New River Estuary sediment sources tracking pilot study

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Cover Photo: Sinking into the sediment in the Waihopai River [Photo: Max Gibbs)

Contents

Tables

Figures

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Executive summary

A pilot study has been undertaken by the National Institute of Water and Atmospheric Research Ltd (NIWA) for the Southland Regional Council to assess the sources of sediment accumulating in the New River Estuary and the possible factors that may be exacerbating soil erosion in the estuary catchment.

Apparent increases in sediment accumulation rates in recent (~10-20) years in the Waihopai arm of the estuary, coupled with a change in the major land use from sheep to dairy farming, has fuelled local community speculation that the sediment increases are associated with dairy conversion. However, while farm survey data show that there has been a >5 fold increase in dairy cows and a 40% decrease in sheep numbers during this period, this hypothesis does not take into account the other possible causes of increased sediment runoff, including climatic changes such as increased rainfall and the timing of rainfall events relative to the farming calendar of cultivation and harvest of crops, or the juxtaposition of farms, dairy or sheep, relative to the main rivers and the slope of the land.

In order to test new technology for identifying sediment sources, Southland Regional Council commissioned NIWA to undertake a pilot study using their forensic Compound-Specific Stable Isotope (CSSI) technique to determine the sources of sediment entering the New River Estuary, by catchment and land use, and to identify any other factors that might exacerbate the erosion processes. This report presents the findings of that pilot study.

The results show that the major source of the terrigenous sediment in the New River Estuary is associated with bank erosion. In the Waihopai arm, less than 40% of the surficial sediment is soil of terrigenous origin with the remainder being reworked estuarine sediment (fine sand). The terrigenous soil proportion decreases to less than 10% in the outer estuary as the sediment blends with coastal material (sand), which is being redistributed around the estuary by wave action and tidal currents. Terrigenous soil contributions to the sediment deposited in the Waihopai arm in the last ~10 years are most likely to have come from the Oreti River (85-95%) with the remainder coming from the Waihopai, Waimatua and Mokotua Rivers.

Further refinement of the source analysis separated the bank erosion contribution proportions into individual land use components. This showed that the primary land use sources to the Waihopai Arm were sheep farming at 35-75%, deer farming at 12-24% and dairy farming at 3-18%. This is despite the large amount of dairy conversion in the New River Estuary catchment, and can be interpreted to imply that dairy conversion has mostly occurred on flat land not prone to erosion and that sediment runoff from these dairy farms has yet to reach the Oreti River. The high proportion of terrigenous soil attributable to sheep farming appears to be consistent with the large areas of sheep farming on the hilly land in the upper Oreti River catchment above Centre Bush and in the Waihopai River catchment.

The large tributaries to the Oreti River, the Makarewa and Waikiwi Rivers, both had high proportions of sediment attributable to sheep farming at ~93% and ~88%, respectively, which may have contributed to the sheep farming isotopic signatures in New River Estuary. However, the distinctive isotopic signatures of these inflows did not persist downstream of their confluence into the estuary indicating that they may have been mixed into the Oreti River and diluted below the discrimination level of the CSSI method.

Because of the apparent infilling in New River Estuary, there is likely to be minimal storage capacity for fine suspended material from the catchment under normal flow conditions, allowing these sediments to be flushed from the estuary. Consequently, the majority of the sediment accumulating in the estuary may be associated with high rainfall events and concomitant high flow events in the rivers. Climate data indicates that mean annual rainfall is about 90 mm y^{-1} higher since 1985 than before, with the average minimum annual rainfall being about 180 mm y^{-1} higher. Whether this change is sufficient to increase sediment erosion is unknown, but it also coincides with the period of dairy conversion.

1 Introduction

Southland Regional Council commissioned the National Institute of Water and Atmospheric Research Ltd (NIWA) to determine and apportion the main sources of soil contributing to the sediment accumulating in the New River Estuary (Figure 1). This request is in response to the results of fine scale sediment monitoring studies by Wriggle Coastal Management (e.g., Robertson & Stevens 2010), which show that sediment accumulation in the New River Estuary has increased substantially in recent years, especially in the upper and central Waihopai Arm), and that the main body of the estuary is also rapidly getting muddier with concomitant deteriorating sediment oxygenation. In the fine scale sediment monitoring report, Wriggle Coastal Management identified that fine sediment was adversely impacting on biodiversity in parts of the estuary through loss of high value habitat resulting in the loss of mud-intolerant species including pipis from some sites. In order to target resources to manage the sediment load entering the New River Estuary, Southland Regional Council need to know what the contemporary contribution of sediment is from each catchment and from which sources.

This report presents the results of a sediment source tracing study using a forensic compound specific stable isotope (CSSI) technique (Gibbs 2008) to positively identify and apportion the sources of terrigenous soil, by land use and catchment, contributing to sediment at different locations in the New River Estuary. This report also assesses where the various soil sources enter the rivers flowing into the estuary and provides an interpretation of soil erosion in the New River Estuary catchment.

1.1 Terminology and concept

Sediments deposited in receiving environments, such as estuaries, are composed of sediments derived from one or more sources. The sources are typically land-based and are referred to as soil sources or just **sources**. The sediments derived from various sources are mixed together during transport by water before being eventually deposited and are referred to as sediment mixtures or just **mixtures.** When following the movement of sediment down the main stem of a river system, the mixture at the bottom of one stretch of the river will become one of the sources for the next stretch of river downstream or for the estuary at the river mouth. This convention is used throughout this report.

An important caveat is that if a particular land use does not erode or cannot reach the deposition zone due to geographic constraints, soil from that land use will not contribute to the sediment mixture. For example, sediment entering a river from a tributary cannot affect the river upstream of the tributary but a land use in the tributary catchment may also be present in the upstream river catchment and will have an effect.

Transport rates by rivers for various particle-size fractions in eroded soil will vary due to differences in entrainment thresholds by fluid shear and particle fall speeds. For example fine silt typically has fall-speed values orders of magnitude lower than fine sand. Consequently, very fine silt will travel further downstream before settling, or it may not settle and be carried out of the river directly to the estuary.

An important assumption is that, once eroded, the soil will mix completely with other soil sources in the river water as it is transported to the deposition zone, and thus the sediment mixture will be representative of all upstream sources.

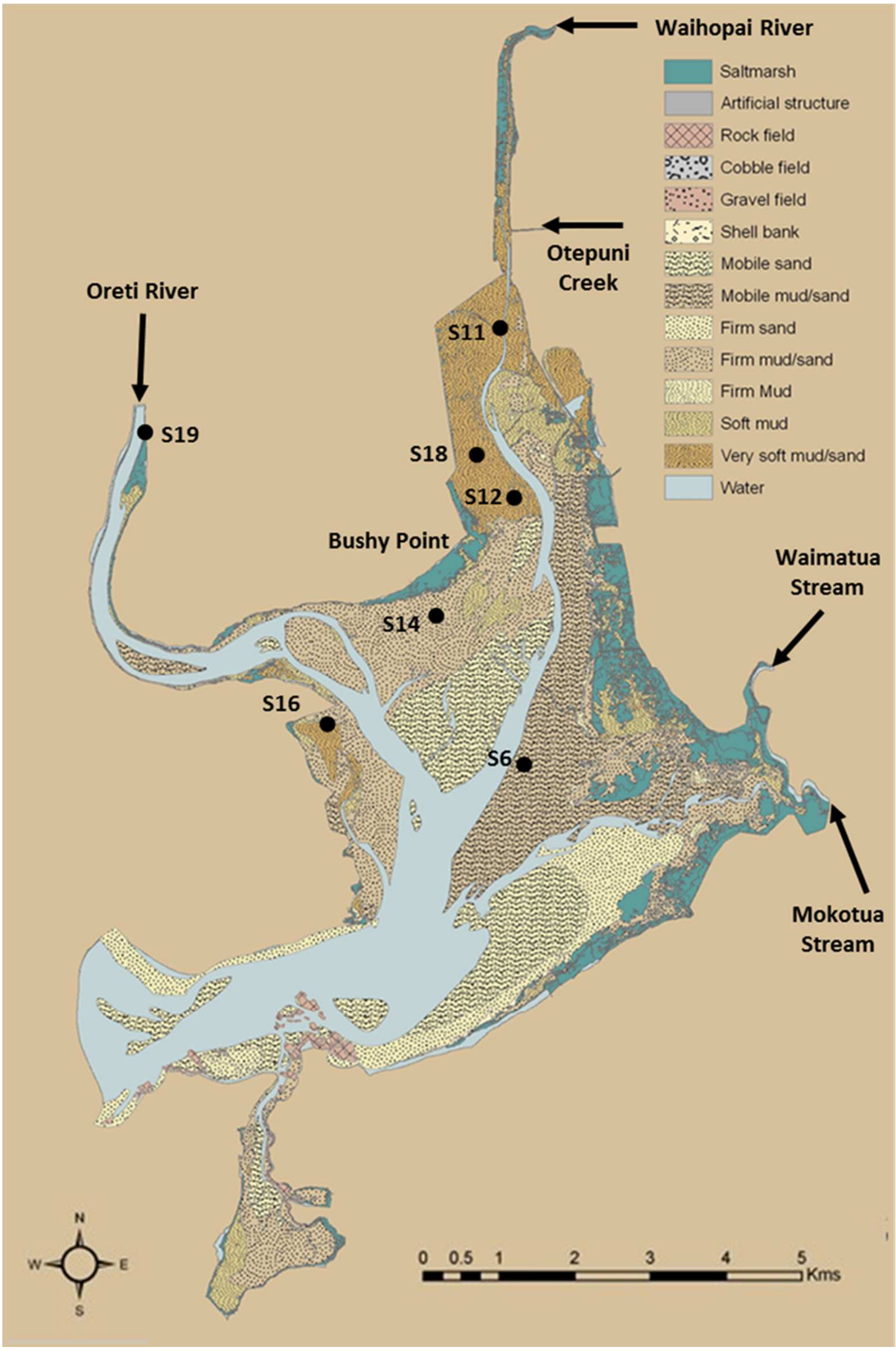

Figure 1: **New River Estuary.** Site map showing the main inflows and the sediment sampling positions (S number), and the distribution of sediment types across the estuary in 2012. Base map kindly provided by Wriggle Coastal Management.

A follow-on from this assumption is that each source soil contribution to the sediment mixture will be proportional to the rate of erosion and the area of that land use eroding. From this it follows that the presence of a particular land use soil source in proportions greater than would be expected from the area covered by that land use, indicates a land use practice exacerbating soil erosion. This information can inform management decisions for the development of strategies to reduce that erosion.

To determine where sediment in an estuary came from in the upstream river catchments or coastal environment, the sediment mixture in the estuary needs to be deconstructed into the component sources. The forensic CSSI technique uses organic biomarkers bound to the soil particles in the mixture to distinguish between different sources. This technique measures the stable isotopic signature of the carbon atoms in a biomarker to obtain a CSSI value for each biomarker. The CSSI data are analysed through a mixing model which deconstructs the sediment mixture into sources and apportions the contribution of each source to the mixture by land use.

While the CSSI technique can identify and apportion the contribution of each land use source in the mixture, it cannot quantify the erosion rate unless sediment mass transport data is provided. Mass transport data may be obtained from separate studies and/or output from catchment models.

1.2 Background

The New River Estuary (Figure 1) is a large tidal-lagoon type estuary with a high-tide area of about 41 km^2. It has an average high-tide depth of 1.5 m and is a strongly tidal influenced system with an estimated residence time of 2-3 days (Southland Regional Council information). The estuary receives freshwater inflows from eight catchment including two large rivers — the Oreti (third largest river in Southland) and the Waihopai — as well as three streams/rivers (Otepuni, Waimatua and Mokotua), and several smaller streams and drains, as well as treated water from the Invercargill wastewater treatment plant.

Studies of the estuary by Wriggle Coastal Management consultants have reported that sedimentation rates in the Waihopai arm of the estuary have recently increased from the 1967-2007 rates of 13-16 mm/yr to 72 mm/yr in 2011 at the Waihopai Central site (Figure 2) (Robertson & Stevens 2010). These changes are thought to coincide with land use changes including the intensification of dairy farming in the estuary catchment, coupled with an increase in annual rainfall (Figure 3).

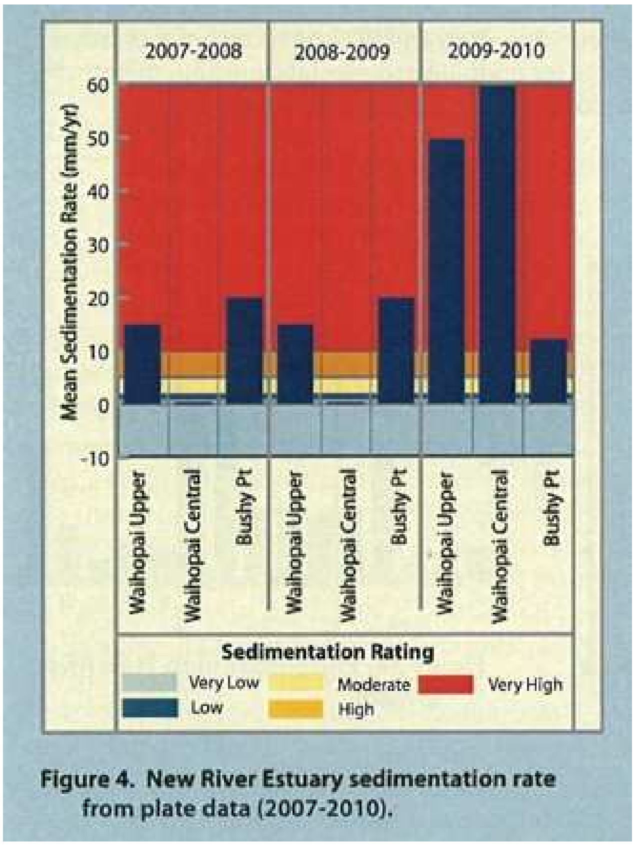

Figure 2: **New River Estuary sedimentation rates.** Figure extracted with permission from Wriggle Coastal Management report (Robertson & Stevens 2010).

The 5-yearly mean annual rainfall is on average 90 mm yr^{-1} higher since 1985 than before 1985. The apparent step-wise increase is more noticeable in the 5-year minimum rainfall, which is an average of 180 mm yr^{-1} higher since 1985 than before 1985 (Figure 3).

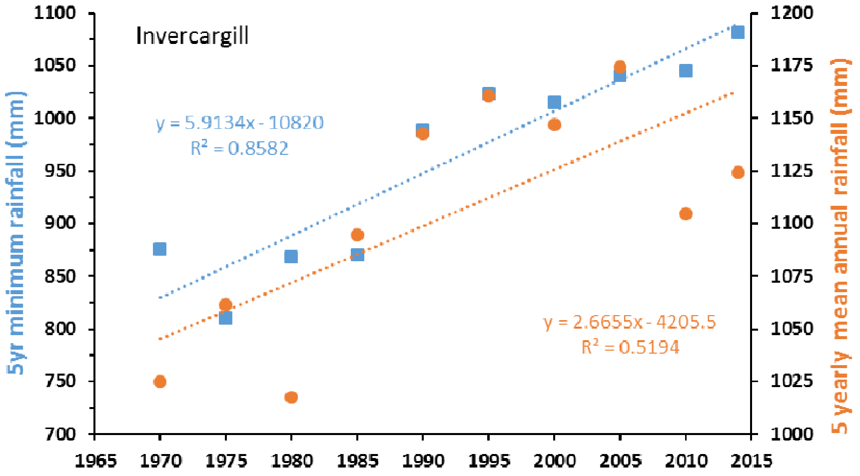

Figure 3: **Rainfall summary from Invercargill** showing 5 yearly mean annual rainfall (round, RH axis) and the minimum annual rainfall in each 5 year period (square, LH axis). Linear regressions indicate the strength of the trends within the data. Data points are for the 5 year period before the date. (Rainfall data from Invercargill airport meteorological station, Agent number 5814).

The major land use change in the New River Estuary catchment has been intensification of dairy farming. Data summarised by Copland and Steven (2012) show that the number of cows in Southland increased from around 114,000 in 1994 to around 599,000 in 2010, a more than 5 fold increase, while sheep numbers declined from around 7.8 million to 4.6 million, a 40% decrease, in the same period. In 2011, of the estimated 1570 dairy farms in Southland, more than 720 were in the New River Estuary catchment (Figure 4) (Southland Regional Council data).

While it appears that there has been a rapid increase in sediment accumulation in the New River Estuary (Figure 2), the timing of the increase does not appear to be directly aligned with either the 1985 apparent step-wise increase in annual rainfall (Figure 3) or the intensification of dairy farming since the mid-1990s (Copland and Stevens 2012). Notwithstanding this, it is likely that the apparent increase in sedimentation rates in the New River Estuary is a response to the cumulative effects from these two major changes as well as other land use changes in the catchment, mediated by the times lags associated with sediment transport through such a large catchment.

As a consequence, the effects of land use changes in the catchment will take time to become apparent in the downstream estuary.

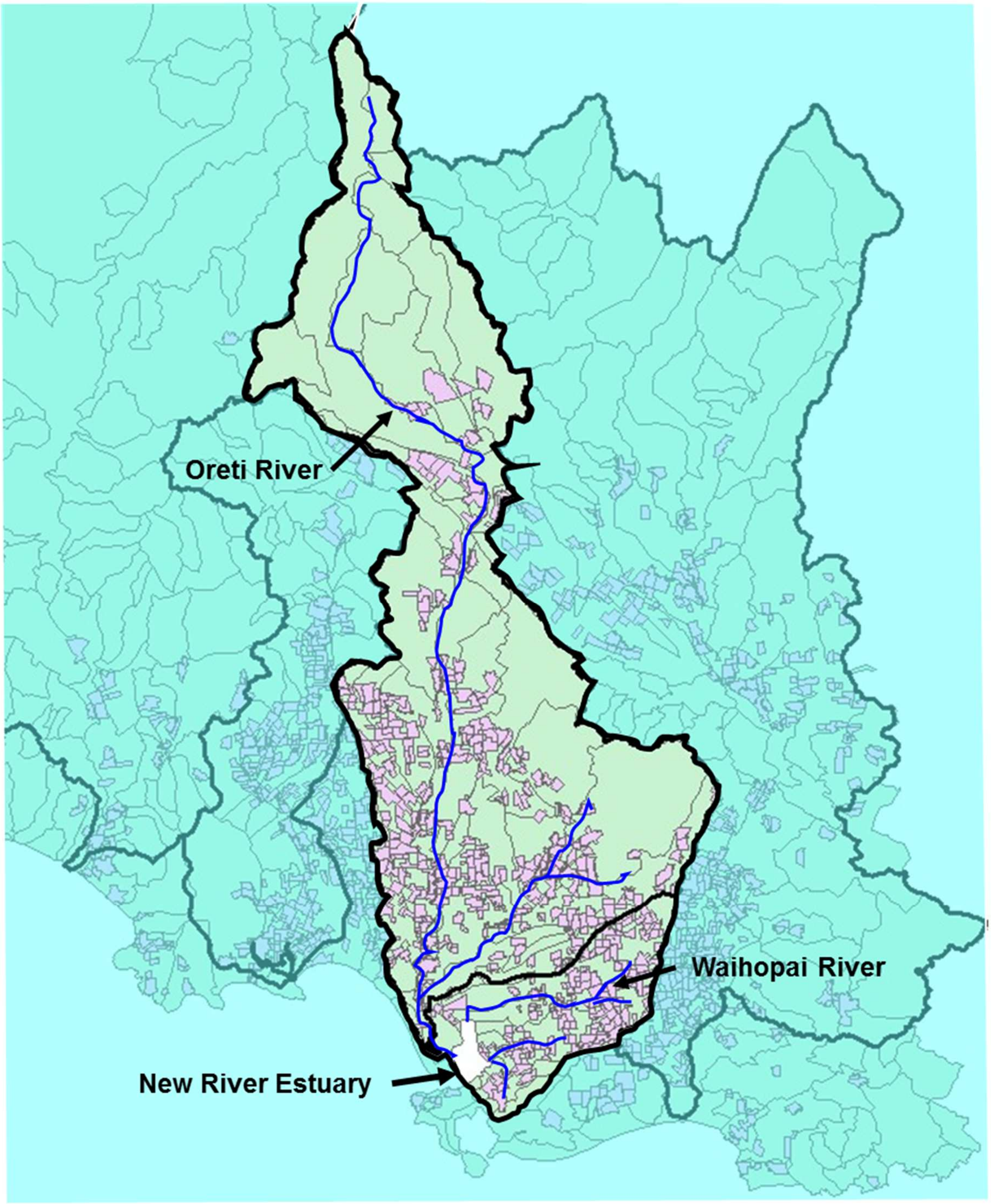

Figure 4: New River Estuary and catchment (area 3950 km²) showing the main rivers (blue line) and the number of dairy farms (pink plots) in the catchment. These farms may be running run more than 275,000 cows (Copland and Stevens 2012). Farm data supplied by Southland Regional Council as at November 2011.

2 The CSSI technique

2.1 Concept

With the exception of urban developments, land use is typically defined by the plant community growing on that land. These plant communities all produce a range of organic compounds which may bind to the soil as biomarkers for that plant community. For use as a tracer, the biomarkers have to be strongly bound to the soil particles, they have to be produced by all plants and yet be capable of being used to distinguish between different plant species or communities. The biomarkers of choice are the common fatty acids, which have straight carbon chain lengths in the range from 14 (i.e., Myristic acid; C14:0) to 24 (i.e., Lignoceric acid; C24:0). These fatty acids are produced by all plants and tend to leak from the plant roots into the soil. They are highly polar which allows them to be initially moved by water from the plant roots to the adjacent soil and then bind strongly to the ion exchange sites on the soil particles. This polar bond is stable and the fatty acids C14:0 (Palmitic acid) and C18:0 (Stearic acid) are regularly used in paleodietary studies of humans more than 4000 years ago (Tripp & Hedges 2004).

By themselves, fatty acids cannot be used as tracers because they are produced by all plants and, despite there being a “fingerprint” of different concentrations of the range of fatty acids from each plant, these concentrations decline due to microbial breakdown in the sediment and the fingerprint merges into the background in few weeks (Banowetz et al. 2006). In contrast, stable isotope signatures of the carbon atoms in each fatty acid compound are stable and do not change over time thus making them good tracers.

Each plant species is different and produces each fatty acid via a slightly different biochemical pathway in the plant. This causes different levels if isotopic fractionation of the carbon atoms in each plant species. The result is small differences in the carbon stable isotopic signature of each fatty in that plant species compared with a different plant species. Even when the concentrations decrease, the stable isotope signature remains unchanged. Consequently, different plant species can be discriminated by measuring the stable isotopic signature of each fatty acid compound i.e., measuring the compound-specific stable isotope (CSSI) signatures.

The fatty acids are extracted from the source and mixture samples collected from the study catchment and the CSSI values of each fatty acid in the sample and the bulk carbon isotopic signature of the whole sample are measured. These isotopic values, expressed in delta notation ($\delta^{13}C$) are put into a mixing model which uses the source isotopic values to deconstruct the mixture based on the isotopic values in the mixture.

The mixing model calculates all feasible solutions that give an isotopic balance from the isotopic signatures of the sources that match the isotopic signatures in the mixture. The model output gives the proportion of each source detected in the mixture as a numerical probability of the frequency of occurrence of each feasible solution, an estimate of uncertainty (standard deviation) and the number of solutions “n” found. The value of n is used to assess the confidence in the output. A large value of n (1000s) indicates a low confidence in some or all of the results. Confidence increases as the value of n decreases with n = 1 being a unique solution with no uncertainty.

The mixing model output is expressed in terms of isotopic proportions. These proportions are converted to soil proportions using a linear equation based on the percent carbon in each source and the assumption that the whole source soil was present in the mixture when it was deposited.

Because the carbon concentration in the mixture can change over time, the carbon content of the mixture is not used in this calculation.

A more detailed description of the method can be found in the paper by Gibbs (2008).

2.2 Sampling strategy

The objective of this study was to identify and apportion the sources of terrigenous soil in the New River Estuary sediment by land use. To achieve this, the sampling strategy used was:

- Treat the river systems separately starting with a river delta sample close to the estuary but far enough upstream to avoid significant cross contamination between the Oreti and Waihopai Rivers. Samples were collected at the road bridge over the Waihopai River and from the left bank of the Oreti River at the end of Coggins Road [2 samples].
- On the Oreti River system, sampling included the confluences above and below the junction of the Waikiwi River with the Oreti River, the junction of the Makarewa River with the Oreti River, and sediment from the Centre Bush SOE site “Bog Burn downstream of Hundred Link Road”. [7 samples].
- On the Waihopai River samples were collected immediately upstream of Kennington Township with an equal amount of sediment from each tributary being combined into a single sample. Samples were also collected from the Otepuni urban stream downstream of Ness Street, from the Waimatua River at the road bridge on SH1 and from the Mokotua River at the road bridge on SH1. [4 samples].
- Land-use reference soil samples required to be collected were:
    - (i) four replicate bulk samples from each pasture type as sheep/beef, dairy and deer farming [12 samples]
    - (ii) three bank erosion material [3 samples]
    - (iii) three replicate samples from each forest type: Eucalyptus, exotic pine (clear-fell) and native [9 samples]
    - (iv) three replicate bulked storm water samples [3 samples],
    - (v) three replicate bulked samples of each of grazing fodder crop as swedes/turnips, brassicas (kale) and fodder beets [9 samples]
    - (vi) single bulk samples of horticultural crops as carrots, potatoes and parsnips [3 samples], and
    - (vii) single bulk samples of bank and drain plants as sweet grass (*Glyceria sp*.), cress (*Nasturtium officinale*) and a composite sample of aquatic macrophytes including water milfoils (*Myriophyllum sp*.), water buttercup (*Ranunculus fluitans*) and pondweeds (*Potamogeton sp.)* [3 samples].

  Multiple samples (10) of each reference material were combined to provide a bulk sample representative of each land use type or plant community.
- In the New River Estuary, composite samples were collected from each of Environment Southland’s six estuarine monitoring sites, plus a river delta sample from the Oreti and Waihopai Rivers. [8 samples].

This required sampling regime produced a total of 61 samples.

During the course of the sampling, it was observed that there were numerous gravel roads in the catchment, which are potential sediment sources. Overseas studies have found that gravel roads can account for 25-30% of the sediment discharged from a catchment (Motha et al. 2003, Mukundanm et al. 2006). Consequently, sediment from several of gravel roads were sampled as part of the land use reference material library.

Additional land use reference data were provided on a shared basis from a concurrent study by Dairy NZ on the Jacobs River Estuary.

2.3 Method

2.3.1 Sampling

Estuarine sediment samples were collected by Southland Regional Council staff from the six monitoring sites in the New River Estuary plus a sample from the Oreti River deltal area (Site S19; Figure 1) by taking scrapings of the top 20 mm of sediment from several points around each site and combining these subsamples in a bucket before sealing an aliquot (~400 g) of the mixture in a zip-lock type plastic bag. Excess water was drained from the sample as the bag was sealed. This bag was rolled neatly and placed in a second zip-lock type plastic bag with the sample label on waterproof paper inside the outer bag, writing facing out. The bagged samples were placed in a chilli bin in a cool, dark place, without ice, pending transport to the laboratory for analysis.

River confluence samples were collected from the Oreti River system by taking surface sediment scrapings from material deposited on the edge of the river in the main channel below the confluence and in each upstream branch or tributary. Confluence samples were collected from above and below where Makarewa and Waikiwi Streams joins the Oreti River, and in the Makarewa and Waikiwi Streams.

Main river channel samples were collected at the Centre Bush and Wallacetown SOE monitoring sites on the Oreti River and from Kennington on the Waihopai River. Samples were also collected from each of the Otepuni, Waimatua and Mokotua streams. Additional samples of bank erosion material were collected along the Oreti River.

Land use reference samples were collected across the Oreti and Waihopai River catchments where they occurred and were augmented with samples collected from the concurrent Dairy NZ study of the Jacobs River Estuary on a shared basis.

Each sample was made up of 10 small, uniform sized subsamples spaced over an area of about 100 m^2 around the selected sampling site. The subsamples were combined in a bucket. Stones, woody debris and plant material were removed by hand picking. These “composite bulked” samples ensured the sample analysed was representative of the land use at that site.

All samples were bagged, labelled and stored as described above.

2.3.2 Sample processing

Drying: On arrival at the laboratory, all samples were sieved through a 2-mm mesh before drying in aluminium trays in a fan oven at 60°C. The drying samples were stirred part way through the drying process to prevent the material forming a hard “brick”. Plant material from the drain weeds were frozen to -20°C and then placed in a freeze drier until dry.

When the samples were dry, they were ground in a food blender to break up lumps and then sieved through a 2-mm mesh before being stored at room temperature in sealed plastic bags pending analysis. All results are expressed in terms of dry weight.

Bulk organic carbon isotopes: To remove inorganic carbonates, about 5 ml of 10% hydrochloric acid (HCl) was added to an aliquot of the dried sample (~5 g) in a 50 ml plastic centrifuge tube. When the effervescence had stopped, a further 2 ml of 10% HCl was added and the mixture was stirred with a plastic rod. This process was repeated until no further fizzing occurred on addition of acid. The sample was then allowed to stand overnight before rinsing.

To remove the acid, the mixture was diluted to 50 ml with deionised (Milli-RQ) water and vigorously shaken for 1 minute before centrifuging at 3000 rpm for 10 minutes. The liquid (acidic) phase was decanted into running water. This rinse step was repeated once more before the acidified sample was dried in a fan oven at 60°C. The dry acidified sample was ground to a fine powder with a pestle and mortar and sealed in a plastic screw-cap mailer tube for sending to a stable isotope facility for determination of carbon-13 isotopic values on a continuous flow, isotope ratio mass spectrometer (IRMS). The isotopic values of the bulk carbon were expressed in delta notation as $\delta^{13}C$, and the total organic carbon content in the sample was expressed as percent carbon (%C).

Compound-specific stable isotopes: To measure the fatty acid biomarkers in the sample, an aliquot (~10-20 g) of the dried sample (not acidified) was extracted twice in hot (100°C) solvent (dichloromethane) and high pressure (2000 psi) for 5 minutes in a Dionex ASE 200 accelerated solvent extractor. On cooling, the solvent extract was reduced to dryness in a 10 ml Kimax screw cap digestion tube. The fatty acids in the extract were then converted to their methyl esters using methanol with 5% boron trifluoride as the catalyst, at a reaction temperature of 70°C for 20 minutes in the sealed tube. The fatty acid methyl esters (FAMEs) produced were extracted from the reaction mixture with non-polar solvent (hexane). The hexane extract was reduced to dryness in a 2-ml screw-cap vial and sent to the Stable Isotope Facility at University of California at Davis, California, USA, for analysis on a gas chromatography-combustion-IRMS. The output from each sample was a suite of FAMEs with a $\delta^{13}C$ value for each FAME in the sample. The data also included an estimate of the amount of each FAME measured.

The $\delta^{13}C$ value of the methanol used in the conversion of the fatty acid to the FAME was also provided so that the $\delta^{13}C$ value of the FAME could be corrected for the methyl carbon added from the methanol and converted to the $\delta^{13}C$ value of the original fatty acid biomarker i.e., the CSSI value.

2.3.3 Data interpretation

Data interpretation used the mixing model “IsoSource” (Phillips and Gregg 2003). Although the analytical results provided CSSI values for all fatty acids in the samples, the CSSI technique was developed around the use of the most common fatty acids — Myristic acid (C14:0), Palmitic acid (C16:0), Stearic acid (C18:0) and Oleic acid (C18:1) — and the bulk organic carbon isotopic signatures. Consequently, only these compounds have been used in the modelling. The other fatty acids could be used but haven’t been tested for their reliability at discriminating between sources in a known mixture.

The concept behind the mixing model is that the isotopic signatures of each fatty acid and the bulk $\delta^{13}C$ value in the sources contributing to the sediment mixture are responsible for the isotopic signatures of each fatty acid and the bulk $\delta^{13}C$ value in the mixture. Consequently, if each of the sources were combined in the correct proportion, the resulting mixture would have the same isotopic signatures as found in the sediment mixture. The mixing model tries to find the combination of feasible solutions which best fit the isotopic balance in the mixture.

The selection of sources is limited by five geographical and logical constraints.

1. The isotopic biomarkers used must be present in all samples.
2. Downstream samples in a linear continuum cannot be sources for upstream sites. The exception is in tidal estuaries where sediment may be moved upstream by the flood tide.
3. If a land use does not occur in a catchment, it cannot be a source of sediment in that catchment (i.e., it must be possible for each source selected / tested to contribute to the mixture being assessed).
4. Where there are several possible sources, the closest sources to the sediment mixture are likely to be more important than those further away. The exception would be in a river with a large, slow-moving bed load.
5. If a potential source is not found to be present in a mixture, even though it meets the above geographical constraints, it is likely that land use is not eroding and is not a source of sediment.

In most modelling exercises, there will be low levels of most potential sources.

To deconstruct the sediment mixture into its component sources, the IsoSource mixing model calculates the isotopic signatures of all possible combinations of all sources. It then selects the combination proportions that come within a specified tolerance of the isotopic signatures of the fatty acids and bulk $\delta^{13}C$ in the sediment mixture. Each combination that falls within the selected tolerance range is regarded as a feasible solution and is counted in the value “n”. The perfect match would be a unique solution with n = 1. It is more likely that there will be a number of feasible solutions so that n > 1. The closer n is to 1 the greater the confidence in the proportional contribution estimated from the mixing model. High values of n (>> 1000+) may indicate a missing source or that there are several sources with very similar isotopic signatures and the model cannot separate them.

To improve the isotopic balance found by IsoSource, the tolerance can be reduced to only include the best matches or one or more sources can be changed and the model re-run. Sources that do not contribute to the sediment mixture will have a contribution at close to zero. These sources can be removed from the model run and the proportional contribution of the other sources will remain unchanged.

The major difficulty with any mixing model used for deconstructing a sediment mixture is the degree of uncertainty in the results. Because IsoSource uses a “brute force” approach to estimating the most likely feasible solutions, rather than calculating the solution, any of the solutions produced are feasible and could be correct. The model does produce 95% confidence levels and standard deviation (SD) estimates based on the number of times a particular solution occurs.

In the CSSI technique, the SD estimates are used as an indicator of the level of uncertainty for the model output about the mean. For example, a result may be that one source contributes a mean proportion of 50% to the sediment and has an SD of ± <1. That implies a 95% confidence range of 48-52% for that source i.e., there is high confidence that that source is present and contributing around 50% of the soil to the mixture. However, another source may contribute a mean proportion of 5% to the mixture and has an SD of ± 2.1. This implies a 95% confidence range of 0.8-9.2% for that source i.e., there is low confidence that that source is present and the result should be reported with caution.

2.3.4 Conversion to soil proportions

The output from the mixing model phase consists of a set of feasible isotopic proportions and SD values to describe uncertainty. These isotopic proportions only relate to the carbon content of the source not the whole source. These values need to be converted to source proportions to assess the contribution of each source to the mixture. To achieve this, it is assumed that the carbon content in a source is evenly distributed through the source. This means that the amount of whole source contributing as an isotopic proportion is a function of the carbon content in the source. Consequently, the amount of whole source is calculated from a linear scaling based on the %C value of each source in the mixture (Gibbs 2008).

The lower the %C in the source, the more of that source is required to produce the isotopic balance, and vice versa.

This approach does not use the %C value of the mixture and thereby eliminates the uncertainty associated with changes caused by decomposition processes in the mixture in the deposition zone.

3 Results and discussion

This study was required to determine (i) where the sediment in the estuary is coming from and (ii) the land uses contributing to that sediment. The answer to part (i) defines the relative proportions of sediment entering the New River Estuary from the five main sources: the Oreti River, the Waihopai River, the Otepuni, Waimatua and Mokotua streams and the coastal waters outside the estuary at each of the six monitoring sites inside the estuary, and the translocation of sediment between sites in the estuary. The answer to part (ii) must look at the land use contributions of soil to the Oreti and Waihopai Rivers as they flow through the catchment before they enter the estuary. These values can then be used to apportion the contribution of each land use to the estuarine sediment at each monitoring site in the estuary.

As a first approximation, the %C content of the sediment at the 6 monitoring sites in the estuary can be used to indicate where the terrigenous sediment may be coming from. Assuming that the proportion of land use sediment at each site will affect the carbon content in the sediment, it can be seen that the carbon content decreases rapidly away from the Waihopai arm (Figure 5). The percent carbon in the Waihopai River (3.13%) at the road bridge is 7 times higher than in the estuary at the river delta (0.43%) but only about 35% higher than the other two sites in the Waihopai arm at 2.29% and 2.35% C, respectively.

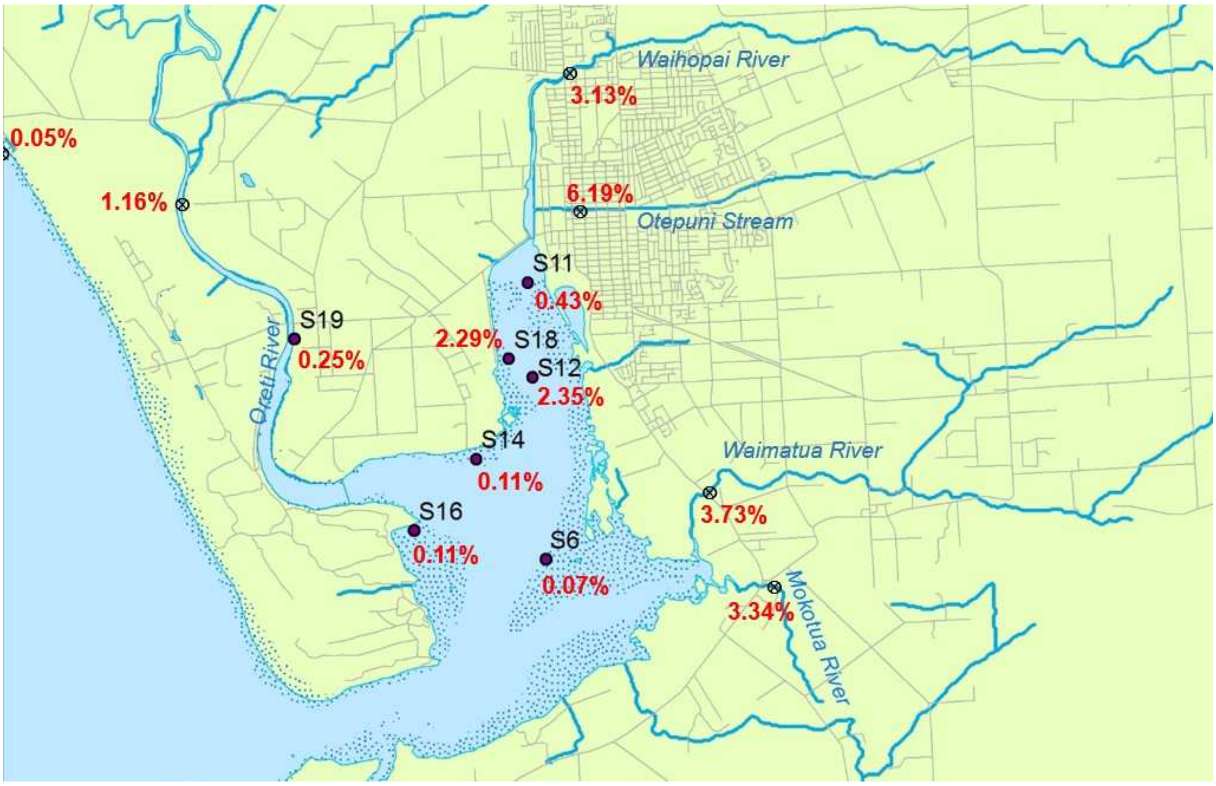

Figure 5: Spatial distribution of carbon in the New River Estuary sediment relative to potential sources. Monitoring site codes (black) and percentage carbon content (red) are given for the sites in the estuary, the river mouth deltas and the ocean endmember at Ocean Beach.

The carbon content in the Oreti River sediment (1.16%) is lower than in the sediment at the two enriched sites in the Waihopai arm. This implies that the majority of the catchment sediment is coming from the Waihopai River or the three smaller rivers and streams on the eastern shores of the estuary, which also have higher carbon contents (Figure 5).

The hydrodynamics in the estuary must also be considered. There are high tidal flows which can be 30-40 times that of the river flows (Environment Southland information: Estuary Health 2010-2011) and will not allow fine sediment to settle. At low water slack tide, the river inflows are confined to the channels between the intertidal flats and cannot deposit sediment on the intertidal flats. However, at high water slack tide, the river water is held back as a surface buoyant layer by the incoming tide moving up the middle of the estuary and would be dispersed as slow moving or nearly stationary water over the intertidal zones around the sides of the estuary. Under these conditions, fine sediment could deposit on the intertidal flats and could have come from any of the river inflows, although the carbon content suggest a greater contribution from the Waihopai and eastern rivers and streams than from the Oreti River.

During the rest of the tidal cycle current speeds may be fast enough to resuspend sediment that has already settled, causing it to be flushed out of the estuary or redistributed around the estuary. The current speeds associated with the large inflow from the Oreti River may be high enough to prevent fine sediment from settling in the estuary except around high water slack tide.

3.1 Where is the sediment in the estuary coming from

The CSSI technique was used to determine where the sediment was coming from by river inflow. The river samples immediately upstream of the estuary NRC 12 (Oreti), NRC 11 (Waihopai), NRC 21 (Otepuni), NRC 10 (Waimatua) and NRC 9 (Mokotua) were used as the primary catchment sources to the estuary. The outer sediment sample from the New River Estuary study (NRE S6) was used as the coastal source, because the carbon content of the actual coastal sample collected (JRL 601) was too low to measure all fatty acids. Justification for using this sample was the similarity of their enriched bulk δ^{13}C values, (JRL 601 = -22.66‰, NRE S6 = -23.18‰), which is the largest component of the isotopic balance.

The other monitoring site samples were used as secondary sediment sources, assuming complete mixing and a linear continuum from the river inflows towards the open sea outside the estuary as well as the possibility that estuarine hydrodynamics could redistribute sediment from any inflow to any location. The one exception to the redistribution concept was site NRE S19 on the Oreti River where the flow is likely to prevent sediment from estuary reaching that location even on a full flood tide. To account for the lower carbon content and the depleted bulk δ^{13}C value (-27.54‰) at site NRE S19, it was considered that the sediment at this and other sites in the Oreti River were more likely to be influenced by fine sediment from higher in the catchment. Consequently, carbon and isotopic values (0.54%C; bulk δ^{13}C -29.08‰) from the top of the catchment (site NRC 1) were used in the modelling of the Oreti River. Because of the extensive bank erosion close the mouth of the Oreti River, a bank erosion sample was also included as a separate source.

The results in Table 1 are the estimated proportional contributions of sediment to each of the six monitoring sites in the New River Estuary (Figure 5). These results indicate that the majority of the sediment in New River Estuary is derived from coastal sediment that has been entrained into the estuary over time. Because of the low %C content of the sediments in the estuary, the background coastal sediments must occur in large proportions to meet the isotopic balance estimated by the mixing model.

Table 1: **Modelled source contributions to New River Estuary.** The number beneath each source name is the site code number (refer to Figure 5 or Appendix). Site S6 has been used as the coastal waters source (see text). The data given are source contributions (%) to each site and values in parentheses below are the standard deviation of the isotopic proportions as an indication of uncertainty in the source proportions. Sources marked * were detected at low proportions (<1%). The value "n" is the number of feasible solutions produced using the selected sources and is an indicator of confidence (see text). Note: the Otepuni Stream flows into the Waihopai River upstream of site S11 and was not detected as a major sediment source.

Site			**Waihopai River**	**Waihopai delta**	**Oreti River**	**Upper Oreti**	**Waimatua**	**Mokotua**	**Inner harbour**	**Outer Harbour**
	Code	**n**	**(NRC-11)**	**(S11)**	**(NRC-12/19)**	**(NRC-1)**	**(NRC-10)**	**(NRC-9)**	**(S18)**	**(S6)**
New River	**S11**	4	*			30.3				69.7
Estuary						(2.5)				(2.5)
New River	**S18**	52	9.8	84.0	3.7	2.5				*
Estuary			(3.5)	(1.7)	(2.5)	(2.3)				
New River	**S12**	3634	*	*	5.2		4.9	*	*	88.3
Estuary					(11)		(19.3)			(3.4)
New River	**S14**	381	*	*	*	*	*	*	*	99.5
Estuary										(0.8)
New River	**S16**	1441	*		*	1.5			*	97.4
Estuary						(3.3)				(4.8)
New River	**S6**	1								100.0
Estuary										(0)

While the majority of the sediment in the New River Estuary is sand derived from coastal sources carried into the estuary by tidal currents, this is the background upon which the sediment derived from land erosion in the catchment has been deposited. At site S11 about 30% of the total sediment at that location came from the upper Oreti River, while at site S18 the sediment came from the Waihopai River delta (~84%), the Waihopai River (~10%) and the Oreti River (~6%). At site S12, about 12% of the sediment came from terrigenous sources, with the Oreti River contributed around 5% of the sediment and another ~5% coming from the Waimatua and Mokotua River inflows. There were high levels of uncertainty around the terrigenous sources contributing to site S12 and either the Waimatua or Mokotua River could be the source, or it could be a mixture of both.

For these and other sources to deposit on the intertidal flats, the tide has to be high or the rivers have to be in flood so that the intertidal flats are submerged. Around high tide, fine sediment from any of the river inflows can be moved around the estuary, flocculating on contact with the sea water and settling before the tide ebbs. At other stages of the tide, the fine sediment will be carried within the river channels in the through to intertidal flats (Figure 6) and discharged out to sea.

Figure 6: New River Estuary at low tide showing the main river channels. Dark water from the Mokotua River (right hand side) flows directly to the estuary mouth. [Google Earth image 16/9/2009].

These results are consistent with a short residence time estuary where sediment infilling has reduced the storage capacity of the estuary, fetch-limited waves are effective mechanisms for sediment resuspension and tidal flushing can eject the majority of the fine riverine sediments on each tidal cycle. There are likely to be localised deposition zones from which sediment can get redistributed by tidal and wave action. Consequently, there will be sediment exchange between the six estuary monitoring sites.

3.2 What land uses are contributing sediment to the estuary

3.2.1 Land use contributions to the river inflows

For this part of the assessment, the contributions of land use soils to the Oreti and Waihopai Rivers were modelled by comparing the CSSI values from the land use samples (Figure 7) with the CSSI values at each river sampling site starting at the SOE site at Centre Bush (NRC 1) and working downstream to the lowest site at NRC 12 on the Oreti, and at sites NRC 4 and NRC 11 on the Waihopai (Figure 8).

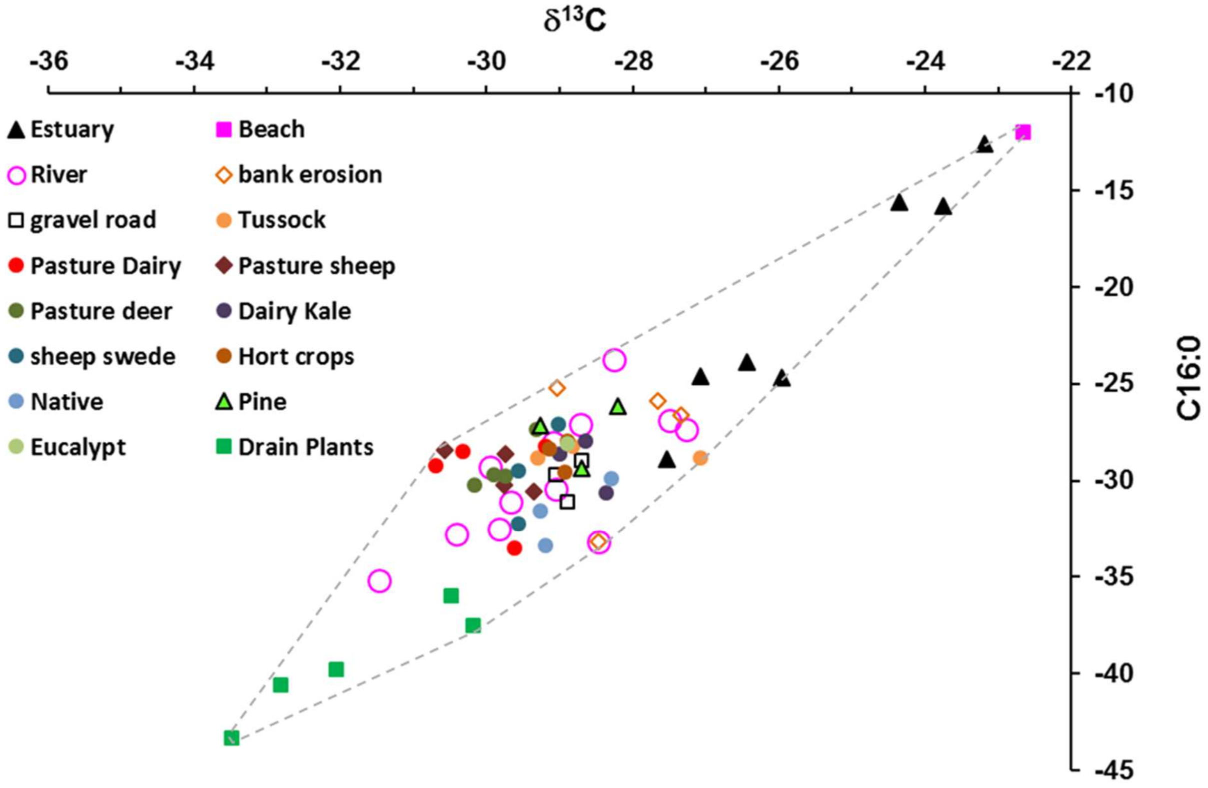

Figure 7: Example plot of the bulk $\delta^{13}C$ isotopic values versus the palmitic acid (C16:0) biomarker isotopic values for all samples (sources and mixtures) collected for the New River Estuary study. (Black triangles represent the estuarine samples, red open circles represent the river samples, pink square represents the ocean beach sample. Broken line represents a polygon drawn through the outer source data that encloses all the mixtures – see text.)

A wide range of land use sources were tested and modelled for each site using sediment from each river sampling site as the sediment mixture for the mixing model. Geographically close potential sources were tested first and then other land use types were included. As the assessment moved downstream, the immediate upstream river sampling site was assumed to be a valid source for the downstream site.

Source selection and isotope selection were passed on the polygon assessment where the isotopic signature of the mixture must lie within a polygon connecting the isotopic signatures of the sources. For example, plotting the bulk $\delta^{13}C$ against the $\delta^{13}C$ values of palmitic acid (C16:0) (Figure 7), show that the isotopic values of the sediment mixtures in the estuary and rivers all fall between the isotopic signatures from the ocean beach sample and the drain plants. These sources are two of the "endmembers" for the mixing model. Similar plots made for other isotope combinations (not shown) also confirm that these sources are endmembers. Further examination of the plotted data (Figure 7) show that the river sample data (red open circles) all lie within the bounds of a polygon drawn through the outer source sample data (grey broken line). This indicates that the isotopic values of the river mixtures could all be reproduced from a mixture of the isotopic values of the land use sources and that there are unlikely to be any missing sources. Modelling used at least three different isotopes.

The estuarine data (black triangles) also lie within the polygon of source data but closer to the ocean beach sample, consistent with the findings that most of the sediment at those sites was associated with coastal rather than terrigenous material (Table 1).

The ability to discriminate between different sources contributing to sediment mixtures requires measurable differences in the CSSI values of each source. While the isotopic values of some replicate land use samples were similar, which would allow an average value to be used in the modelling, others were quite different, possibly reflecting a relatively recent change in land use. For example, it can be seen that there were three different values for 'pasture dairy' (red dots, Figure 7). Two of these data were very similar to 'pasture sheep', which may indicate a recent change from sheep to dairy at those locations, consistent with the intensification of dairy in the catchment. Of the other two 'pasture dairy' samples, one was similar to 'sheep swede' and the other was similar to 'Hort crops', the latter being potatoes.

If there has been a recent change in land use for a source, it is possible that the CSSI values from that source will be a mixture of the new with the old land use resulting in an intermediate value proportional to the dilution effect of each contributing source. For example (from observations in other studies), this transition phase is usually less than a year when maize is planted in pasture because of the strong isotopic signature from the maize. Returning maize to grass by planting through, produces an intermediate signature which may be present for at least two years before the grass signature becomes dominant. The transition phase for dairy replacing sheep on pasture may be several years since the sheep signature has been establish in the soil for many years and change in land use practice to dairy farming will take time have a large effect. Consequently, to allow for the possibility of intermediate values being important, the modelling of each river site used the source data closest to that site rather than an average of the data from the four source samples.

Note that the 'gravel road' data (open black squares) cluster within the polygon close to 'pine', 'eucalypt', 'Hort crops' and 'dairy kale' data. This may reflect the soil dropped from vehicles using the roads or the proximity of the road material quarry to those land uses.

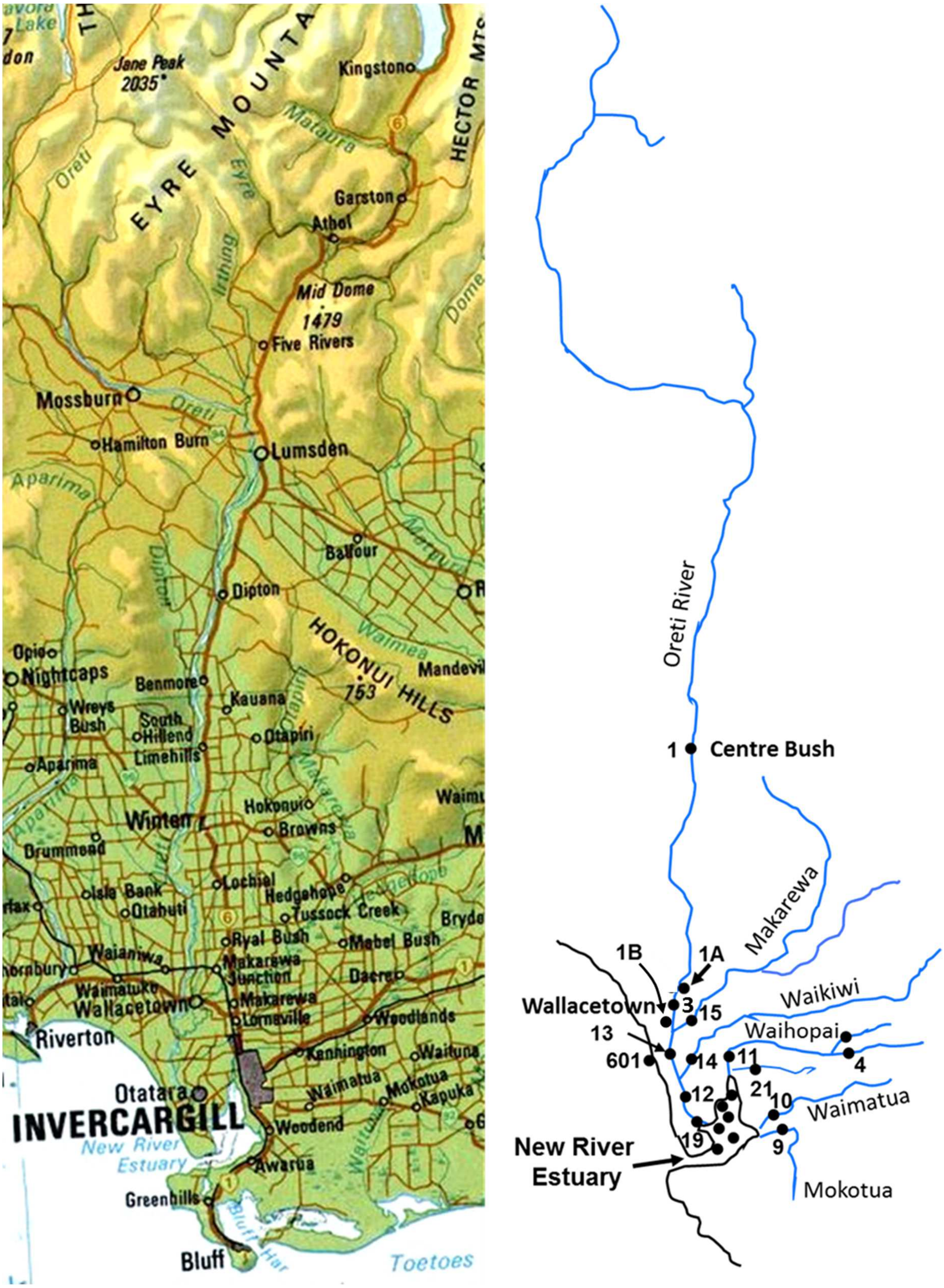

Figure 8: **Map and schematic diagram of the Oreti and Waihopai River systems** showing the relative locations of the river sampling points. The topographical map indicates areas of hill country and lowland river flats.

Oreti River system

Bank erosion samples were collected on both sides of the Oreti River (1A = true left; 1B = true right) because there was a visual difference in the appearance of the bank material on opposite sides of the river (Figure 9). There were small amounts of most land use sources in each river sample but at very low levels. The results report only the larger sources and even those were sometimes reduced to minor contributions when the isotopic proportions were converted to soil proportions.

Figure 9: Extensive bank erosion on the Oreti River. NRC-1A shows the erosion on the true left bank upstream of Wallacetown; NRC-1B shows erosion on the true right bank between Wallacetown and the Makarewa River inflow. [Photo date 22/05/2013].

The analysis of the Oreti River data began at the upstream site at Centre Bush (NRC-1) and worked downstream. River confluence analyses used the sediment contribution from the upstream sites in the main stem of the Oreti and the tributary to determine the contribution of the tributary to the main stem of the Oreti River below the confluence (Table 2).

To improve the discrimination between sources contributing to a mixture, other fatty acid biomarkers are used in the modelling. Where possible, the stable isotopic values used in the modelling were bulk $\delta^{13}C$ and the $\delta^{13}C$ values of palmitic acid (C16:0), oleic acid (C18:1w9c), stearic acid (C18:0) and myristic acid (C14:0). The bulk carbon, palmitic acid and oleic acid are the primary isotopes around which the CSSI technique was developed (Gibbs 2008).

Table 2: Proportional contributions from upstream sites to the downstream site. The two sources below a tributary confluence are the proportion contributions from main river channel upstream of the confluence and the tributary.

Site	Code	Upstream contribution	
		% (Source)	% (Source)
Oreti River (Centre Bush)	**NRC-1**		
Oreti River (Wallacetown)	**NRC-3**	**65.5** (NRC-1)	
Makarewa River (Tributary)	**NRC-15**		
Oreti River (below Makarewa)	**NRC-13**	**46.4** (NRC-1)	**45.5** (NRC-15)
Waikiwi River (Tributary)	**NRC-14**		
Oreti River (below Waikiwi)	**NRC-12**	**1.4** (NRC-1)	**1.8** (NRC-13)
Oreti River (Upper estuary)	**S19**	**92** (NRC-1)	
Waihopai River (Kennington)	**NRC-4**		
Waihopai River (Mouth)	**NRC-11**	**16** (NRC-4)	

The results in Table 3 are the estimated proportional contributions of sources to each of the sampling sites on the Oreti River (Figure 9) as well as the Waihopai River, Otepuni Stream and Waimatua and Mokotua Rivers. For the Oreti and Waihopai Rivers, the upstream mixture becomes a source for the next sampling site downstream. All river sediment results were converted to their appropriate land use soil source proportions before summation in Table 3. This process used the upstream proportional contribution of each river (Table 2) to convert the river source to the equivalent land use in the sediment at that site.

For example, at site NRC-1 (Table 3), the source proportions were sheep pasture 74%, dairy pasture 2.5% and deer pasture 23.5%. At the next site downstream, Site NRC-3, 65% of the sediment came from the upstream site (NRC-1) (Table 2) and 34% came from bank erosion plus some minor sources. When the NRC-1 contribution is converted into its land use component proportions (sheep pasture 74%, dairy pasture 2.5% and deer pasture 23.5%), the sediment at site NRC-3 contains 48% sheep pasture, 1.6% dairy pasture and 15.8% deer pasture. These sediment contributions have been carried down the river by the bed load transport mechanisms. The ~34% bank erosion is a new source of sediment that has entered the river between the two sites, NRC-1 and NRC-3.

Site NRC-3 now becomes a source of sediment for the next site downstream, site NRC-13, together with the sediment from the tributary, NRC-15). When the modelling was done, it was found that the sediment from sight NRC-3 was a minor source and bed load from site NRC-1 was the major upstream source (Table 2).

The results in Table 3 are separated in the sources most commonly found during the modelling phase and reported as percentage contribution to the sediment at the site specified. Results for the Oreti River have been separated from the Waihopai and other river results for ease of discussion.

Table 3: Mean source proportional contributions (%) by land use to the Oreti, Waihopai and other rivers flowing into the New River Estuary. Values in parentheses are standard deviations of the isotopic proportions, as an indication of uncertainty. (* this source was detected in the sample at low level and high uncertainty).

Site	**Code**	**n**	**Pasture** (Sheep)	**Swede** (Sheep)	**Pasture** (Dairy)	**Kale** (Dairy)	**Pasture** (Deer)	**Bank Erosion**	**Horticulture** (Potatoes)	**Drain weeds** (Watercress)	**Tussock Grassland**	**Forest** (Native)	**Forest** (Exotic)
Oreti River (Centre Bush)	**NRC 1**	2	74 (0)	*	2.5 (3.5)	*	23.5 (3.5)				*	*	
Oreti River (Wallacetown)	**NRC 3**	71	48.4 (1.8)	*	1.6 (1.8)	*	15.4 (1.8)	33.9 (1.6)					*
Makarewa (Tributary)	**NRC 15**	210	1.4 (1.9)	93.1 (3.3)	*	1.1 (1.6)	*	1.1 (1.0)	1.90 (2.4)	*			
Oreti River (Main channel)	**NRC-13**	576	35.5 (2.6)	42.4 (1.2)	1.2 (2.6)	0.5 (1.2)	11.1 (2.6)	7.5 (2.1)	0.9 (1.2)	*			
Waikiwi (Tributary)	**NRC-14**	283	1.7 (1.7)	87.6 (3.0)	*	2.5 (1.8)	*	1.1 (0.8)	2.26 (2.3)	3.3 (0.7)			
Oreti River (Mouth)	**NRC-12**	212	1.65 (0.4)	0.77 (1.1)	0.06 (0.4)	88.8 (2.1)	0.52 (0.4)	4.6 (0.5)	0.02 (1.1)	3 (1.5)			
Oreti River (Upper estuary)	**S19**	84	68.07 (4.2)	*	2.30 (4.2)	*	21.62 (4.2)	7.90 (2.2)	*	*			
Waihopai (Kennington)	**NRC-4**	4	2.1 (0.6)	*	23 (0.6)			*	67.7 (0.8)	7.3 (0)			
Waihopai (Mouth)	**NRC-11**	1	8.8 (0.6)	*	3.7 (0.6)	52.9 (0)		*	33.4 (0.8)	1.2 (0)			
Otepuni (Channel)	**NRC-21**	7	1.0 (0.8)	97.2 (0.7)	*	*			*				
Waimatua (mouth)	**NRC-10**	40	*	*	11.2 (1.9)	3.1 (2.0)			84.7 (3.4)	*			
Mokotua (mouth)	**NRC-9**	893	*	1.2 (3.7)	33.0 (2.5)	5.1 (2.5)			60.3 (4.2)	*			

The n values for the Oreti River sites (Table 3) ranged from 2 to 576, which suggests very high (2) to medium (576) confidence in these results. Testing a wide range of potential sources could not improve on these results. In almost all of these samples there were indications of pine forest and native forest sediment but at very low levels. Gravel roads were occasionally detected but were not the major sources of sediment that have been found in overseas studies (e.g., Motha et al. 2003). Drain weeds, where detected, are interpreted to indicate that there had been recent clearance of drains on the farmland upstream of that sampling site.

> **Error terms:** Values given in Table 3 are the mean proportional contributions as calculated. The apparent precision implied by the decimal place is not real but allows summation of the source proportions at each site to equal ~100%. The error term for each value is twice the standard deviation given in parenthesis below the value. The mean values are given in the following discussion for convenience and clarity with the caveat that each value has a range of possible values and is not just the mean.

Sediment in the upper Oreti River at Centre Bush (site NRC-1) came mostly from sheep pasture (74%) with deer farming (23.5%) and a small contribution from dairy pasture (2.5%) (Table 3). The Dairy pasture contribution had a high uncertainty giving a possible range from 0-9.5%.

At Wallacetown (site NRC-3), there had been no apparent direct input of sediment attributable to sheep farming below Centre Bush (site NRC-1) and the sheep pasture soil contribution of 48% was attributable to bed load transport of sediment from the upstream site at Centre Bush. Similarly the dairy pasture and deer pasture materials were from bed load sediment transport. In contrast, bank erosion (34%) was a new major source to this site. This is consistent with observations of eroding banks (Figure 9) between these two sites and the reason for collection bank erosion samples at the location shown (Figure 8).

The sediment in the Makarewa River (true left bank) was mostly from sheep (94.5%) consistent with observations of land use in the immediate area of the sampling site (Figure 10).

Figure 10: Sheep farming beside the Makarewa River.

Below the confluence of the Makarewa River with the Oreti River, site NRC-13, the sediment sources were approximately equal at ~46% from both the Makarewa River and the upstream sources in the Oreti River. However, the major Oreti River source was NRC-1 at Centre Bush. This implies that bed load transport may be the major transport mechanism in the Oreti River and the bank erosion source was a local effect due to a plume of sediment carried along the side from the eroding banks upstream of Wallacetown.

Sediment in the Waikiwi River was also mostly from sheep (89.3%) with small contributions from dairy, deer, bank erosion and drain clearance. However, below the confluence of the Waikiwi River with the Oreti River, the main source of sediment was dairy (89%) mostly from dairy kale or swede (Figure 11). As this land use was relatively localized, this also suggests that the apparent impact on the Oreti Rive may have been a localized sediment accumulation along the true right side of the river rather than a generalised sediment source contribution to the whole river.

Figure 11: **Dry stock grazing on swedes near the Oreti River below Wallacetown.**

This concept is supported by the results from site S19 in the upper estuary in the Oreti River arm, which indicate that more than 90% of the sediment came from sources higher up the Oreti River with sediment isotopic signatures similar to those at Centre Bush (NRC-1). The remainder came from bank erosion sediment from the true left bank.

When interpreting these results, it is important to consider the hydrology and hydrodynamics of the Oreti River. As a large broad gravel-bed river it is reasonable to expect tributary inflows will be slow to mix through the whole river. Consequently, the sediment from tributaries are likely to deposit on the river edge immediately downstream of each inflow. Sediment plumes from the Makarewa and Waikiwi River inflows can be seen along the true left bank of the Oreti River downstream of each confluence (Figure 12).

Figure 12: Sediment plumes from the Makarewa and Waikiwi Rivers cling to the shore on the true left bank of the Oreti River rather than mixing through the whole river below each confluence. [Google Earth images flown 22/08/2013].

The deposition zones associated with both the Makarewa and Waikiwi River inflows are in the tidally influenced zone of the Oreti River and this could also strongly influence how and where the sediment deposits. Fine sediment will be slow to settle from flowing water. Under normal river flows, the current speed is likely to be too high for the silt to settle. However, around high tide the slack water period allows sedimentation of Makarewa and Waikiwi River water in their downstream reaches and in the Oreti River around the confluences. At all other times the fine suspended sediment from these tributaries will be confined to the left bank of the Oreti River (Figure 12). This could bias the results of samples collected below these tributaries and may explain the high proportion of sediment from the Makarewa River in the Oreti River at site 13 (Table 2).

Waihopai, Waimatua and Mokotua Rivers

Assessment of the sediment sources contributing to the Waihopai River began with evaluation of all possible sediment sources entering the river upstream of Kennington (site NRC-4). The modelling results indicated that largest sediment source to the Waihopai River was associated with horticultural crops (68%) with the main isotopic signature being potatoes. Of the remainder, ~23% was attributable to dairy pasture, ~7% to drain clearance and ~2% to sheep pasture (Table 3). At the downstream site (NRC-11) near the estuary, about 56% of the sediment was attributable to dairy farming with stock grazing kale being the main component (~53%). Other sources included horticulture potatoes (~33%), sheep pasture (~9%) and drain clearance (~1%) (Table 3).

In the Otepuni Stream, the sediment source was attributable to sheep swede land use (~97%). In contrast, the main source of sediment to the Waimatua and Mokotua Rivers was attributable to horticulture potatoes, ~85% and ~60%, respectively. The remaining sediment sources were mostly associated with dairy farming with ~14% contribution to the Waimatua River and ~38% contribution to the Mokotua River (Table 3).

Table 4: Mean source proportional contributions (%) of terrestrial soil to sediment in the New River Estuary by land use. Values in parentheses are standard deviations of the isotopic proportions, as an indication of uncertainty. (* this source was detected in the sample at low level and high uncertainty.)

Site			**Pasture**	**Swede**	**Pasture**	**Kale**	**Pasture**	**Bank**	**Horticulture**	**Coastal**
	Code	**n**	(Sheep)	(Sheep)	(Dairy)	(Dairy)	(Deer)	**Erosion**	(Potatoes)	**(S6)**
New River	**S11**	4	22.4	*	0.8	*	7.1			69.7
Estuary			(2.5)		(1.7)		(3.5)			(2.5)
New River	**S18**	52	24.0	*	2.6	5.2	7.4	0.3	3.3	58.5
Estuary			(3.5)		(2.5)	(2.3)	(2.3)	(1.7)	(2.3)	(2.5)
New River	**S12**	3634	3.6	*	0.8	0.2	1.2	0.4	4.1	90.0
Estuary			(2.0)		(2.5)	(1.7)	(2.5)	(1.7)	(2.3)	(3.4)
New River	**S14**	381	*	*	*	*	*	*	*	99.5
Estuary										(0.8)
New River	**S16**	1441	1.1		0.1		0.4		*	97.4
Estuary			(3.3)		(3.3)		(3.3)			(4.8)
New River	**S6**	1								100.0
Estuary										(0)

3.2.2 Sediment sources in the estuary by land use

The sediment sources identified in the CSSI technique were assessed in terms of specific land uses at each sampling point down the Oreti River and the Waihopai River and upstream from the estuary in the Otepuni Stream and the Waimatua and Mokotua Rivers (Table 3). These source proportions were used to assess the source contributions by inflow at each of the six monitoring sites in the New River Estuary (Table 1) and convert these values into land use proportions (Table 4). Modelling showed that around 65-85% of the terrigenous sediment in the estuary was derived from bank erosion. This material carried the underlying signatures of the original land use before that soil was deposited in the river bank and that deconstruction was applied to the bank sediment to show the actual sediment sources (Table 4). Consequently, the bank erosion component in Table 4 is small and represents that material for which a source could not be assigned.

The majority of the sediment in the New River Estuary is old sediment deposited by floods and redistributed by estuarine processes including wave resuspension and tidal flows, and is not related to land use either as a source or to land use practices. To examine the proportional contribution of different land use to the estuary, the underlying coastal sediment source proportions were removed and the residual contemporary soil source proportions from Table 4 were scaled total 100% (Table 5).

Table 5: Mean % terrigenous source soil contributions to the estuarine sampling sites after removal of the underlying coastal sediment component. The data is derived from **Table 4** after combining all the sheep components as pasture (sheep) and the dairy components as pasture (dairy). **(**Values in parentheses are standard deviations of the isotopic proportions, as an indication of uncertainty). A value of 0 indicates that source was below the discrimination level in the mixing model. Data values rounded to reflect the high uncertainty.

Site	**Code**	**n**	**Pasture (Sheep)**	**Pasture (Dairy)**	**Pasture (Deer)**	**Bank Erosion**	**Horticulture (Potatoes)**
New River	S11	4	75	3	23	1	0
Estuary			(2.5)	(1.7)	(3.5)	(0.3)	
New River	S18	52	56	18	18	1	8
Estuary			(3.5)	(2.3)	(2.3)	(0.3)	(2.3)
New River	S12	3634	35	9	15	4	38
Estuary			(2.0)	(2.5)	(2.5)	(1.7)	(2.3)
New River	S14	381	100	0	0	0	0
Estuary			(0.8)				
New River	S16	1441	53	5	19		10
Estuary			(3.3)	(3.3)	(3.3)		(3.3)
New River	S6	1	0	0	0	0	0
Estuary							

The data in Table 5 are indicative only, because the data transformed from total sediment proportions to proportions of terrigenous soil only, have increasing uncertainty as the proportional contribution of terrigenous soil in the total sediment decreases. For example, the value of 100% for Pasture (sheep) at site S14 is potentially correct but was at the limit of discrimination by the method due to the large proportion of coastal sediment at that site, and is therefore not included in the discussion below. Effectively, only three sites, 11, 12, and 18, have sufficient soil proportions in the total sediment to be assessed in this way with confidence.

With this in mind, the soil proportion data (Table 5) show that most of the recent terrigenous sediment deposited in the Waihopai arm of New River Estuary is associated with sheep farming (35-75%) and deer farming (15-23%), and sediment associated with dairy farming (3-18%) was the third largest sediment component (Table 5, Figure 13). Undefined bank erosion was a minor component in the estuarine sediment but horticulture soils associated with potato growing was a substantial component (38%) of the contemporary sediment at site S12 (Table 5; Figure 13).

While these five land uses contributed the most soil to the estuarine sediment, almost all other land use materials were detected albeit at very low levels. The results for these five land uses effectively swamp the less dominant land use source soils.

From further examination of the sources of sediment, it is apparent that the sediment from dairy farming has come from the lower reaches of the Waihopai and Mokotua Rivers while the sheep and deer farming soils have come from the Oreti River, with most of that being attributable to the upper Oreti River. This implies that fine sediment entering the estuary from the Oreti River is being carried into the Waihopai arm of the estuary on the rising tide and then settling on the intertidal flats most likely during high water, slack tide.

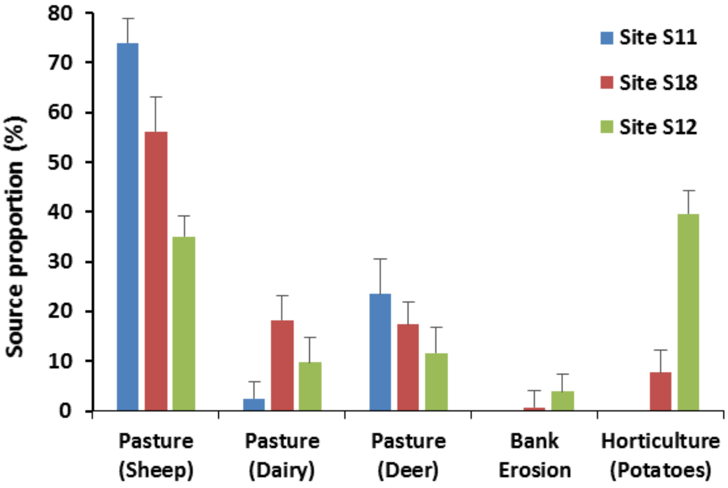

Figure 13: **Mean total non-estuarine catchment soil source proportions** at three sites in Waihopai arm of New River Estuary scaled to total 100%, based on the data in Table 4. The large proportions of sediment from coastal and estuarine sources were excluded in order to determine the sources of recent deposits by catchment land use. Error bars are twice standard deviation of isotopic proportions, only positive value shown.

The implied sediment distribution pattern (Figure 13) is reasonable when considering the relative sizes of the Oreti and Waihopai Rivers — the mean flow in the Oreti River at Wallacetown is 26.9 $m^3 s^{-1}$ while the mean flow in the Waihopai River at Kennington is 4.3 $m^3 s^{-1}$ (Southland Regional Council online river flow data). However, the lack of sediment input directly attributable to the Makarewa River (mean flow ~18 $m^3 s^{-1}$) in the Oreti River at the upper estuary site (S19) (Table 3) may indicate mixing in the lower Oreti River causing dilution below discrimination level. Both the Makarewa and Waikiwi Rivers sediment were dominated by sediment attributable to sheep farming at 94% and 88%, respectively (Table 3), but the sheep farming isotopic signature may have merged with the sheep farming isotopic signature already in the Oreti River from higher up the catchment. Almost all the sediment at site S19 is attributable to sources in the upper Oreti River above Centre Bush. This implies that fine sediment was being carried through the whole river system and that the majority of the erodible land is or was used for sheep farming.

Flood events will be important sediment transport mechanisms for fine to course sediment. For example, the flood event of 26 April 2010 had peak flows of >1200 m^3 s^{-1} in the Oreti River, >260 m^3 s^{-1} in the Makarewa River and >60 m^3 s^{-1} in the Waihopai River. These disproportionate inflows to the New River Estuary during such events would favour sediment from the Oreti River being the main source on the intertidal flats, consistent with the CSSI results. The bed load material carried down the rivers in such events would be the main cause of the estuary infilling.

4 Conclusions

The majority of the sediment in the New River Estuary comprises old sediment and coastal material delivered by flood flows and reworked by waves and tidal currents. Recent soil contributions to the sediment deposited on these coastal and estuarine sediments in the Waihopai arm of the New River Estuary are most likely to have come from the Oreti River during high flow events. The dominance of sheep signature in these sediments appears to be consistent with the large areas of the upper catchment still in sheep farming, despite the conversion of large areas of the catchment to dairy farming.

Contemporary sediment attributable to dairy farming appeared to come from the lower reaches of the Oreti River and the Waihopai and Mokotua Rivers. The presence of horticulture soils mainly potatoes may indicate exposed cultivated land used for cropping or a strong background soil CSSI signature from land that was recently used for growing potatoes.

The lack of a strong source of sediment from dairy farming despite rapid dairy intensification in the catchment implies that much of the dairy conversion has occurred on flat land where runoff to the rivers is minimal and has not occurred and/or the sediment has yet to reach the rivers from these farms.

Based on these findings, the cause of the apparent increased sedimentation rates in the Waihopai arm of the estuary are more likely to reflect a change in climatic effects such as the higher rainfall 1985 (section 1.2). Because of past infilling and possible reclamation of New River Estuary there is reduced storage capacity to allow fine sediment to settle in the estuary. Consequently, under normal flow conditions the fine sediment will be flushed out of the estuary. This implies that the majority of the sediment accumulating in the estuary may be associated with high rainfall events and concomitant high flow events in the rivers. Under flood flow conditions, fine sediment from the Oreti River is likely to be held up in the Waihopai arm allowing it to settle there.

5 Acknowledgements

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Appendix A Stable Isotope data

Stable isotope, compound-specific stable isotope and %C data by land, used in the modelling of the estuary and river sites. Empty cells indicate missing data where the fatty acid peak has been too small for the analyst to measure the isotopic value,

Location (NZMT2000)		Site ID	Land Use		Bulk Carbon	Myristic	Palmitic	Palmitoleic	Stearic	Oleic	Arachidic	Behenic	Lignoceric
Easting	Northing	Code	description	%C	$\delta^{13}C$	c14:0	C16:0	c16:1w9c	c18:0	c18:1w9c	c20:0	c22:0	c24:0
2143509	5407531	JRL_601	Beach	0.05	-22.66	-29.86	-12.00	-31.94	-30.60			-28.35	-28.72
2151681	5404375	NRE S6	Estuary	0.07	-23.18	-20.16	-12.56	-15.41	-16.20	-13.94			
2151324	5409946	NRE S11	Estuary	0.43	-26.44	-26.75	-23.87	-26.59	-19.37	-23.25		-24.35	-25.37
2151421	5408036	NRE S12	Estuary	2.35	-25.95	-27.49	-24.68	-31.28	-29.37	-28.17	-30.32	-29.87	-28.92
2150284	5406393	NRE S14	Estuary	0.11	-24.36	-21.88	-15.60	-18.06	-20.50	-20.48			
2149037	5404953	NRE S16	Estuary	0.11	-23.76	-18.19	-15.78	-18.85	-18.56	-15.80		-25.44	-21.40
2150944	5408406	NRE S18	Estuary	2.29	-27.07	-26.49	-24.59	-30.53	-28.39	-28.07	-29.93	-29.09	-28.93
2146630	5408806	NRE S19	Estuary	0.25	-27.54	-33.90	-28.88	-28.16	-23.27	-27.55	-26.43	-23.89	-25.76
2147206	5451284	NRC1	River	0.54	-29.08		-28.02	-31.00	-24.38	-33.60	-30.18	-29.59	-29.45
2146416	5444336	NRC2	River	0.08	-28.71		-27.10					-23.39	
2145321	5420997	NRC3	River	1.27	-28.27	-27.31	-23.72	-24.57	-26.46	-25.33	-30.12	-28.20	-26.81
2163293	5414346	NRC4	River	1.85	-30.41	-35.36	-32.78	-39.45	-34.04	-33.19	-33.83	-34.87	-34.51
2156036	5403826	NRC9	River	3.34	-27.49	-25.12	-26.87	-31.64	-31.31	-29.21	-30.92	-32.37	-32.01
2154946	5405715	NRC10	River	3.73	-27.27	-27.25	-27.38	-33.50	-30.68	-28.95	-28.64	-30.12	-30.72
2152105	5414096	NRC11	River	3.11	-29.04	-32.71	-30.45	-23.82	-32.71	-33.22	-32.26	-32.37	-32.18
2144368	5411509	NRC12	River	1.16	-28.47	-34.48	-33.19	-36.29	-35.62	-32.03	-35.45	-34.93	-32.46
2143738	5413260	NRC13	River	1.42	-29.67	-35.00	-31.13	-42.75	-30.08	-30.69	-33.28	-31.59	-31.75
2146493	5413613	NRC14	River	4.54	-31.47	-40.11	-35.16	-52.18	-32.35	-33.10	-31.17	-32.07	-32.78
2145088	5416426	NRC15	River	1.63	-29.83	-33.96	-32.50	-44.46	-32.37	-29.75	-32.90	-33.04	-32.98
2152415	5411433	NRC21	River	6.19	-29.96	-34.93	-29.27	-38.75	-26.70	-30.78		-26.92	-29.11
2145472	5420825	NRL1a	Bank Erosion	0.47	-29.04		-25.22	-30.67	-25.77	-35.77	-33.03	-31.09	-28.39
2144074	5417661	NRL1b	Bank Erosion	1.24	-27.34	-32.18	-26.60	-31.29	-27.54	-24.32	-30.33	-30.00	-30.20
2157902	5425391	NRE_11	Bank Erosion	1.38	-28.46	-32.51	-33.15	-32.89	-32.29	-25.77	-33.77	-35.15	-35.44
2158539	5443251	NRE_5	Bank Erosion	1.71	-27.66	-27.76	-25.89	-27.93	-32.27	-10.26	-30.85	-29.95	-30.43
2145348	5413624	ORL 501	Gravel Rd	1.50	-28.90	-39.95	-31.11	-25.49	-32.95		-30.01	-29.63	-28.81
2147794	5436814	ORL 502	Gravel Rd	2.63	-28.70	-34.24	-28.97	-28.60	-29.41	-23.02	-31.79	-32.05	-32.01
2156222	5425596	ORL 503	Gravel Rd	1.48	-29.05	-29.66	-29.70	-25.01	-32.41	-25.55	-32.28	-31.47	-31.36
2153783	5414403	NRL 501	Stormwater sump	0.91	-27.78					-19.71		-14.36	
2151771	5413275	NRL 502	Stormwater sump	10.05	-28.66					-34.11		-41.58	-35.85
2152072	5411665	NRL 503	Stormwater sump	4.22	-28.01				-35.77			-29.51	
2153558	5408936	NRL 504	Stormwater sump	7.01	-26.87	-34.90		-42.93	-27.89		-34.64	-35.66	-32.42
2134572	5531450	NRL TUS1	Pasture/Tussock	1.11	-27.08	-33.92	-28.84	-30.33	-29.02	-23.48	-33.38	-31.50	-31.21
2127559	5484686	JRL TUS	Pasture/Tussock	8.41	-28.81	-33.25	-28.20	-29.55	-29.86	-24.41	-34.39	-31.67	-30.49
2127618	5484707	JRL Strm Sed TUS	Pasture/Tussock	4.53	-29.30	-30.12	-28.84	-25.45	-31.22	-27.46	-33.51	-33.98	-31.48

Stable isotope, compound-specific stable isotope and %C data by land used in the modelling of the estuary and river sites. (Continued). Samples for drain weed plants were collected from wherever they were found and are not specific to any location.

Location (NZMT2000)		Site ID	Land Use		Bulk Carbon	Myristic	Palmitic	Palmitoleic	Stearic	Oleic	Arachidic	Behenic	Lignoceric
Easting	Northing	Code	description	%C	δ^{13}C	c14:0	C16:0	c16:1w9c	c18:0	c18:1w9c	c20:0	c22:0	c24:0
2145956	5431652	NRE_13	Dairy Pasture	10.43	-30.70	-41.31	-29.22	-32.23	-32.57	-22.50	-32.59	-32.19	-30.86
2161593	5413732	NRE_10	Dairy Pasture	8.81	-30.32	-34.70	-28.50	-32.02	-31.98	-24.96	-29.78	-29.71	-34.53
2149385	5479910	NRE_103_COW_PAST	Dairy Pasture	4.06	-29.20	-30.78	-28.22	-30.61	-29.74	-24.69	-31.28	-30.66	-29.74
2154117	5483811	NRE_19	Dairy Pasture	5.46	-29.63	-41.07	-33.50	-40.21	-32.68	-24.26	-33.24	-33.32	-32.93
2146089	5482689	NRE_101_SHP_PAST	Sheep Pasture	3.99	-30.57	-31.42	-28.41	-29.88	-32.12	-28.98	-31.03	-32.27	-29.84
2144052	5465009	NRE_14	Sheep Pasture	3.59	-29.36	-37.92	-30.57	-33.72	-34.29	-36.62	-35.05	-33.75	-33.59
2152425	5463144	NRE_7_SHEEP	Sheep Pasture	3.73	-29.73	-36.78	-28.64	-31.00	-32.53	-25.43	-32.72	-33.87	-31.52
2163321	5408217	NRE_8	Sheep Pasture	12.29	-29.75		-30.22	-29.44	-30.91		-28.18	-26.19	-30.38
2147432	5432178	NRE_12	Deer Pasture	5.27	-30.17	-31.60	-30.22	-31.74	-34.58	-33.72	-34.14	-34.29	-34.01
2142935	5477052	NRE_15	Deer Pasture	2.64	-29.74	-34.61	-29.76	-31.55	-33.79	-35.79	-35.01	-32.99	-32.98
2150821	5437290	NRE_18	Deer Pasture	5.51	-29.90	-34.71	-29.71	-31.26	-32.88	-27.64	-33.10	-33.18	-31.23
2148782	5463269	NRE_21	Deer Pasture	5.64	-29.32	-31.47	-27.37	-30.98	-30.35	-23.73	-32.53	-32.36	-31.81
2154749	5437218	NRE_17	Dairy Kale	2.89	-28.36	-32.83	-30.63	-37.38	-33.77	-24.07	-34.04	-33.78	-31.92
2148910	5472086	NRE_20	Dairy Kale	4.54	-28.65	-43.76	-27.99	-38.56	-31.29	-20.27	-31.84	-31.61	-31.68
2148758	5480116	NRE_102_KALE	Dairy Kale	4.28	-28.99	-33.07	-28.61	-33.18	-30.59	-23.15	-33.40	-30.94	-31.27
2145879	5482836	NRE_100_SWE	Sheep Swede	3.73	-29.02	-31.04	-27.09	-33.37	-30.21	-29.68	-31.27	-35.42	-31.19
2152228	5463323	NRE_6_SWE	Sheep Swede	3.76	-29.57	-32.58	-32.27	-33.86	-32.46	-25.03	-32.93	-33.18	-31.67
2163321	5408466	NRE_9_SWEDE	Sheep Swede	20.16	-29.56		-29.49		-28.54		-26.65	-28.22	-30.34
2153556	5418973	NRE_1	Hort Carrots	3.19	-29.14		-28.36	-30.53	-33.75	-24.12	-33.28	-31.26	-30.92
2154669	5421349	NRE_3_PAR	Hort Parsnip	3.67	-28.89	-32.80	-27.97	-30.71	-30.53	-23.83	-31.54	-32.80	-30.97
2160969	5420151	NRE_2_POT	Hort Potatoes	3.81	-28.93	-33.21	-29.58	-32.38	-32.61	-24.38	-31.88	-33.25	-31.31
2157178	5435010	NRE_16	Native Forest	6.79	-28.30	-34.50	-29.87	-30.96	-30.05	-26.44	-32.41	-32.39	-30.68
2170168	5443579	NRE_4_NTV	Native Forest	5.10	-29.27	-38.84	-31.60	-46.06	-29.63	-24.29	-31.89	-30.87	-33.13
2137976	5507628	NRL_4_NATIVE	Native Forest	14.30	-29.19	-39.42	-33.36	-54.04	-30.66	-28.84	-33.20	-29.02	-30.12
2140407	5505388	NRL_22_PINE	Pine Forest	7.92	-28.21	-36.54	-26.13	-32.74	-29.61	-20.22	-27.22	-28.39	-29.19
2140254	5476609	NRL_23_PINE	Pine Forest	3.32	-29.26	-37.91	-27.15	-27.46	-26.17	-22.56	-29.76	-28.25	-28.58
2172571	5435427	NRL_24_PINE	Pine Forest	3.54	-28.70	-39.69	-29.38	-28.30	-27.61	-25.94	-29.20	-26.68	-27.86
2141453	5466850	NRL 600 EUC	Eucalyptus Forest	2.50	-28.90	-31.74	-28.09	-36.58	-34.85	-30.96	-36.25	-34.57	-34.32
2134290	5499291	NRL 601 EUC	Eucalyptus Forest	3.72	-28.42	-30.18		-31.70	-36.12	-32.44	-36.03	-40.03	-43.56
		Drain weed 1	Watercress	34.47	-32.06	-38.85	-39.79	-27.02	-37.50	-38.28		-37.39	-41.38
		Drain weed-2	Potamogeton	36.69	-33.49		-43.31		-39.35	-40.17			
		Drain weed-3	Glyceria den	40.02	-30.48	-31.41	-35.95	-36.07	-34.95			-36.53	-37.49
		Drain weed-4	Musk	28.85	-32.82	-37.14	-40.61	-38.56	-40.83	-39.71	-43.24	-43.26	-42.10
		Drain weed-5	Water Buttercup	36.35	-30.18	-39.57	-37.55	-38.94	-34.05		-40.37	-45.30	-35.41
		Drain weed-avg	(Data averaged)	35.28	-31.80	-36.74	-39.44	-35.15	-36.83	-39.39	-41.81	-40.62	-39.10