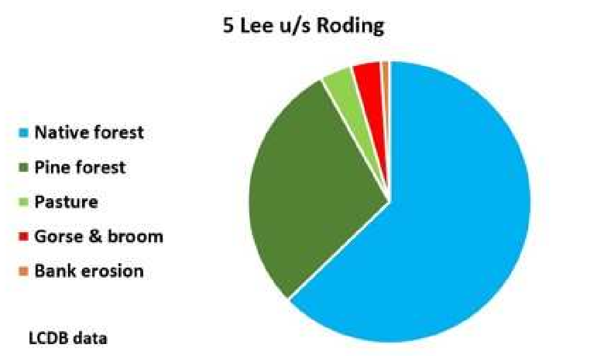


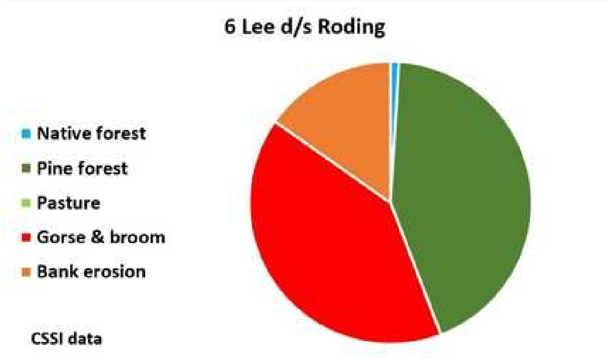
Between Site 2 and Site 3, there was a large area of recently harvested pine with runoff pathways that could reach the Roding River at the time of sampling. This would explain the high proportion of pine sediment at Site 3 and at the downstream sites.

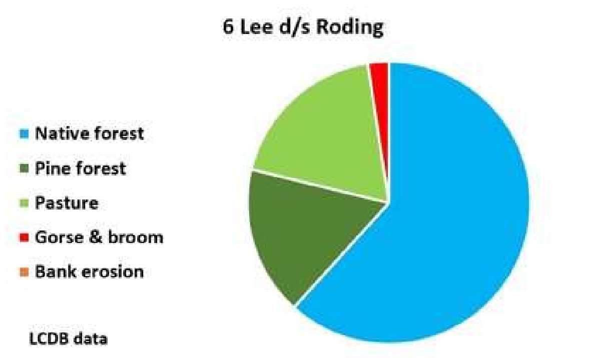

4 Roding u/s Lee
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data

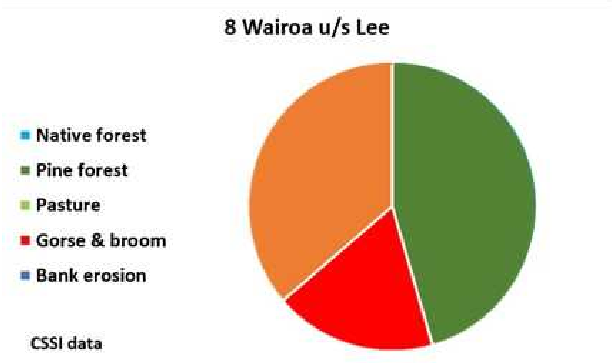

4 Roding u/s Lee
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data

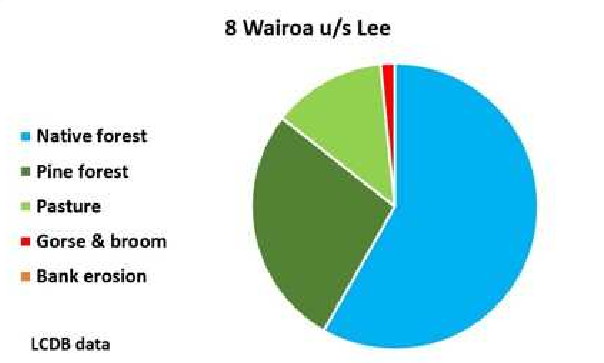

5 Lee u/s Roding
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data

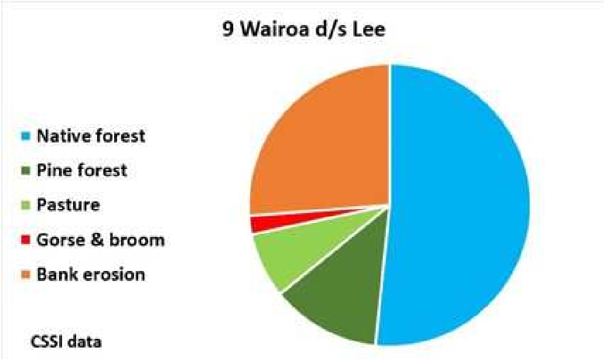

5 Lee u/s Roding
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data

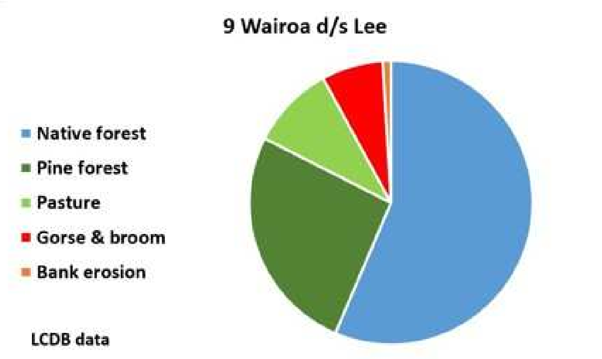

6 Lee d/s Roding
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data


6 Lee d/s Roding
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data


8 Wairoa u/s Lee
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data


8 Wairoa u/s Lee
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data


9 Wairoa d/s Lee
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data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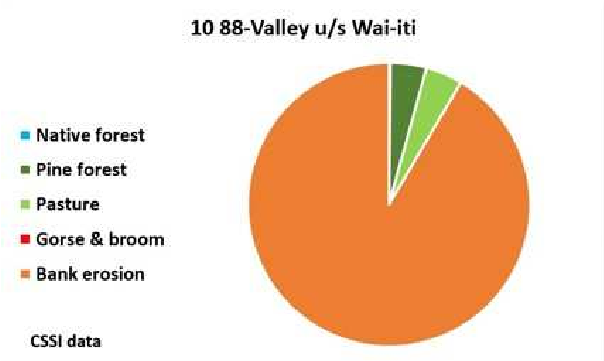
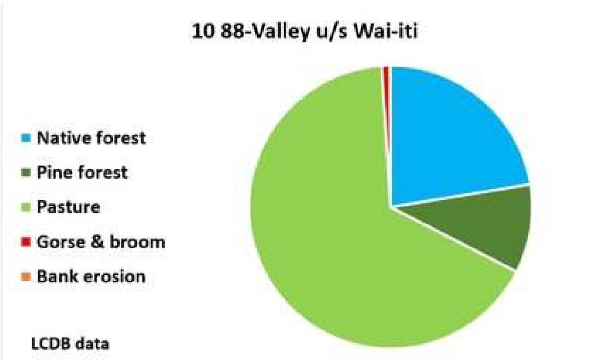
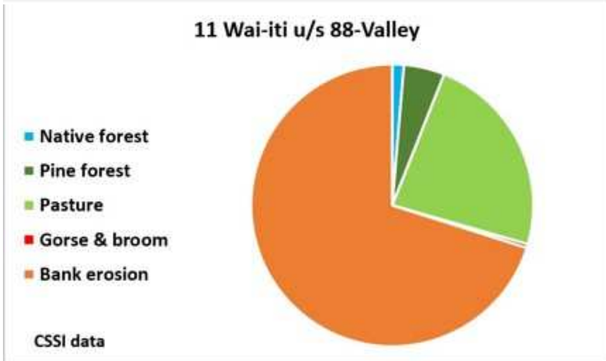
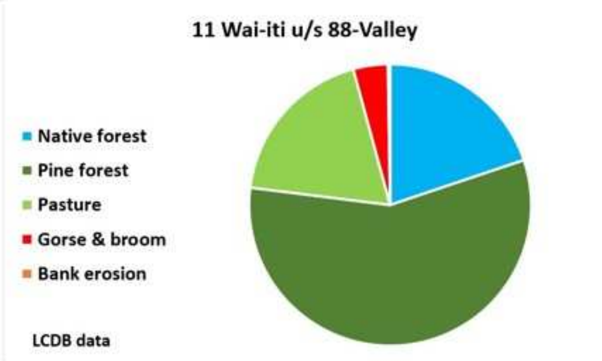
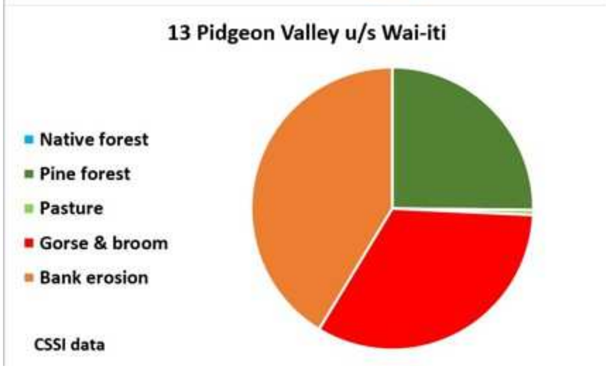
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data

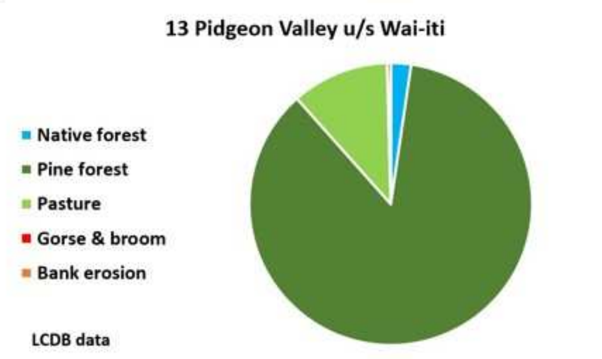

10 88-Valley u/s Wai-iti
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data


10 88-Valley u/s Wai-iti
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data

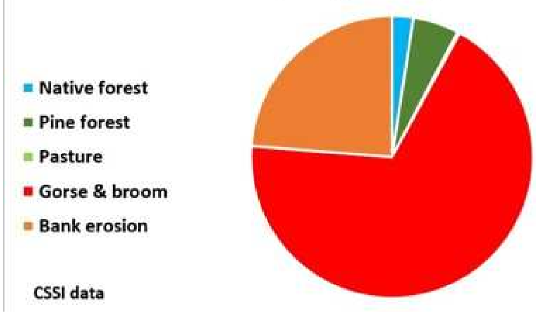

11 Wai-iti u/s 88-Valley
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data


11 Wai-iti u/s 88-Valley
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data

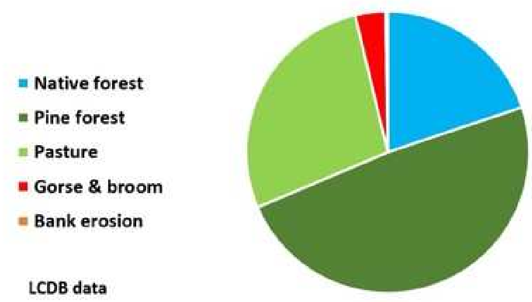

13 Pidgeon Valley u/s Wai-iti
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data


13 Pidgeon Valley u/s Wai-iti
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data

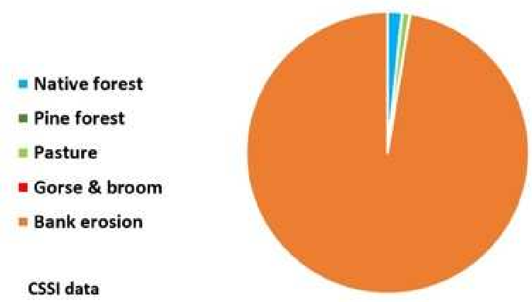
14 Wai-iti u/s Pidgeon Valley



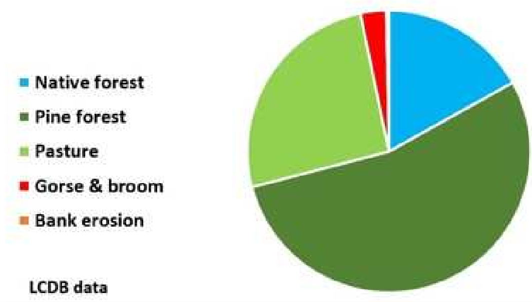
14 Wai-iti u/s Pidgeon Valley



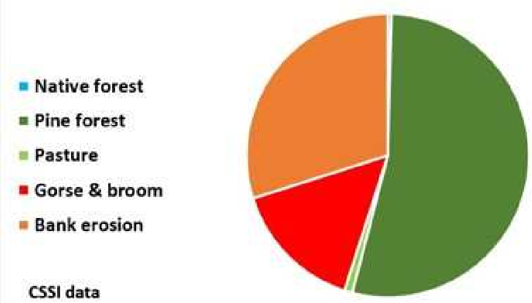
15 Wai-iti d/s Pidgeon Valley



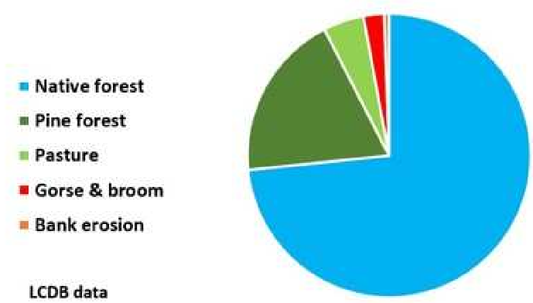
15 Wai-iti d/s Pidgeon Valley



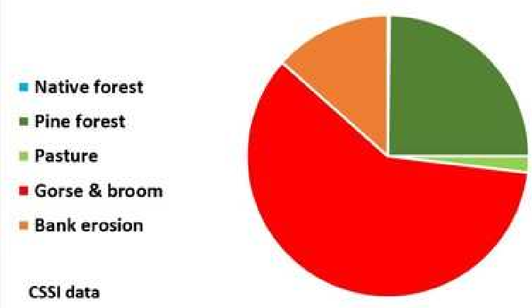
16 Wairoa - Right Branch



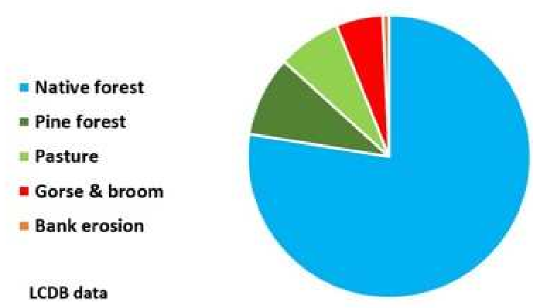
16 Wairoa - Right Branch

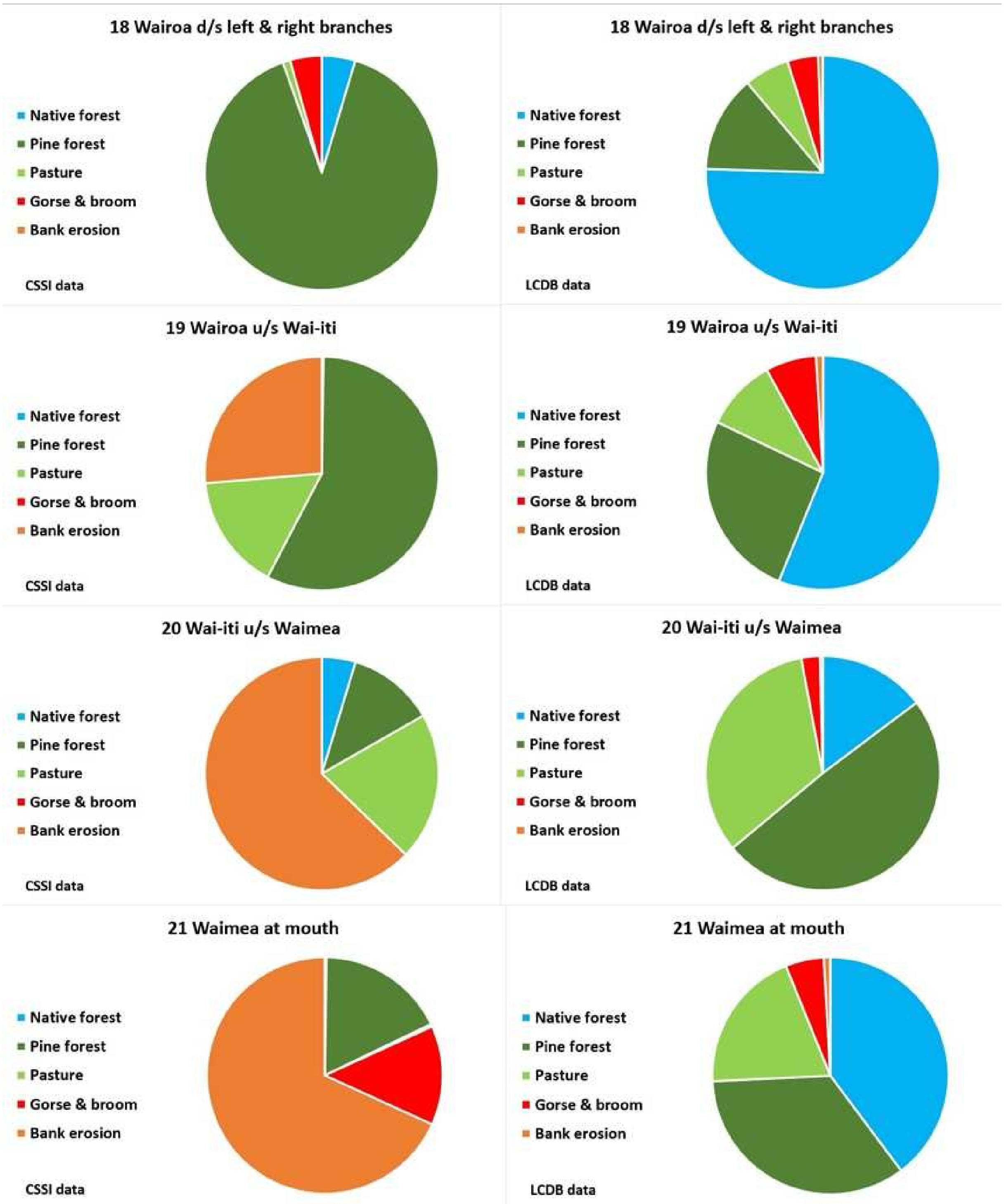


17 Wairoa - Left Branch

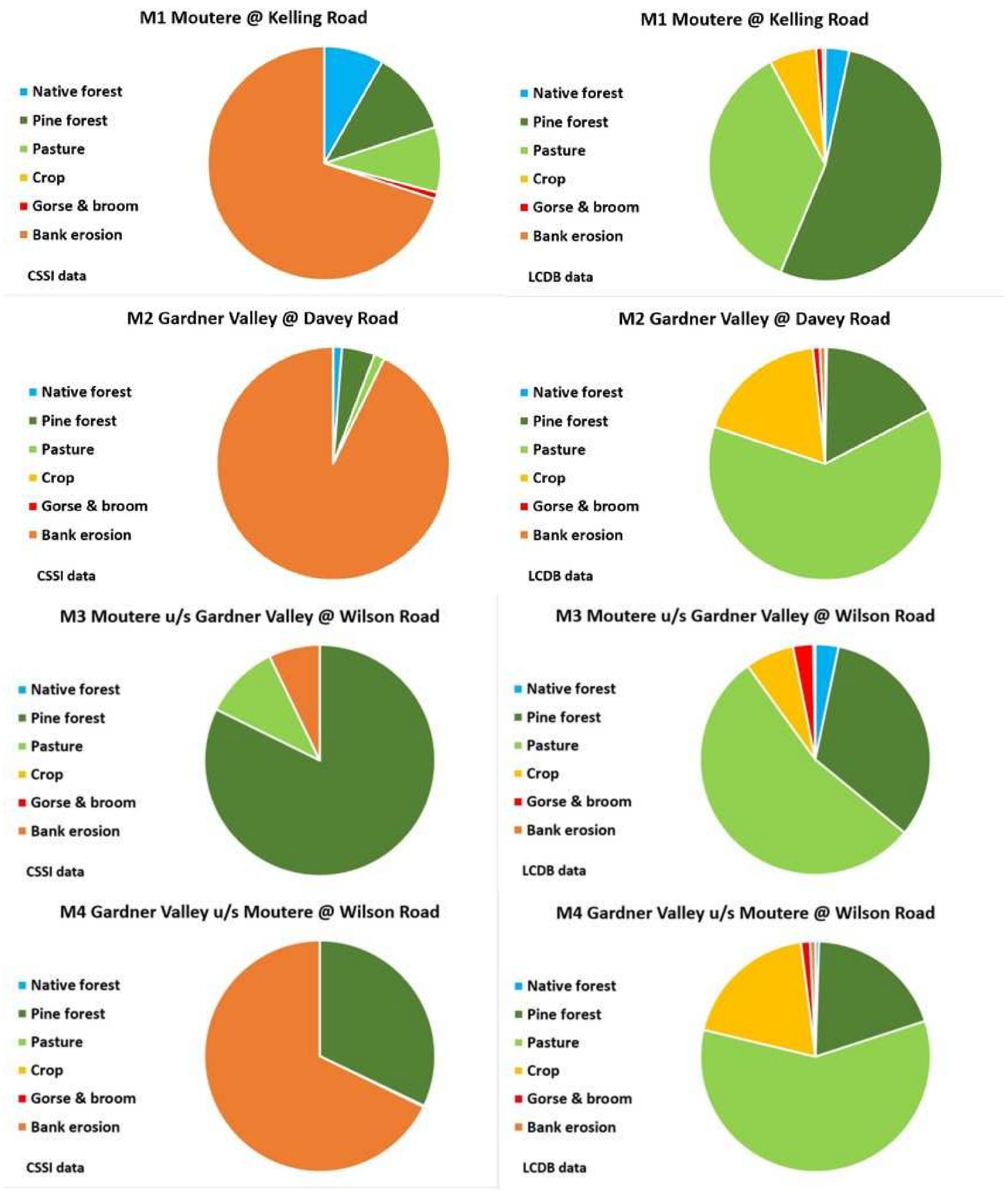


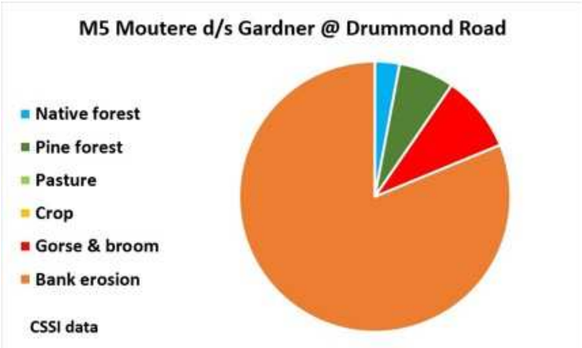
17 Wairoa - Left Branch

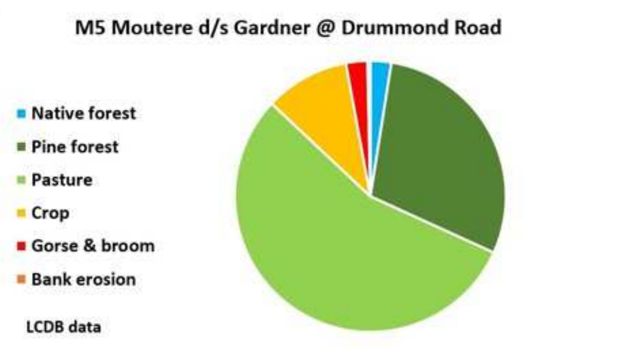


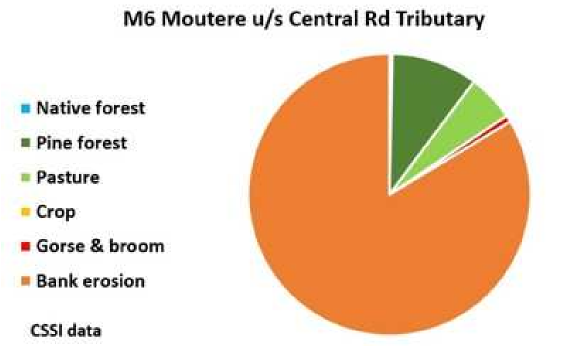

18 Wairoa d/s left & right branches
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data
18 Wairoa d/s left & right branches
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data
19 Wairoa u/s Wai-iti
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data
19 Wairoa u/s Wai-iti
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data
20 Wai-iti u/s Waimea
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data
20 Wai-iti u/s Waimea
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data
21 Waimea at mouth
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
CSSI data
21 Waimea at mouth
Native forest
Pine forest
Pasture
Gorse & broom
Bank erosion
LCDB data

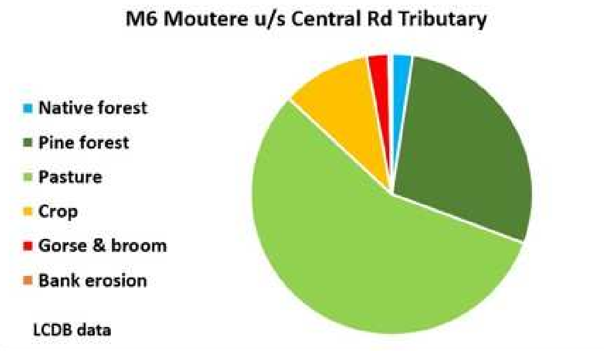
Moutere River system

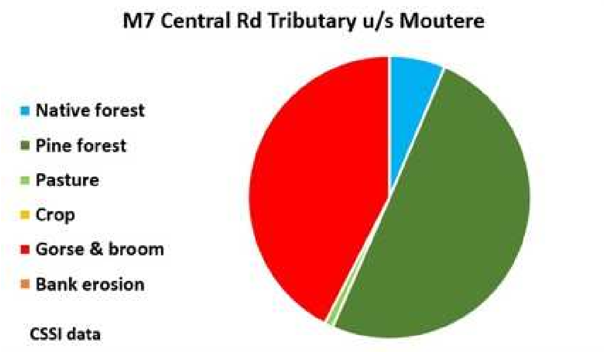


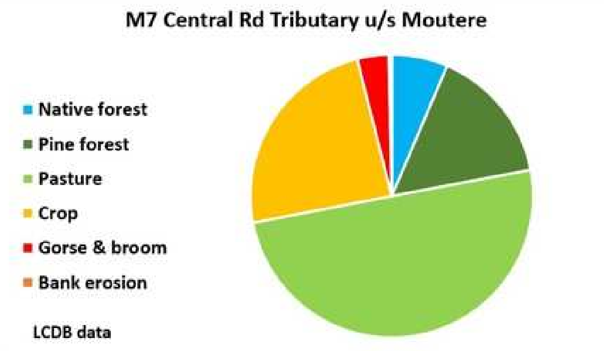

M5 Moutere d/s Gardner @ Drummond Road
Native forest
Pine forest
Pasture
Crop
Gorse & broom
Bank erosion
CSSI data

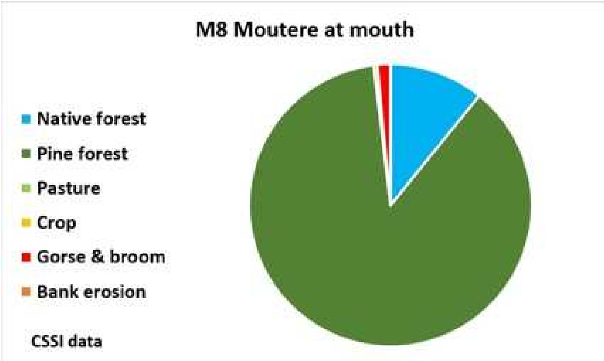

M5 Moutere d/s Gardner @ Drummond Road
Native forest
Pine forest
Pasture
Crop
Gorse & broom
Bank erosion
LCDB data

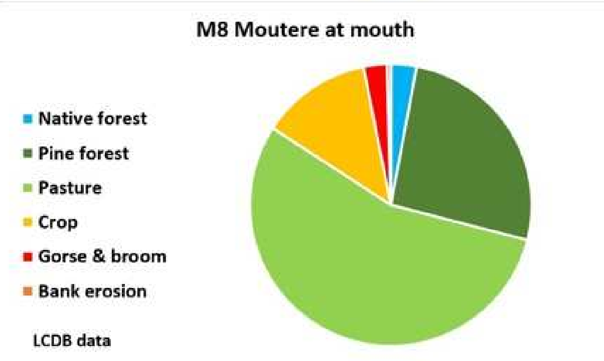

M6 Moutere u/s Central Rd Tributary
Native forest
Pine forest
Pasture
Crop
Gorse & broom
Bank erosion
CSSI data


M6 Moutere u/s Central Rd Tributary
Native forest
Pine forest
Pasture
Crop
Gorse & broom
Bank erosion
LCDB data


M7 Central Rd Tributary u/s Moutere
Native forest
Pine forest
Pasture
Crop
Gorse & broom
Bank erosion
CSSI data


M7 Central Rd Tributary u/s Moutere
Native forest
Pine forest
Pasture
Crop
Gorse & broom
Bank erosion
LCDB data


M8 Moutere at mouth
Native forest
Pine forest
Pasture
Crop
Gorse & broom
Bank erosion
CSSI data


M8 Moutere at mouth
Native forest
Pine forest
Pasture
Crop
Gorse & broom
Bank erosion
LCDB data