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Wharekawa Estuary Sediment Sources

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Contents

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Executive Summary

Sedimentation rates in the Wharekawa Estuary are higher now than prior to human land use changes in the catchment. The major land uses in the catchment are exotic pine forestry (managed by Rayonier), Department of Conservation (DOC) indigenous forest and agriculture. As part of the consent conditions, Rayonier (and, previously, Carter Holt Harvey) is required to carry out sediment and biological monitoring of the Wharekawa Estuary. This monitoring has been ongoing for a number of years and is showing a decline in invertebrate species sensitive to sedimentation at the monitored sites within the estuary.

The source of sediments causing these ecological effects was unknown. Environment Waikato contracted NIWA to determine the sources of sediments deposited in the estuary, using a forensic stable isotope technique. This report presents the results from a study of the Wharekawa Estuary using this technique to identify and apportion the sources of soil, by land use and by sub-catchment, contributing to the sediments at three locations along each of seven monitoring transect lines across the estuary and the ocean beach. The samples were collected in April 2007, and the results are indicative of the sediment source contributions at that time.

To determine the proportion of different land use soils contributing to the estuary, reference source soil samples were collected from pine forestry as mature, recent clear-felled, and young three to five year old pine, agriculture as flood plain, low-slope, and steep-slope pasture, native forest from low-slope and steep-slope sites, and subsoil from slips. A sample of seagrass was analysed from the estuary as this material is known to influence the isotopic signatures of sediments that have been in contact with it for extended periods and thus that isotopic signature can be used to indicate sediments which may have been in the estuary for some time, either stored or being reworked by tidal action. Stream bed sediment samples were also collected upstream of the estuary to enable analysis of soil contribution by sub-catchment.

Initially the data was modelled to evaluate the sources of soil contribution to the estuarine sediments by land use. The results indicate that terrigenous soil contributions were present at all estuarine sites from pine (1-23%), pasture (<1-10%), native forest (<1-3%) and slip (<1-13%) land use sources. Because of the recent history of intense local storms causing flood events in the Wharekawa catchments (12 July 2005 and 28 April 2006), the flood-plain soil was also used as a discrete source to represent silt or bank erosion of sediment from within the river and stream channels. It was found that this material contributed high proportions (29-95%) of the soil in the sediments across the estuary. While this result is consistent with soil deposition across the estuary during the original flood event, analysis of the stream bed sediment samples indicated that slip and flood-plain silt made up about a quarter of the soil transported in the Wharekawa River, suggesting that there was a continuing supply of the flood material being washed out of that river.

As only about 25% of the soil transported in the Wharekawa River is flood-plain silts, the amount of flood-plain silt in the estuary appears to be disproportionately high. This apparent inconsistency is explained by examining the bulk density of the estuarine sediments, which were higher than the terrigenous source soils. This indicates that terrigenous soils entering the estuary are being water sorted with the coarser materials being deposited on the intertidal zones while the finer materials are carried out of the estuary where some can wash up on the beach. Consistent with this scenario, the modelling results showed that there was a higher proportion of the pine (50%), pasture (10%), native forest (16%), and slip (14%) soils but lower proportion of flood-plain silt (7%) in the beach sample.

When the data were modelled to evaluate the soil contributions by sub-catchment, the results showed that the major sediment contributions in the mid-to-upper estuary came from the Wharekawa River sub-catchment (20-60%) with the Kapakapa sub-catchment producing 7-50% and the Tawatawa and Wahitapu sub-catchments each producing about 1-10%. The study results indicated that only the inshore parts of the large pine-slash debris field deposited in the estuary near the Kapakapa Stream mouth during the July 2005 storm are still producing fine silt which is accumulating along the upper tide level downstream of the Kapakapa Stream. The significance of this is that it indicates that the sediment load from the Wharekawa River sub-catchment, which has a high proportion of the flood-plain soil, is gradually burying the older sediments and seagrass beds in the mid-to-upper estuary. It is possible that the accumulation of this mainly heavy sand is altering the alignment of the channels in the estuary allowing sedimentation of new and redistributed sediments to occur in the areas showing an ecological impact in the biological monitoring.

While sedimentation rates in the Wharekawa Estuary may be higher now than prior to human land use changes in the catchment, the results of this study highlight the effects of changing weather patterns and the impacts of extreme weather conditions, the extremity and frequency of which have been increasing in recent years. Land use practices which remove the protective cover of plants on steep land will exacerbate the production of sediment during extreme events. Furthermore, flood material deposited in the river and stream channels during extreme events may continue to be discharged into the estuary over extended periods as chronic loads long after the extreme event has passed. This chronic sediment load may adversely affect some invertebrate species such as the cockle, *Austrovenus stutchburyi*, which are sensitive to sedimentation or enhanced suspended solids. The accumulation of water sorted sands near the inflows may also adversely affect species such as the mud snail, *Amphibola crenata*, that favour muddy habitats.

1. Introduction

The source of sediments causing adverse ecological effects in Wharekawa Estuary is currently unknown. In order to determine the sources of sediments deposited in the Estuary, Waikato Regional Council (aka Environment Waikato) contracted NIWA to use a new forensic stable isotope technique to evaluate the land use sources of sediment deposited in the Wharekawa Estuary and to determine where those sediments were coming from within the catchment. The NIWA study was required to include samples from monitoring sites used for a concurrent study by Bioresearches (Figure1) to allow linkage between the two studies.

1.1 Background

A report by Swales and Hume (1995) is the main source of information on sediment rates in the Wharekawa Estuary. It shows that sedimentation rates are higher now than prior to human land use changes in the catchment. The major land uses in the catchment are exotic pine forestry (60%, managed by Rayonier), DOC indigenous forest (20%), and agriculture (13%, mostly in pasture) and about 7% scrub land. Total catchment area is about 9200 hectares. As part of the consent conditions, Rayonier (and, previously, Carter Holt Harvey) was required to carry out sediment and biological monitoring of the Wharekawa Estuary. This monitoring, undertaken by Bioresearches (e.g., West 2006), has been ongoing for a number of years and is showing a decline in invertebrate species sensitive to sedimentation or habitat changes at the monitored sites within the estuary. The results are also showing changes in the distribution of plant species in the estuary with mangrove progradation in the upper estuary and seagrass bed areas decreasing in the middle reaches of the estuary but slowly expanding in some areas closer to the sea (West 2006). These changes are also consistent with changes in sedimentation rates and the accumulation of sandy sediment in the estuary.

It is known that removing forest from the steep slopes of a catchment will promote soil erosion and thus enhanced sediment run-off into streams and rivers during heavy rain. There has also been much recent debate about the role of pine forestry versus pasture in the supply of sediment to downstream aquatic habitats (Phillips et al. 2005; Eyles and Fahey 2006; Mardon et al. 2006). Results from the Pakuratahi Land Use Study in Hawkes Bay (Eyles and Fahey 2006) included a comparison of sediment yield from paired forestry and pasture catchments. That study determined that, over a 12-year period, “the farmed catchment produced almost four times more suspended sediment than the catchment in mature forest”. This means that there was substantially less sediment production from undisturbed mature pine forest [or native forest] than from pasture on similar sloping land. However, the Pakuratahi study also found that "during harvesting, sediment yields from the forested catchment were two and a half times more than the farmed catchment, and six times higher than before harvesting."

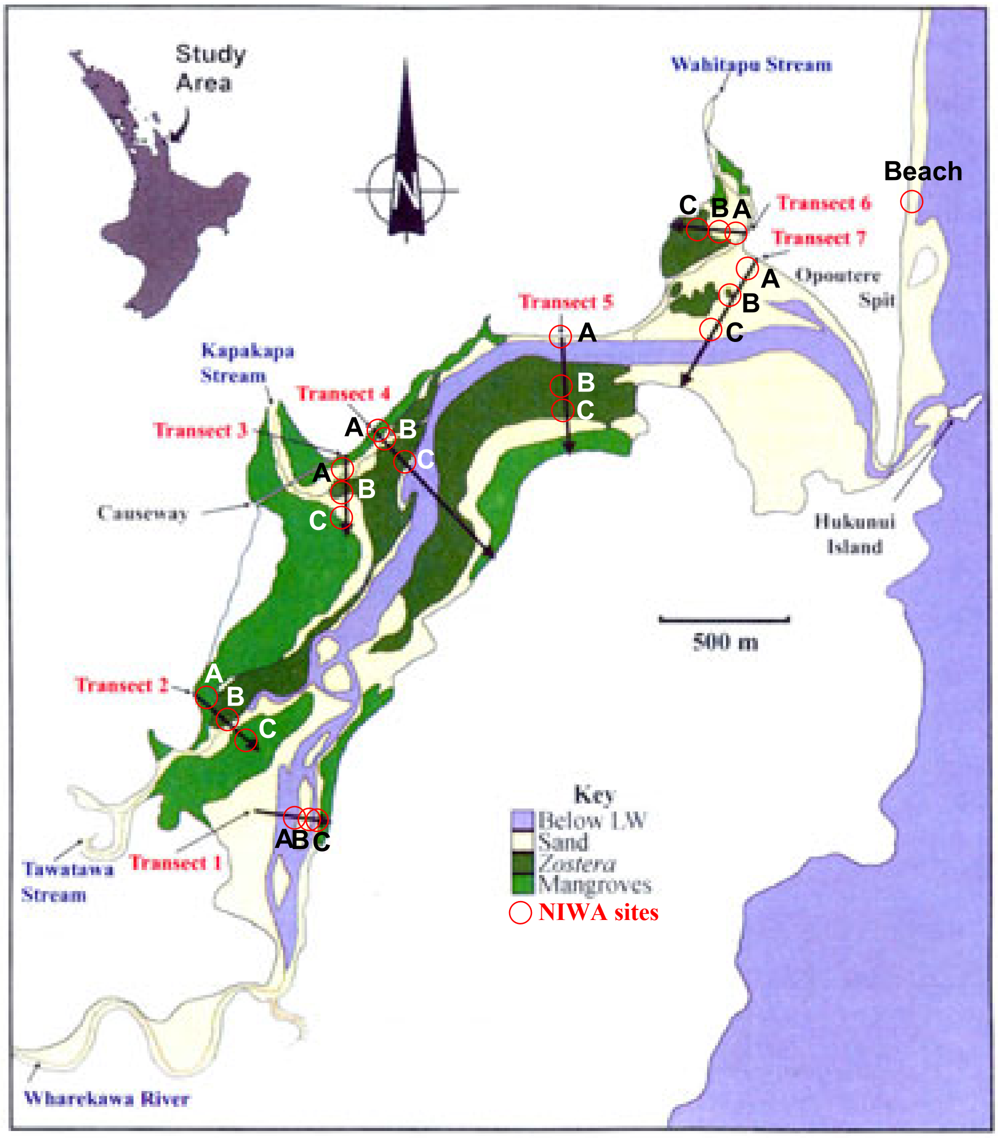

Figure 1: Estuary sample locations (red circles) plotted as an overlay of the Bioresearches monitoring program map (West 2006). The letters A, B, or C beside each location coupled with the Bioresearches transect line number give the sample code as listed in Appendix 1. Sample 8A was from the ocean beach.

Gibbs (2006a) found high proportions of sediment deposition from recently harvested pine forest in the Mahurangi River delta, consistent with the Pakuratahi Land Use Study. A recent study of the Whangapoua Harbour (Gibbs 2006b) also demonstrated that sediment from disturbed steep land produced enhanced sediment loads on the intertidal zones of that harbour. Much of the recent (since 1990) sediment deposited in the Whangapoua Harbour was from a high intensity localised rainstorm or 'weather bomb' which caused localised extensive land slippage on the steep land, irrespective of land use. Despite this, specific land use sources were also identified and contemporary sediment contributions were apportioned between soil from pine forest, pasture, and native forest/scrub.

Such extreme events cause massive soil mobilisation which may smother the sediments, and thus the benthic communities, in an estuary (Thrush et al. 2004). In recent years (i.e., since 1990) there appear to have been more 1-in-100 year rainfall events striking the Coromandel Peninsula (J. Salinger, NIWA, pers. comm.). Recent extreme storm events that affected the Wharekawa Estuary occurred on 12 July 2005 and 28 April 2006. The July 2005 event caused a major washout of soil and pine-slash debris from the Kapakapa Stream sub-catchment depositing a large delta of this material adjacent to the mouth of the stream in the estuary (Figure 2).

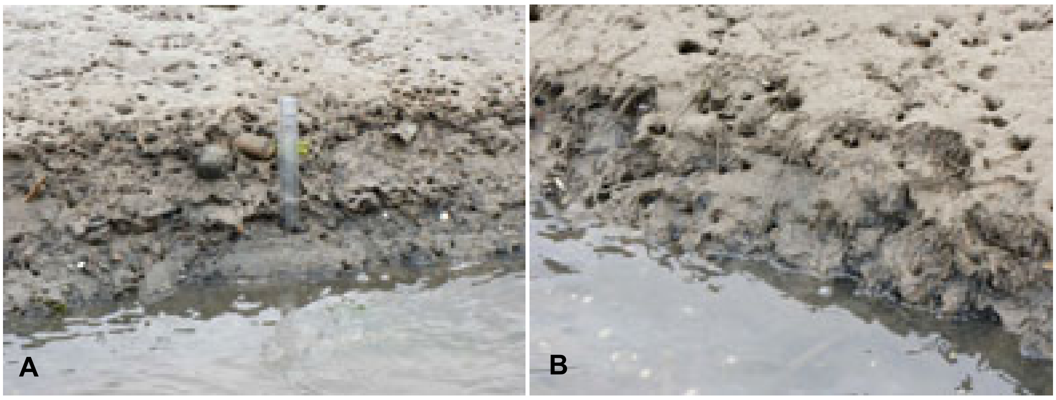

Figure 2: Pine-slash debris from the Kapakapa sub-catchment from the 12 July 2005 event. (**A**) shows a 20-30 cm thick layer over a cockle bed. (**B**) Close-up showing the inter-bedded pine needles still clearly identifiable after more than a year. The debris field was extensively colonised by crabs - note numerous burrows.

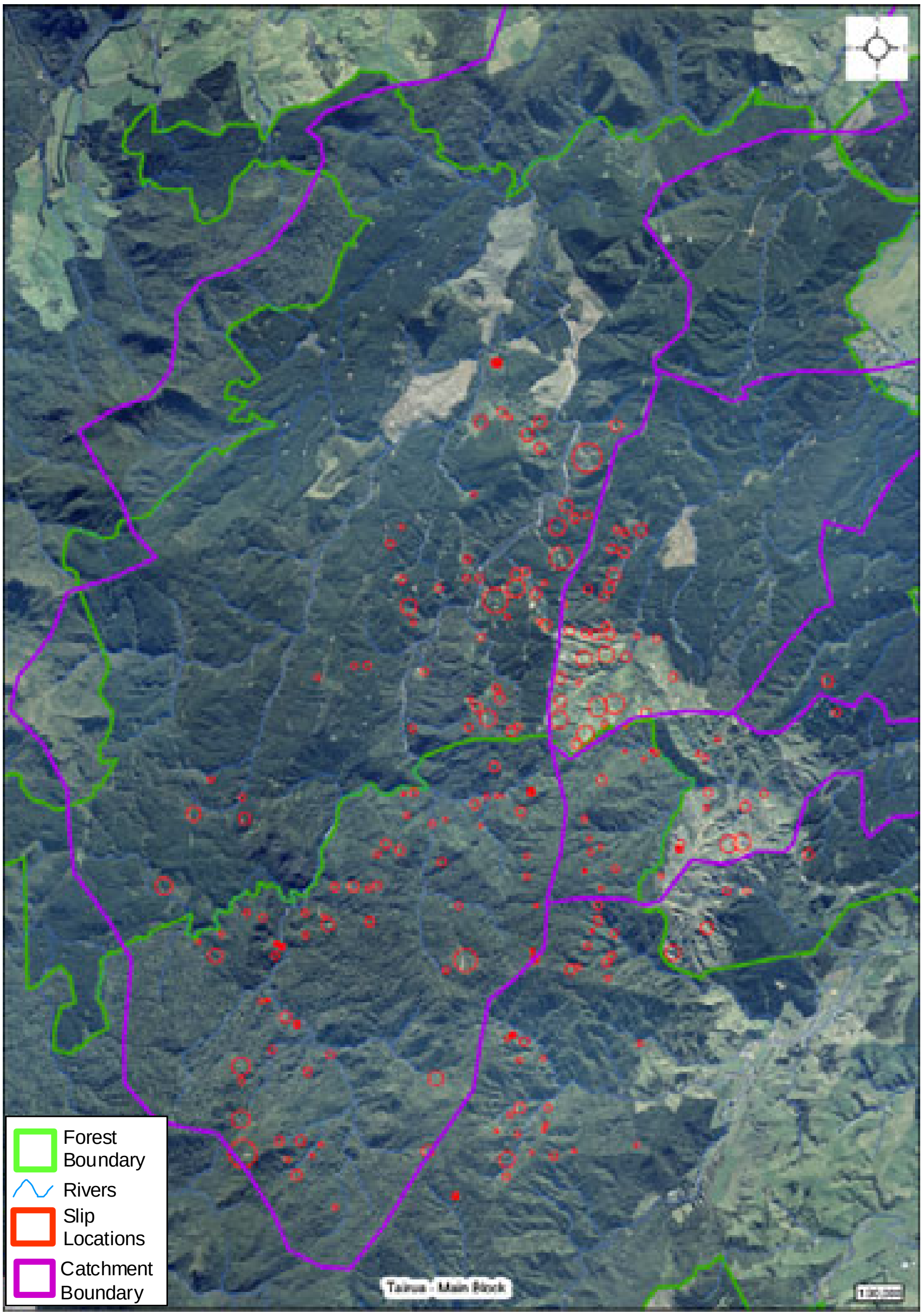

Figure 3: Aerial photo overlay of the central region of the Wharekawa River catchment (largest area enclosed by purple line) showing the proportion in pine forest (enclosed by green line) and the slips caused by the intense localised storm on 28 April 2006 (red circles). Figure provided by Kelvin Meredith of Rayonier.

The April 2006 event caused extensive slippage of steep land mostly in the Wharekawa River sub-catchment (Figure 3). This resulted in flooding and the deposition of silt across the low-lying farmland beside the Wharekawa River (Figure 4). This sandy material appeared to be the same as bed-load material in the river channel which would be gradually washed into the estuary in subsequent storm events.

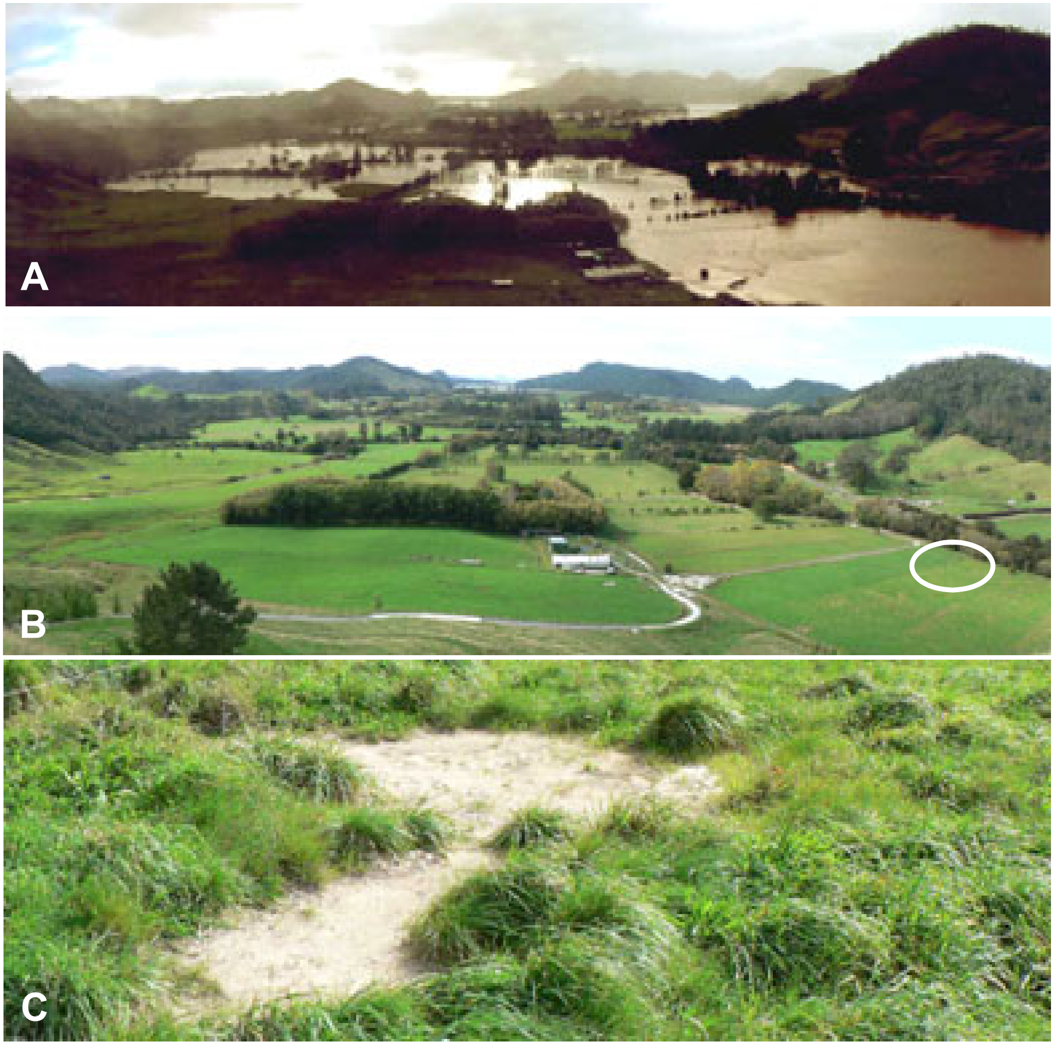

Figure 4: **A**) Flood event in the Wharekawa River on 28 April 2006 showing the inundation of the flat land beside the river. (Photo courtesy of Mrs Foster) **B**) View of the same area in April 2007 showing the re-grassed flood-plain pasture. **C**) Close up of the flood-plain soil showing the silt layer through the new grass. The photo (C) location is indicated by the circle in (B).

Analysis of the number of slips by land use in the zone of impact for the April 2006 event (Figure2) suggests that both mature pine and native forest had about three slips per 100 hectare while pasture had about nine. There is no data on the relative magnitude of the slips in the different land use areas, but the 3:1 ratio of slips for pasture versus forest is consistent with the Pakuratahi Land Use Study findings.

The occurrence of these major deposition events will have had a major effect on the sediment composition in the Wharekawa Estuary. Particle size and density differences means that coarse gravels and sands have a longer lag time between erosion and delivery to the estuary compared with the fine suspended muds which are of greater ecological concern (Thrush et al. 2004). However, the continued bed load transport of stored coarser material into the estuary may mask the less dramatic but chronic fine sediment contribution from the different land use sources, which may be having a pervasive deleterious influence on the biota, especially invertebrate species sensitive to sedimentation or enhanced suspended solids, and habitats in some areas of the estuary.

It is also possible that seasonal changes in the Wharekawa Estuary such as the proliferation of sea-lettuce (*Ulva*) may impact on the sediments and thus the benthic communities when these plants die and decompose (Figure 5). However, decomposition of such plants may also supply the organic matter to support many of these communities.

Figure 5: Panoramic photo of the extensive *Ulva* beds across the lower Wharekawa Estuary (Transect line 5) on 18 December 2006, showing fresh and decomposing plant material on the sediments in the foreground.

1.2 Objectives

Following a site visit on 18 December 2006 by NIWA and Environment Waikato, objectives of the present study were revised:

- Determine and apportion the sources, by land use, of terrigenous soil contributing to the sediment in the Wharekawa Estuary.

- Determine and apportion the contribution of sediment, by sub-catchment, in the Wharekawa Estuary and identify where there has been lateral movement between sub-catchment zones-of-influence in the estuary on the flood and ebb tides.

Another question asked was "How do sediment loadings compare between forestry, native forest, and farmland on the same slope?" Although an indication of the likely answer may come from the present study, this question is not a specific outcome for this report.

2. Methods

2.1 Sampling

Samples were collected on 17-18 April 2007 in fine weather after several light to moderate rainfall events following the summer dry period. Bulk sediment samples were collected by taking the top 20 mm of soil or sediment from a number of patches within an area of about 10 m^2 at each location. At each location the sub-samples were combined in a 5-litre plastic bucket before sealing with an air-tight lid. Bulk density samples were collected by taking a core of the top 20 mm of soil or sediment at each site with a 70 mm internal diameter (ID) corer. The core obtained was transferred to a pre-weighed 100 ml sealable screw-cap polyethylene jar, and sealed before transport to the laboratory for analysis.

2.2 Sites

A total of 38 samples was collected from different terrestrial sources and estuarine sediments. A list with ‘approximate’ map coordinates, that is, locations taken off a map as the GPS failed, is presented in Appendix 1. The locations are plotted on a GIS coast and river plot (Figure 6). As there was only minimal scrub within the catchment, it was decided to replace that land use type with a low-slope ($<10^o$) native forest. Aerial photographic data provided by Rayonier (Figure 3) indicated that there had been numerous slips in the forests in the Wharekawa River catchment and the location for the slip sample was chosen within that general area (Figure 6).

The terrestrial samples were all collected within the Wharekawa catchment, except for the sample of low-slope native forest (12B). This sample was taken from a site in the Wentworth valley on the eastern side of a ridge defining the upper Wharekawa River catchment boundary (Figure 6). This site was considered appropriate because the land use had essentially the same type and density of native forest and, being within 1 km of the Wharekawa River catchment, was likely to be on similar soil type to the adjacent Wharekawa catchment.

The mature pine forest sample (9A) was collected from an area of undisturbed forest on the steep ($>20^o$) slopes of the middle Wharekawa River catchment. The steep-slope native forest (12A) and the slip (11A) samples were also collected in the same area. The slip sample was taken from the alluvial tailings in a large cutting where the cut surface was crumbling and falling into drifts into a drainage system. Clear-felled pine forest soil (9B) was taken from an area being logged and had been exposed for less than a month. The thee to five year old pine forest sample (9C) was collected from the replanted forest in the upper Wahitapu Stream catchment.

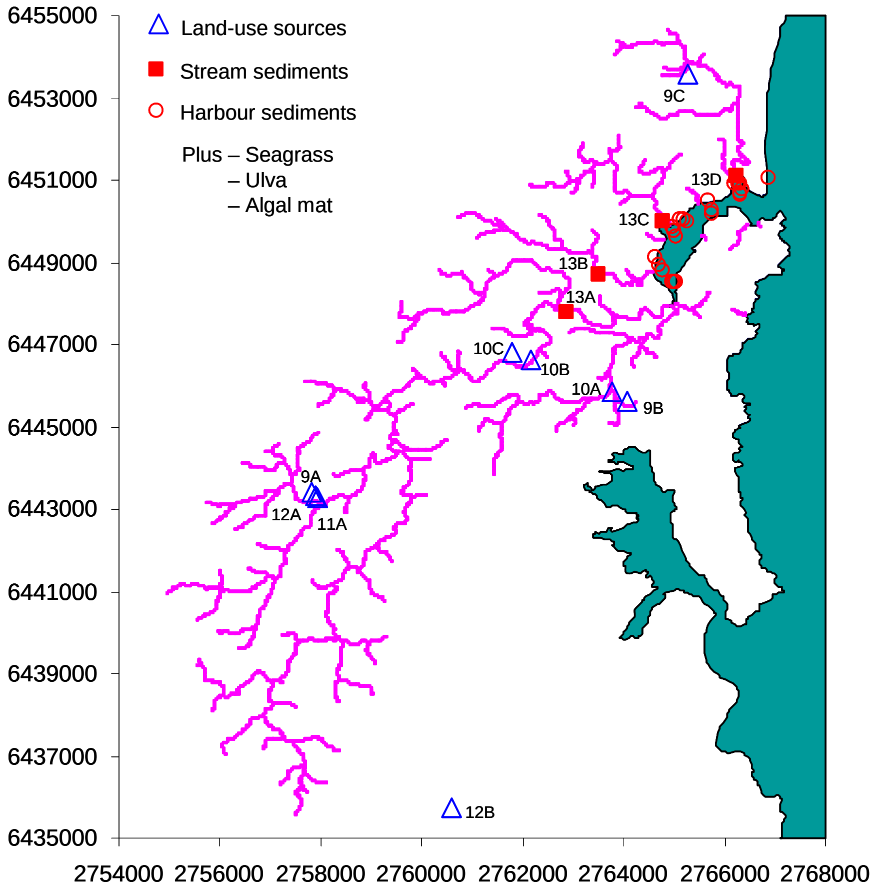

Figure 6: Site map of Wharekawa catchment showing the locations for all samples collected. Terrigenous samples (blue triangles) have their sample codes as listed in Appendix 1. Code 9 = pine, 10 = pasture, 11 = slip, 12 = native, and 13 are the main streams including the Wharekawa River. Unlabelled red circles are estuarine samples and the ocean beach sample (See Figure 1).

The pasture samples were taken from the Wharekawa River catchment closer to the estuary. The steep-slope pasture (10C) was collected from a similar elevation and land slope as the mature pine, steep-slope native and slip samples by rumbling the soil from grass sods from the top of a recent land slip. Two low-slope (<2^{o}) pasture samples were collected, one from the Wharekawa River flood plain pasture (10B) adjacent to the steep-slope pasture site, and the other from beside the drainage channels through the pasture further east (10A) and away from direct influence of any flood event in the Wharekawa River.

The river and stream beds in the catchment are typically stony bottom with little silt accumulation upstream of the tidal zone, but areas of silt occur on the banks above the normal stream water level. Samples representing the four main rivers and streams were collected from these silt deposits on the sides of the stream channels. The

Wharekawa (13A) and Tawatawa (13B) samples were taken above the zone of tidal influence beside the road bridges. The Kapakapa (13C) and Wahitapu (13D) samples were at the top end of the tidal zone.

Sediment samples from the estuary were collected along the transect lines established by Bioresearches (West 2006), to enable correlation of the changes observed by Bioresearches monitoring with the source proportions of sediments at those locations. By chance, the estuary samples were collected at the same time as other teams were making the estuary surveys for Bioresearches. Consequently, where possible, we selected our estuary sediment sites within five metres of selected Bioresearches monitoring points (Figure 1), to enable direct comparisons. The ocean beach sample was collected from the beach adjacent to the walking track access.

Additional samples collected were seagrass, which was washed to remove any silt, *Ulva*, which was a sun-bleached dead leaf as there was no live material in the estuary at the time of sampling, and a sample of a very obvious algal mat that coated the sandy sediments in the lower estuary adjacent to the Wahitapu Stream mouth. This material was widespread between transect lines 6 and 7, and about 5 mm. thick. It was beginning to peel back and looked like patches of carpet on the sand.

2.3 Analyses

Bulk density samples were weighed then dried at 105 ˚C for 12 hours before re-weighing to determine moisture content. A portion of each dried sample was combusted at 500 ˚C for 12 hours and the organic content (%) was estimated from the loss of weight. Note that some estuarine sediment samples had shellfish (small cockles) which were removed before drying and combusting.

Bulk soil and sediment samples (1-1.5 kg) were sieved through 2-mm mesh to remove shellfish or insects, etc., stones, leaves, roots, and other woody debris before drying at 60 ˚C in an air fan oven. The dried samples were then ground to a fine powder in a coffee grinder and sieved through a 100 µm mesh before storing in wide-mouth screw-cap polyethylene terephthalate (PET) plastic jars pending analysis. Seagrass, Ulva, and algal mat samples were also dried at 60 ˚C, ground in a pestle and mortar and stored in sealed containers pending analysis.

An aliquot of each sample was acidified to remove inorganic carbonates by suspending the sample in 1N hydrochloric acid (HCl) overnight. Further HCl was added as required until no further effervescence and then the acid was removed by washing twice with deionised water (Milli-RQ) and centrifuging. The sample was dried at 60ºC, and then hand ground to a fine powder in a pestle and mortar. The C and N bulk stable isotope composition of each sample was determined by mass spectrometry. About 20 mg of sample was weighed into a pure tin capsule which was combusted at 1020ºC in a Fisons NR1500 elemental analyser coupled on line via a Finnigan Con-Flo 2 to a DeltaPlus (Finnigan) continuous flow, isotope ratio mass spectrometer. Stable isotope ratios are reported in standard delta (δ) notation per mil (‰) as: $\delta X = [(Rsample/Rstandard) - 1] \times 10^3$ where X is ^{13}C or ^{15}N and R is the ratio of $^{13}C/^{12}C$ or $^{15}N/^{14}N$, respectively. Standard reference materials are PDB limestone for carbon (a calibrated working standard of CO_2 gas was used), and air was the standard for nitrogen (a calibrated working standard of N_2 gas was used). Analytical precision for $\delta^{13}C$ and $\delta^{15}N$ were 0.1 and 0.2 ‰, respectively.

All samples were analysed for compound specific isotopes (CSI) of organic lipid acids (Gibbs 2007) after compound separation by gas chromatograph (Figure 7). This method uses the $\delta^{13}C$ isotopic signatures of fatty acids produced by the plant groups defining the land use. As these fatty acids bind to the soil particles they may be used as biomarkers to positively identify and thus link sediment delivered to the estuary to soil eroded from those land use areas. The proportional contribution of each source soil at a location was estimated using the mixing model, IsoSource (Phillips and Greg 2003).

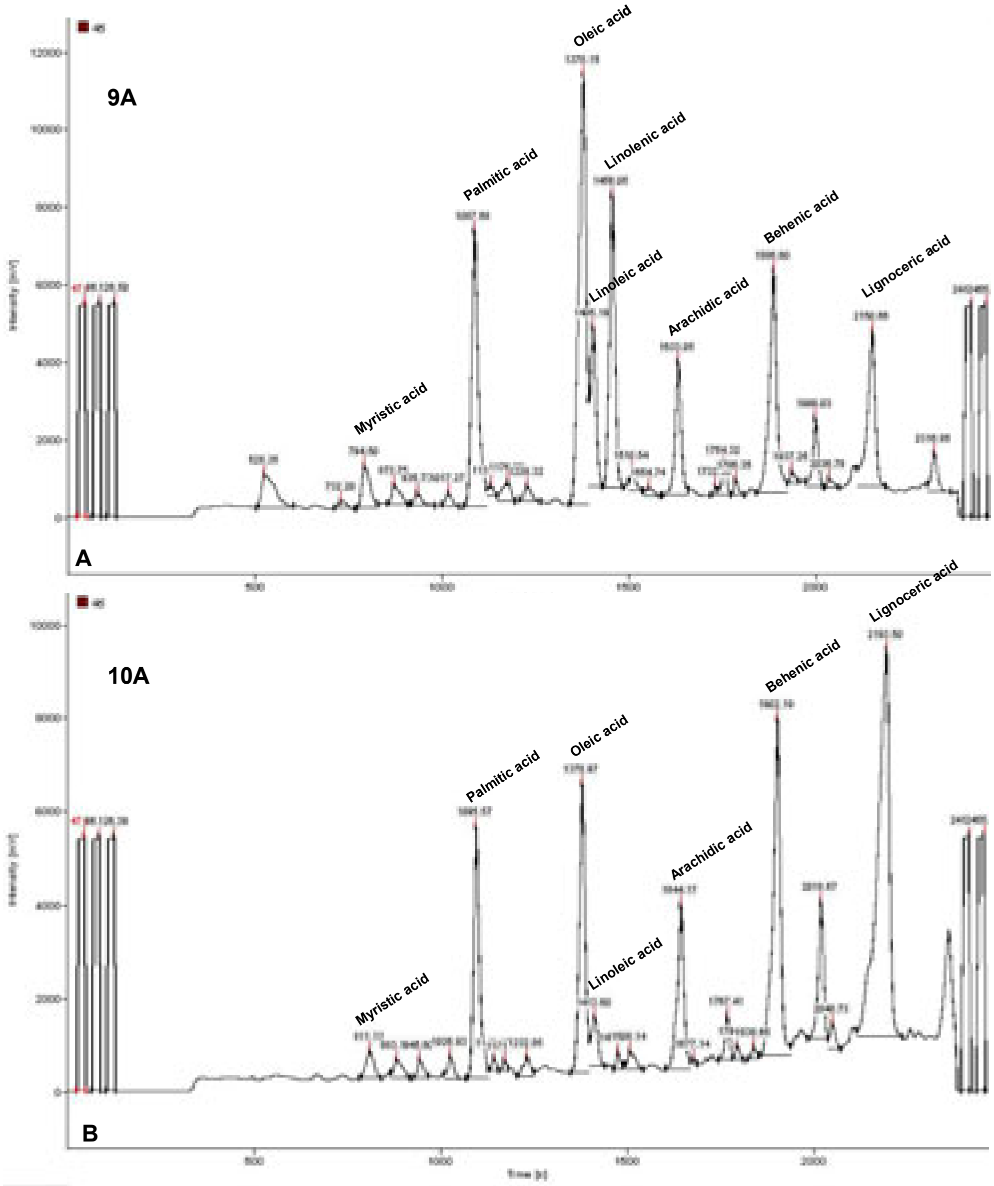

Figure 7: Examples of gas chromatograms of source extracts from **A**) mature pine (sample 9A) and **B**) low slope pasture (sample 10A) vertically aligned by peak retention time (X-axis). Peak heights are not corrected for the mass of sample extracted. Only the $\delta^{13}C$ isotopic signature of the compound represented by each peak is used in the mixing model for source apportionment. Named compounds are those which have CSI values able to be used in the modelling.

2.4 Interpretations

Data interpretations were as described in Gibbs (2006a, 2007) using bulk isotopic and CSI values in the mixing model, IsoSource (Phillips and Gregg 2003), to identify and apportion the contribution of each soil source to the sediment mixture at each sampling location. The interpretation method (Gibbs submitted) requires the use of the bulk $\delta^{13}C$ value plus the CSI values of Palmitic (C16:0) and Oleic (C18:1) acids in preference to longer or shorter chain length fatty acids. However, as there was not a complete sequence of these acids in all samples collected, the decision was made to use compounds with the same chain length i.e., Palmitoleic (C16:1) and Stearic (C18:0) acids to complete the sequence for the mixing model runs. The results of modelling using this modification to the method were checked for each sample affected (8) by using combinations of other fatty acids. The results were within 2%, which confirmed their validity.

Although the mixing model output is given as a range of feasible solutions, the statistical evaluations included in the model output also provides the mean values which may be the most feasible apportionments. As it is impractical to use all feasible solutions in the data interpretations, only the statistical mean values from the mixing model apportionments were used although the range of feasible apportionments was up to ± 10% about the statistical mean. These were corrected for % source using the %C data from the bulk isotopic analysis (Gibbs 2006a, submitted).

Because all inflows to Wharekawa Estuary have the potential to contribute the same range of source soils, the bulk isotopic and CSI values of the upstream samples were used as sources in the IsoSource model to determine the distribution of sediment from each sub-catchment to the estuary. The mixing model apportionments for these sources were corrected using the %C of the natural sediment.

2.5 Graphical representations

The large distances between transect lines relative to distance between sample points on these lines makes it inappropriate to attempt data contouring. Consequently, aspects of the physical data and % contribution of each land use or inflow source to each location inside the estuary have been graphically represented by distribution plots using a colour scale with linear interpolation between points along the transect lines. Discussion of the data reflects the analytical results and the observations made at each site at the time of sampling.

Data processing and interpretation are undertaken using best professional practice and within the current understanding of the forensic isotopic technique. Proportions and distribution plots are indicative rather than absolute within the limited sampling of the estuary and the use of statistical mean values from the isotopic modelling.

3. Results

Summary tables of all results are included in Appendix 1. Distribution plots and other graphical representations of selected data are presented below for discussion later.

3.1 Sediment characteristics

The sediments in the Wharekawa Estuary ranged from firm sands to soft sticky muds. Where mangroves have invaded the intertidal flats, mud has accumulated on top of the sands. By comparison, sands often overlay the seagrass beds near the stream channels. In general, the sandy sediments of the lower estuary had higher bulk densities compared with the wetter muddy sediments of the middle and upper estuary, and especially in the mangroves (Figure 8). There was also a sandy/gritty band around the three stream channels in the estuary. The bulk density of the estuary samples was consistently higher than the source soils indicating water sorting of the source material.

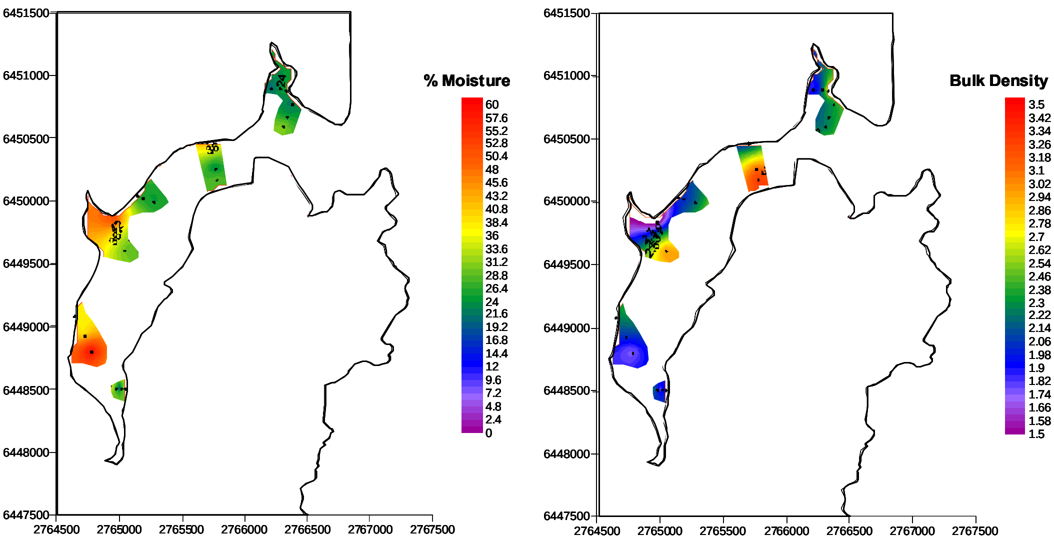

Figure 8: Spatial distribution of muddy sediments as indicated by high moisture content and low bulk density. High bulk density sediments correspond with firm sandy sediments. Sampling points used are plotted as dots.

The carbon content of the bulk sediments was mostly in the range of 3-5%, while the organic content ranged from 10-18 % (Figure 9). Higher %C near the mouth of the estuary may reflect the decomposition of *Ulva* from the summer bloom (Figure 5). Highest organic content was found in the sediments trapped in the mangroves, while lowest organic content was in the central sand flats near the Kapakapa Stream.

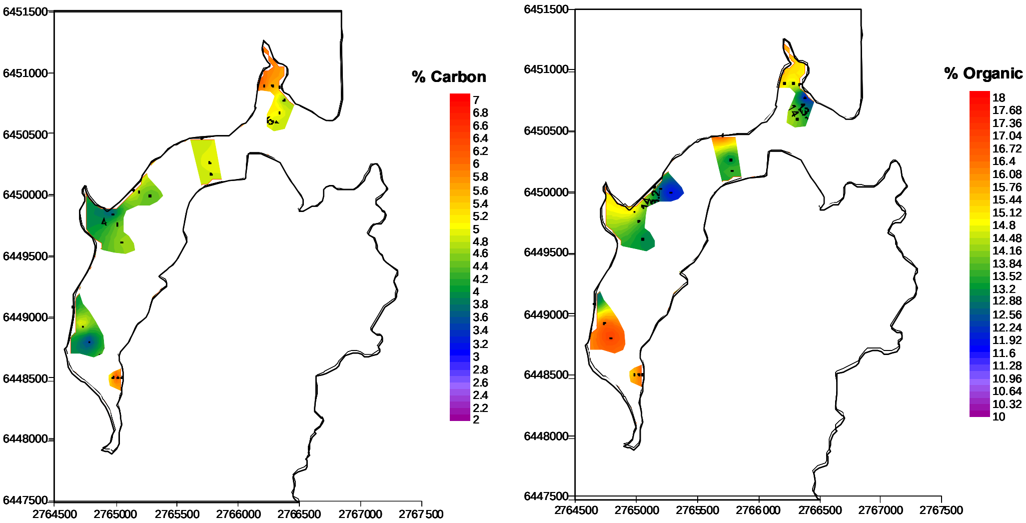

Figure 9: Spatial distribution of carbon and organic material in the bulk sediments. Highest organic content was associated with the sediment trapped in the mangroves. Sampling points used are plotted as dots.

3.2 Isotopic characteristics

A summary of all bulk isotope and CSI values are listed in Appendix 1. X-Y plots of bulk $\delta^{13}C$ values versus CSI values of Oleic acid for all samples (e.g., Figure 10) show that the estuarine sediment isotopic signatures were more isotopically enriched than the terrestrial samples. While this was expected, the ocean beach endmember plotted closer to the terrestrial samples than the more enriched estuarine sediments. Subsequent analysis of source contributions to the ocean beach site indicate that it included considerable amounts of terrigenous sediment, presumably flood material washed back onto the shore after leaving the estuary.

Closer examination of the estuarine sample data showed that the isotopically enriched sediment was from within the large seagrass beds. The level of enrichment indicated that some of that sediment had been associated with the seagrass beds for a considerable period of time. Consequently, the sediment from the seagrass beds may be an indicator that sediment was being stored in the estuary and could be moved around the estuary by the tidal currents during storm events. As the sediment in the seagrass beds did not have the same isotopic signature as the seagrass from those beds (Figure 10), it is apparent the seagrass beds also contain sediment from recent inputs from the different terrigenous sources. This sediment was also present in the algal mats and may be linked with *Ulva*. However, because there were no C18 CSI data available from the *Ulva*, this potential source has not been included in the subsequent data analysis and interpretation. Also, as the algal mat was only present between transect lines 6 and 7, this material has not been included in the data analysis on the assumption that it will be included with the seagrass interpretation.

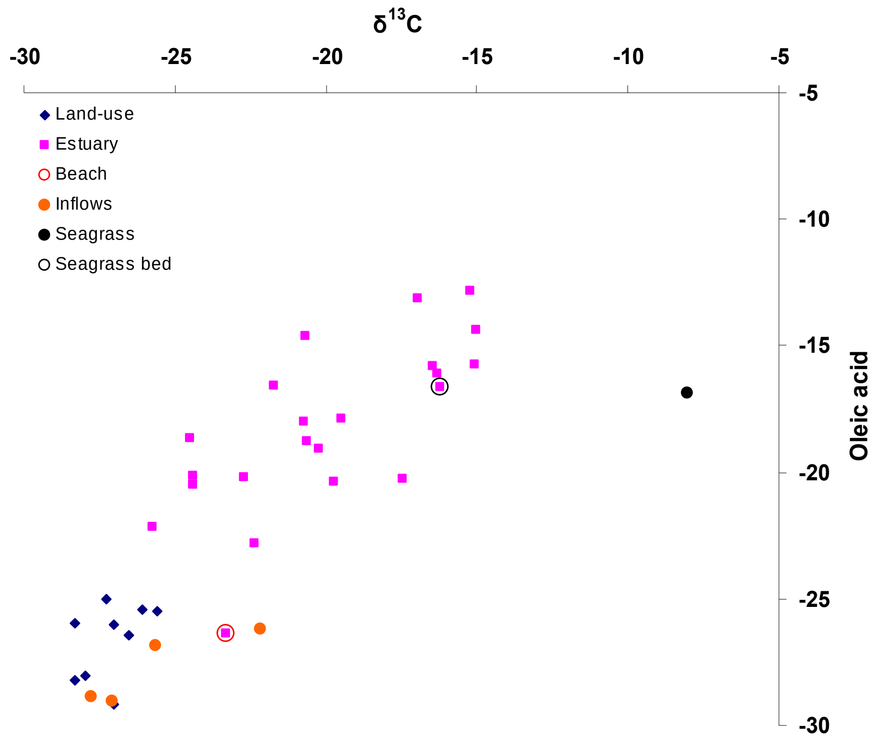

Figure 10: Plot of bulk $\delta^{13}C$ values versus CSI values of "Oleic acid" (i.e., C18:0/1) of all samples. Data point circled in red is the ocean beach sample. Data point circled in black is the sediment from inside a seagrass bed.

3.3 Sediment distribution by land use source

The proportional contributions of land use sources are based on statistical means from the IsoSource modelling and are not absolute values. The range of feasible solutions from the model still applies but is difficult to present except in tables. Graphically, the different land use source contributions to Wharekawa Estuary are presented as a series of distribution plots of mean % contribution of total Pine, Pasture, Native forest, and Silt derived from land slips and erosion of bank storage zones to give the general distribution pattern of these major land use types. Sediments with a seagrass influence to their isotopic signatures are assumed to have been in the estuary for a long time (>1 yr) and thus may represent sediment that is stored or reworked in the estuary. Where there are several components in the total data, these have also been presented individually. Numerical mean data are listed in Appendix 1, section 8.2.

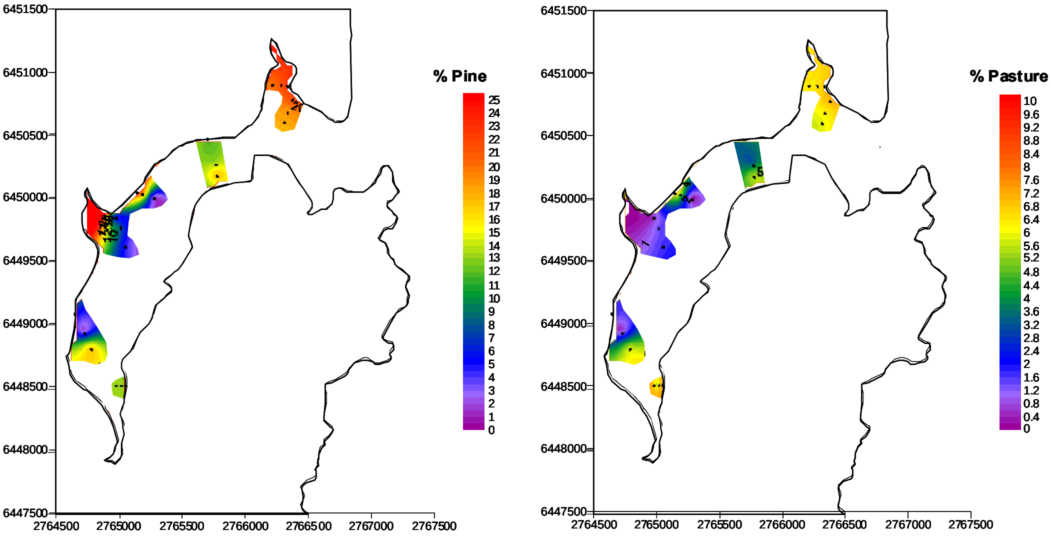

Figure 11: Plots showing the spatial distribution of soil contribution from pine forest and pasture in the Wharekawa catchment along the transect lines in the estuary. Sampling points used are plotted as dots.

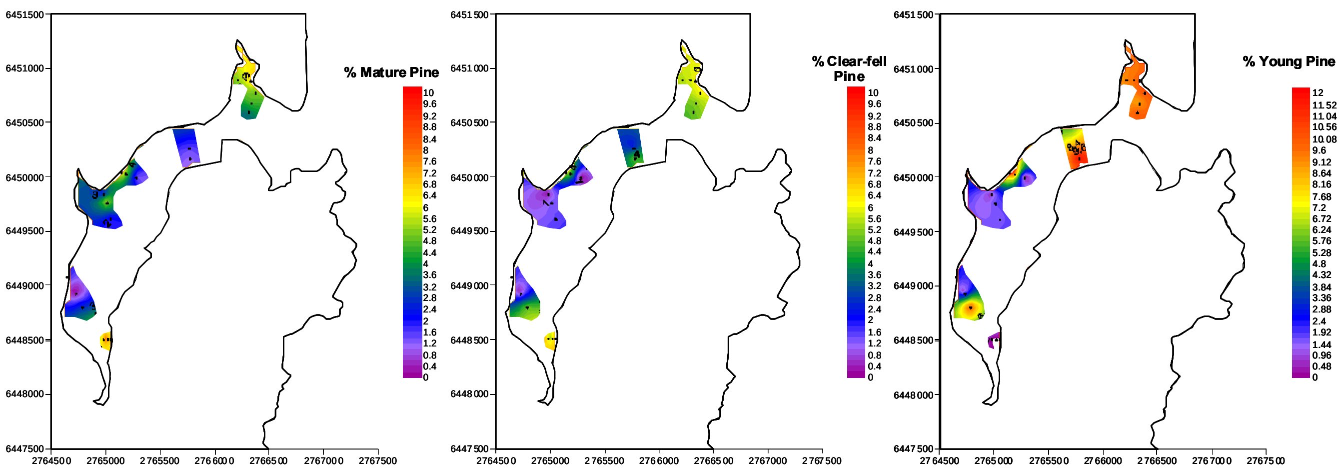

Figure 12: Plots showing the spatial distribution of soil contributions from mature pine forest, clear-felled pine forest, and young (3-5 yr) pine forest that make up the total pine forest contribution to the Wharekawa Estuary. Sampling points used are plotted as dots.

The total pine influence (Figure 11) was focused around the mouths of all 4 inflows as might be expected from the amount of land in the catchment used for pine forestry. In contrast the total pasture influence (Figure 11) was confined to zones around the Wharekawa, Tawatawa and Wahitapu inflows consistent with these sub-catchments having areas of pasture. The lack of pasture derived soil around the mouth of the

Kapakapa inflow is consistent with there being little or no pasture in that sub-catchment.

While the total pine contribution may be as high as 25% in parts of the Wharekawa Estuary, the separation of the total pine forest contribution into mature, clear-felled and young pine forest (Figure 12) suggest a similar amount of soil is coming from each land use at each point in the estuary, with higher quantities of soil from mature pine around the mouth of the Wharekawa River and Wahitapu Stream. Recent clear felled pine was also associated with these two inflows while the contribution from young pine was mainly associated with the Wahitapu inflow. Although there was visible evidence of the delta of pine slash debris around the mouth of the Kapakapa stream (Figure 2), the sediment from this area showed little fresh pine signature indicating that it has been covered with at least 20 mm of sediment from another source since it was deposited in July 2005.

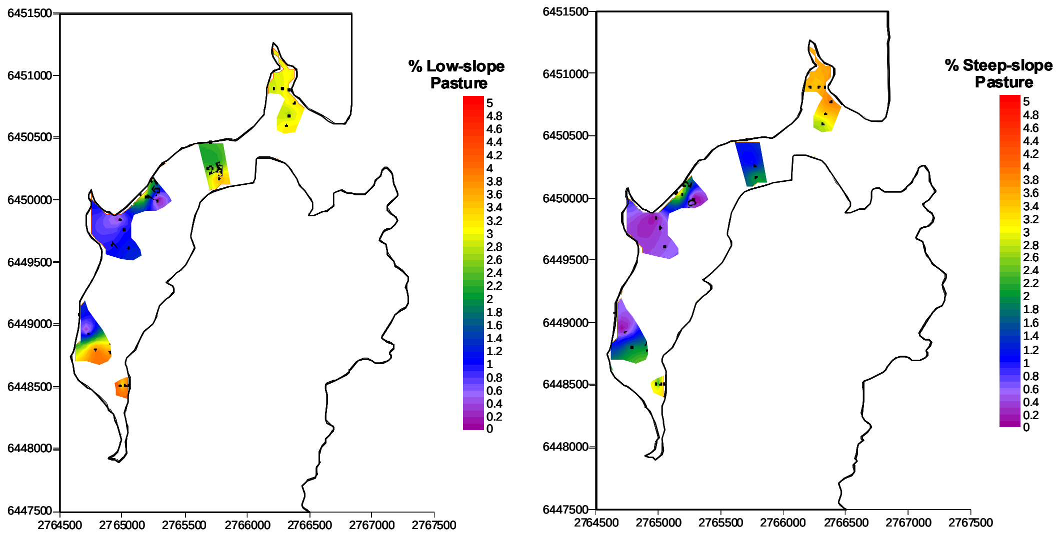

Figure 13: Plots showing the spatial distribution of soil contributions from low-slope pasture, and steep-slope pasture that make up the total pasture contribution to the Wharekawa Estuary along the transect lines. Sampling points used are plotted as dots.

A similar pattern of soil contribution was obtained from the low-slope and steep-slope pasture data separations, with most of sediment being produced from the Wharekawa and Wahitapu sub-catchments (Figure 13). These separations indicate that the Wharekawa sub-catchment produces more low-slope pasture sediment than the Wahitapu, which is consistent with there being large areas of low-slope pasture in the Wharekawa sub-catchment. Soil contributions from low-slope pasture may be enhanced by the numerous drainage channels through the flood-plain near the river mouth, allowing the soft organic soils to be eroded with the rise and fall of the tide.

From these data, the contribution from pastured land use appears to be about half that from pine forest, which is surprising given that there is substantially more pine forest than pasture in the Wharekawa Estuary catchment.

Native forest soil contributions to the Wharekawa Estuary (Figure 14) were low at <5% of the total sediment and were found mainly around the mouths of the 4 inflows. This is despite the large areas of native forest in the headwaters of the Wharekawa River (Figure3). In contrast, the ‘silt’ fraction contribution from the inflows was very high at <70% across the centre of the estuary (Figure 14).

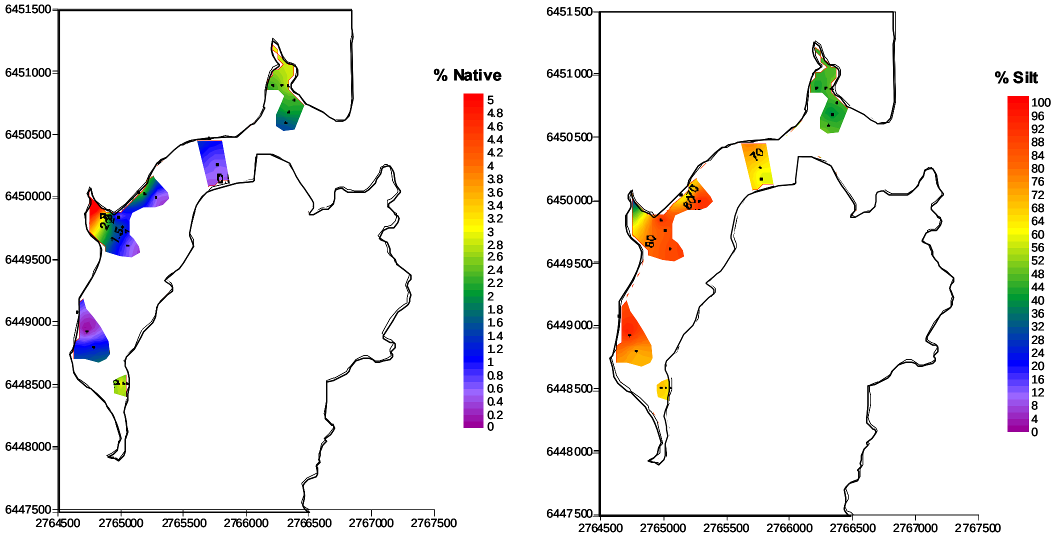

Figure 14: Plots showing the spatial distribution of soil contributions from native forest and ‘silt’ to the Wharekawa Estuary. The ‘silt’ includes bank erosion and fresh slip material. Sampling points used are plotted as dots.

Although described as ‘silt’, the term is not an indication of a size fraction but is used loosely to describe slip material and stored material slowly being washed out of the streams from earlier flood events or deposited in the estuary during the original flood event. The isotopic signature for this bank erosion material was taken from the flood-plain pasture silt sample beside the Wharekawa River channel (Figure 4) which has a known provenance, having been deposited at that site 1 year before sampling. CSI analysis showed that that material was almost entirely (<85%) derived from slip material (Table 1). As the slip data analysis indicates that the April 2006 event affected similar areas of pine and native forest, but little pasture, in the Wharekawa River sub-catchment, it is reasonable to assume that the slip material came in similar proportions from pine and native forest sources. However, CSI analysis of the slip material suggests that almost 90% was derived from pine forest (Table 1). This result might be expected as the slip soil sample was collected from a slip/cut face within the pine forest. As a slip sample from within the native forest area was not available for comparison, it is unreasonable to assume that all slip material came from pine forest given the approximately even number of slips per unit area in both pine and native forest land use from the April 2006 event.

Separation of these components of the silt fraction (Figure 15) shows that the bulk of this material was older silt spread across the central parts of the estuary. This probably reflects the deposition of much of that material during the flood event in April 2006.

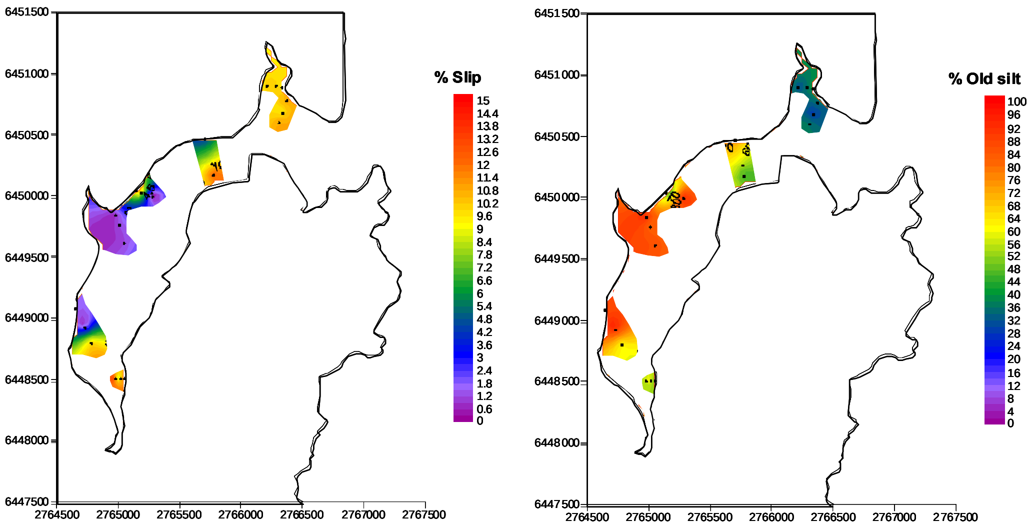

Figure 15: Plots showing the spatial distribution of soil contributions from recent slips and older 'silt', from earlier flood events, to the Wharekawa Estuary. Sampling points used are plotted as dots.

The presence of slip material around the mouths of the Wharekawa and Wahitapu inflows (Figure 15) is indicative of that material having been deposited after the April 2006 flood event. Of interest is that there was minimal recent slip material around the mouth of the Kapakapa Stream which had the major washout in the July 2005 flood event.

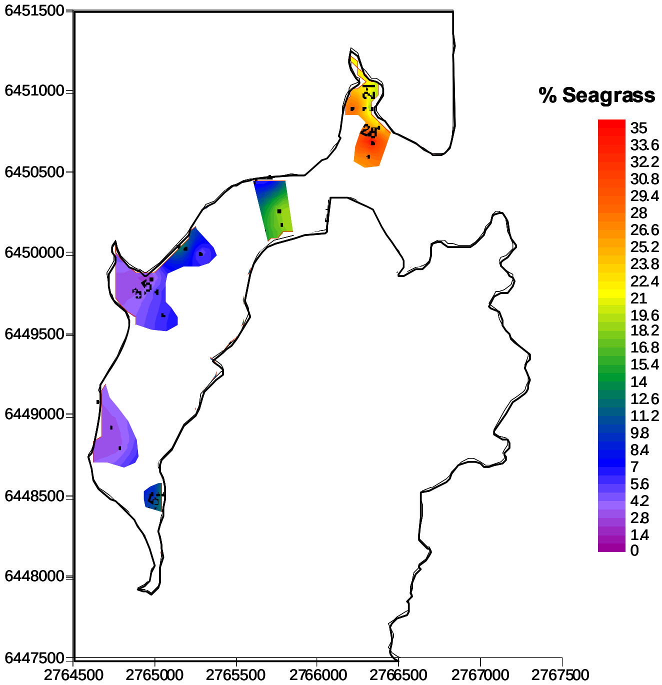

Figure 16: Plot showing the spatial distribution of sediments influenced by seagrass within the Wharekawa Estuary. Sampling points used are plotted as dots.

Sediment with isotopic signatures indicating a seagrass influence was mostly confined to lower reaches of the estuary (Figure 16) and generally coincided with obvious areas of seagrass on the intertidal sandflats on transect lines 5, 6, and 7. The small patches of seagrass observed on transect line 3 and near the Tawatawa Stream mouth on transect line 2 were being buried with either fine mud or sandy silt (Figure 17). Bioresearches reports indicate that this area has also shown a decline in populations of the mud snail, *Amphibola crenata*, (e.g., West 2006) which is consistent with a change from fine mud to coarser sands. Mud snails are intolerant of habitats with >2% coarse sand and <25% mud (NIWA unpub. data; J. Hewitt, pers. comm.).

Figure 17: **(A)** Sandy sediment deposits slowly burying the seagrass bed adjacent to the Tawatawa Stream channel on transect line 2, site B. (B) Closer view of the edge of the sand on the seagrass bed. (C) Finer sand and mud accumulating and smothering the seagrass on transect line 3, site C. (Bulk density sediment sampler in foreground is 75 mm OD).

3.4 Sediment distribution by sub-catchment

While the previous section evaluated the distribution of sediment sources by land use, the isotopic signatures from the upstream samples can be used to identify and apportion the sources of sediment at each location in the estuary by sub-catchment. Analysis of these upstream samples (Table 1) shows that they comprise a mixture of pine forest, pasture, native forest and slip/silt soils. It is assumed that each upstream sample mixture represents the material coming from that sub-catchment. Consequently, when used as sources in the IsoSource mixing model, only the resultant isotopic signatures of those mixtures are used and the apportionments are calculated for each sub-catchment without reference to the land use soil sources.

Table 1: Source soil proportions (mean data) in the sediment from river and stream samples. The flood-plain soil came from a pasture buried in silt from a flood event in April 2006. The slip soil came from a slip/cutting in steep pine/native forest. The ocean beach sample proportions are included as an indication of source material reaching beyond the estuary and washing ashore. (*Kapakapa and Wahitapu samples were within the tidal zone of the estuary and thus included some estuarine sediment. **Bank material is the pasture flood-plain soil.)

	Source soil contributions (%)								
Source	Pine			Pasture		Native	Silt		Estuary*
	Mature	Clear-felled	Young (3-5yr)	Low-slope	Steep-slope	All	Slip	Bank**	
Wharekawa River	30.0	10.6	0.0	3.4	15.4	14.0	10.7	15.9	
Tawatawa Stream	2.9	5.1	13.3	2.5	5.6	1.4	69.2		
Kapakapa Stream	17.9	15.5	27.7	0.0	0.0	7.5	28.0		3.4
Wahitapu Stream	13.4	4.3	60.8	2.1	2.3	4.4	8.1		4.6
Beach	40.7	3.4	5.7	1.0	8.2	16.0	14.7	6.5	3.9
Pasture flood-plain	2.2	4.7	0.0	5.3	1.3	0.5	86.0		
Slip	19.7	69.0				11.3			

The Wharekawa River sample soil proportions are consistent with the observations of a catchment dominated by largely mature pine forest and native forest on the steep hill sides. The contribution from steep pasture appears to be larger than that catchment land use area consistent with a greater loss of topsoil from exposed steep land. Although there have been numerous small slips in the Wharekawa River catchment (Figure3) the proportion of slip soil was small in the sample collected. However, the pasture flood-plain soil was mostly slip soil consistent with that material originating from slips and being deposited during the April 2006 flood event. For the purposes of the apportionment by catchment, the pasture flood-plain soil was used as being representative of the bulk of the material coming from the Wharekawa River catchment. Note that some flood-plain sediment may also come from other streams where slip material is being stored in the stream channel. The proportions of that material from the smaller streams may introduce an error but this is likely to be small. Sensitivity testing of the model using the Wharekawa upstream sample and the flood-plain soil produced total changes of <1% in the smaller streams while the sum of the Wharekawa upstream and flood-plain soil contributions were mostly within 1.5% of the proportions obtained using just the flood-plain soil in the modelling.

As noted earlier, the bulk density of the sediment in the estuary was consistently higher than the source soils implying water sorting in the estuary. The soil contributions to the organic matter in the beach sample (Table 1) show a high proportion of pine, almost 50%, but low (20%) proportions of 'silt'. This is also consistent with water sorting in the estuary allowing the lighter parts of the soils to be carried out of the estuary and deposited on the ocean beach. The longevity of this material in the high-energy environment of the ocean beach is unknown but light silt particles not permanently trapped above high water are likely to be winnowed away by the receding tide. However, this material is probably being replaced by fresh material ejected from the estuary on each ebb tide.

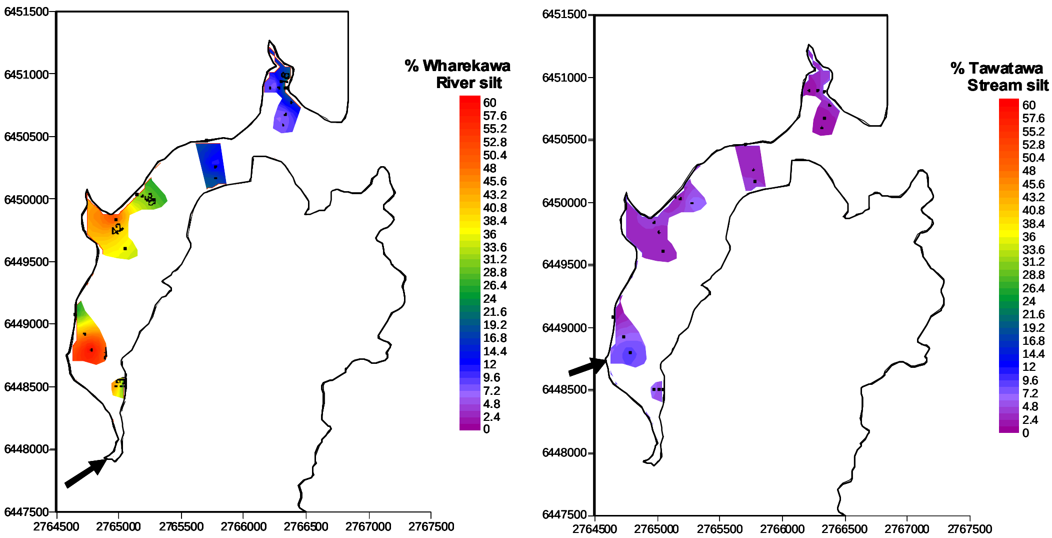

Figure 18: Spatial distribution of the estimated soil proportions from the Wharekawa River and the Tawatawa Stream (arrows) on the Wharekawa Estuary sediments. Sampling points used are plotted as dots along the transect lines.

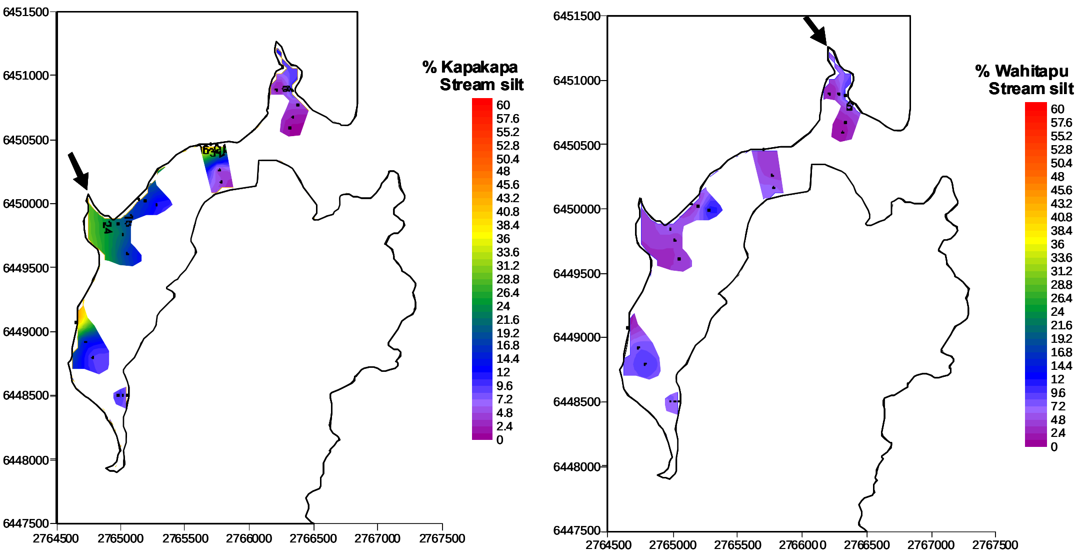

Figure 19: Spatial distribution of the estimated soil proportions from the Kapakapa and Wahitapu Streams (arrows) on the Wharekawa Estuary sediments. Sampling points used are plotted as dots along the transect lines.

Plots of the spatial distribution of sediment contributions to the Wharekawa Estuary by sub-catchment (Figs. 18 and 19) indicate that the majority of the contemporary sediment in the estuary has come from the Wharekawa River catchment. As these four plots are all drawn on the same scale, it is immediately obvious that the inputs from the Tawatawa and Wahitapu sub-catchments are small and have contributed less than 10% of the sediment across most of the estuary. Also, the sediment input contribution from the Kapakapa sub-catchment has been locally higher, at up to 50%, along the shore adjacent to the inflow.

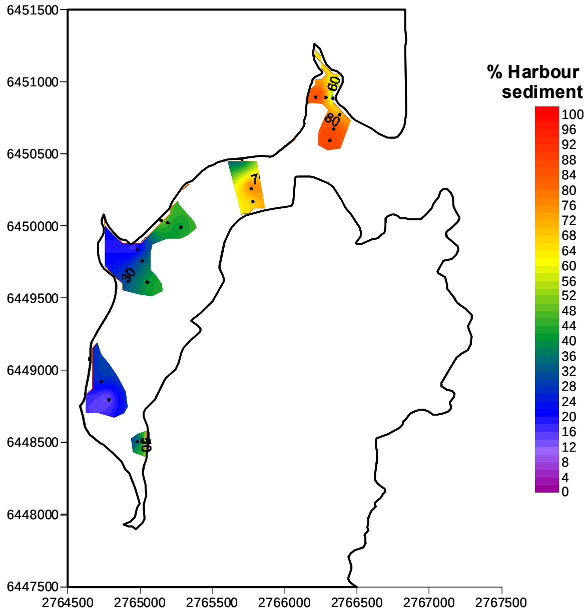

Figure 20: Spatial distribution of the estimated proportions of the Wharekawa Estuary sediments that have been in the estuary for a considerable period of time. Sampling points used are plotted as dots along the transect lines.

The sediment influenced by the seagrass signature was used as an indicator of sediment that has been in the estuary for a long time, and therefore potentially represents sediment stored in the estuary. The distribution plot of these 'estuarine' sediments (Figure 20) shows that higher proportions of that 'stored' material is in the lower estuary consistent with the seagrass distribution in the estuary (Figure 16).

4. Discussion

Although the data values used in the production of this report are mean estimates from the IsoSource model and do not represent absolute values, the distribution plots of these data show patterns which are consistent with most expectations for this estuary. Consequently, qualitative statements can be made and conclusions can be drawn about the sources of sediment in the estuary and sediment movement in the estuary which will reflect the actual changes occurring, or changes that have occurred.

Because of the high proportion of exotic pine forestry (60%) in the Wharekawa catchment, it is little surprise that the source apportionments of terrigenous soil contributions to the Wharekawa Estuary sediments show high proportions (up to 25%) from pine forestry across the whole estuary (Figure 11). The real surprise was that the contribution was not higher. Conversely, this study shows that, at the time of sampling, the major sediment source to the estuary was from sub-soils exposed by recent slips or slip material delivered to the estuary during an intense local storm in April 2006 and presumably progressively flushed from the Wharekawa River with successive rain events.

The effect of the 28 April 2006 storm is distinct from the earlier 12 July 2005 storm. This earlier event struck mainly in the Kapakapa sub-catchment resulting in the washout of a large amount of pine-slash debris and soil into the estuary adjacent to the mouth of that sub-catchment (M. Felsing, Environment Waikato, pers. comm.). That material is still clearly visible in the cut-backs along the sides of the Kapakapa Stream in the estuary (Figure 2), and the presence of at least two distinct layers (Figure 2A) probably reflect water sorting as the storm peak flow entered the estuary and the flow velocity dropped across the intertidal zone.

However, while the pine debris field is visible, the pine source soil distribution data (Figs. 11 and 12) show only minimal amounts of pine source soil in the upper 20 mm of the debris field adjacent to the Kapakapa Stream mouth. The reason for this is that the July 2005 debris field has been covered with sediment from the April 2006 storm that occurred in the Wharekawa River catchment (Figs. 14 and 15). The major difference between these two events is that parts of the Kapakapa sub-catchment had been clear-felled at the time of the July 2005 storm and there were large amounts of pine-slash that could be washed into the estuary. In contrast, the Wharekawa catchment was predominantly mature stable forest without large areas of recent clear-fell logging. Consequently, the April 2006 storm, which caused extensive slips (Figure 3), washed out mainly subsoil sediments into the estuary. This sandy silt deposited throughout the upper estuary, particularly around the mangroves (Figure 17A) and on the sand-flats in the central estuary where there are extensive intertidal zones.

If we assume that the sediment deposition from the April 2006 event has become the base material for subsequent sedimentation events in the last year, the distribution patterns of soil contributions by sub-catchment (Figs. 18 and 19) show how recent sediment is being moved around the estuary and deposited.

Because the Wharekawa River is the largest inflow at the head of the estuary, water and thus sediment from the Wharekawa River sub-catchment will be backed up into the mangroves near the river mouth on the rising tide. Flocculation and sedimentation of material from the Wharekawa River can occur on these intertidal zones only around high tide. At other phases of the tide, the Wharekawa River water is channelised and carried out of the estuary completely on the ebb tide. The higher proportions of Wharekawa River sediment near the Tawatawa and Kapakapa Stream mouths (Figure 18) suggests that the likely zone of flocculation and sedimentation of material from the Wharekawa River extends along the true left bank through the mangroves as far as the Kapakapa Stream where it has covered the debris field from the storm event the previous year.

Discrimination of the sediment input from the Tawatawa sub-catchment is indicative only at the levels shown. Obviously sediment is coming from this sub-catchment as small amounts were found on top of grass along the sides of the stream. However, sediment from the Wharekawa River immediately upstream may be masking the input from this small sub-catchment.

The distribution plot of sediment from the Kapakapa sub-catchment (Figure 19) suggests bimodal deposition around the high tide level. This pattern is consistent with a medium sized inflow being carried upstream along the shore on the rising tide and then downstream as the tide turns but before the stream becomes channelised near the bottom of the tide. Given that, at the time of sampling, the sediment in these two zones was particularly sticky mud, and the sediment in the upstream sample from the Kapakapa Stream was a gritty sand, it may be that new slip material had recently been washed down the Kapakapa Stream burying the finer silty sediments in the stream channel. It is also possible that the finer silts are being sorted and carried further than the heavier sands on each tidal cycle.

Like the Tawatawa Stream sub-catchment, the Wahitapu Stream sub-catchment is relatively small and the sediment distribution patterns presented are indicative only. Sediment is coming down the Wahitapu Stream and fine orange clay material was observed on the sandy sediments around the stream mouth. Data (Table 1) shows that a high proportion of soil in the Wahitapu upstream sample came from young pine forest. The soil sample from the young pine forest area had a high orange clay content and thus these results and observation are consistent.

The distribution of sediment with a seagrass influence was largely confined to the lower estuary (Figure 20). However, while the distribution of that type of sediment largely coincided with the major seagrass beds, other areas with seagrass beds did not carry that sediment type. The reason for that may be a function of the deposition of fresh sediment over these seagrass beds (Figs. 17 and 21). While part of the recent sediment deposition on the seagrass beds adjacent to the Kapakapa Stream mouth appears to have come from that sub-catchment, the majority of the sediment in the top 20 mm across this transect line has come from the Wharekawa River.

Figure 21: Extensive seagrass bed adjacent to the Kapakapa Stream mouth showing the orange-brown newly deposited sandy sediment between the seagrass and the stream channel. Transect line 3 crosses from the surveyor to the point of the mangroves by the Wharekawa River channel (See Figure 1).

In support of this conclusion, site observations show that the sediment carrying the Kapakapa sub-catchment isotopic signatures was a fine sticky mud confined to the inshore side of the Kapakapa Stream channel downstream (Figure 22) and upstream of that inflow. Because of this sharp separation of the two sediment sources, it would be reasonable to suggest that flood-plain soil deposition during tidal inundation of this area of the intertidal zone has been held off-shore by the freshwater plume from the Kapakapa Stream.

Figure 22: View upstream at the mouth of the Kapakapa Stream. The Kapakapa Stream channel separates recent flood-plain sandy sediment mostly from the Kawakawa River (true right bank) from the finer silt and older pine slash debris from the Kapakapa sub-catchment (true left bank). Soil released from the debris field is being moved along the mid-to-high-tide range of the intertidal zone of the estuary while the sandy sediment from the Wharekawa River covers the mid-to-low-tide range of the intertidal zone.

The amount of sandy silt across the estuary from the Wharekawa River seems disproportionately large considering that that soil component makes up <30% of the soil transported by the Wharekawa River. However, water sorting of the backed up river water around high tide would allow the heavier sandy sediments to settle across the intertidal zones leaving the less dense materials to be carried out of the estuary via the main channel on the ebb tide. These less dense materials could be deposited on the ocean beach, consistent with land use soil source proportions estimated (Table 1).

5. Conclusions

The results from this study are estimates based on best professional practice and a limited number of irregularly spaced samples from the Wharekawa Estuary.

The study results indicate that the Wharekawa Estuary may periodically receive large amounts of terrigenous sediment from the whole catchment during heavy rain and that extreme erosion events caused by intense local rain storms may produce flooding and massive sediment deposition from relatively small parts of the catchment. Two such events have been documented in the news media. A storm on 12 July 2005 mainly affected the Kapakapa sub-catchment during logging operations. This produced a large debris field of pine-slash and soil around the Kapakapa Stream mouth, covering local cockle beds to a depth of 20-30 cm.

A second storm on 28 April 2006 caused numerous land slips in mature pine forest, native forest and steep pasture in the Wharekawa sub-catchment (Figure 3). Much of that slip material was carried into the estuary where, the results of this study suggest, it deposited throughout the upper estuary burying seagrass beds and most of the debris field from the earlier event in the Kapakapa sub-catchment. The slip material left in the river channel and across adjacent low-lying farm land is gradually being washed into the estuary with each new rain event. This chronic deposition of silt has the potential to adversely affect the benthic macrofauna, especially those invertebrate species sensitive to sedimentation or enhanced suspended solids, and growth of plants such as seagrass. Mangrove progradation may be enhanced.

Because of the location of the three smaller tributaries on the true left bank of the estuary and the size of the Wharekawa River, it is unlikely that water, and thus sediment, from the smaller tributaries can influence the intertidal zones on the true right bank of the estuary. This means that changes in the size of seagrass beds around the middle and eastern end of transect line 5 are most likely being caused by sediment from the Wharekawa River. Conversely, the results of this study suggest that the increased muddy sediment along the western side of the estuary from transect line 3 to transect line 5 are most likely from the Kapakapa sub-catchment or the breakdown of the inshore part of the debris field from the July 2005 storm releasing stored soil along the mid-to-high-tide range of the intertidal zone.

It is unclear why that sediment is accumulating at the western end of transect line 5. Based on the location near the inside of a bend in the main channel, this site should be an erosion zone. One possibility is that the major deposition of sandy sediment across the seagrass beds on the opposite bank has altered the channel alignment to the extent that sedimentation can now occur.

The results of this study highlight the effects of changing weather patterns and the impacts of extreme weather conditions, the extremity and frequency of which have been increasing in recent years. We know that disturbed land is vulnerable to soil erosion and that the steeper the land the higher the sediment yield, irrespective of whether that land use is native forest, production pine forest or agricultural pasture. Consequently, management strategies being developed for these land uses should include climate variability as an increasingly important factor for consideration in the mitigation of sediment run off effects.

6. Acknowledgements

For the pasture samples, I visited Mrs Foster who told me about the 2006 flood event which covered their farm with about 300 mm alluvial deposits. She also gave me a photo of the event (see Figure 4A). I thank Mrs Foster for the photo and access to her farm for soil sampling, especially the lift on the quad bike to the top of the hill for the steep-slope pasture sample and the 'now' photo (Figure 4B). We also thank Kelvin Meredith for the slip data (Figure 3) and access to the pine forest, Ken Neal at Iso-trace Ltd for the CSI analyses and the GC mass spec traces (Figure 7), and Julie Brown for the bulk stable isotope analyses.

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8. Appendix 1

8.1 Soil and sediment characteristics

Wharekawa sediment and source soil samples collected 17-18 April 2007.

				Sample characteristics				Stable isotope data					
Sample Code	**Sample description** (Transect lines run from west [A samples] to east [C samples])	**Easting**	**Northing**	**Bulk density** ($g\ cm^3$)	**Moisture** (%)	**Organic** (%)	**Carbon** (%)	**Nitrogen** (%)	**$\delta^{15}N$** (‰)	**Carbon*** (%)	**$\delta^{13}C$** (‰)	**$\delta^{13}C$-C16:0/1** (‰)	**$\delta^{13}C$-C18:0/1** (‰)
Estuarine samples													
1A	Transect line 1 - by river channel - east side of river (Bio A)	2764970	6448520	2.20	31.03	15.27	5.27	0.025	4.31	0.21	-21.72	-13.67	-16.59
1B	Transect line 1 - mid point of silt flats - east side of river	2765010	6448520	1.59	13.20	15.93	6.92	0.023	3.78	0.18	-20.72	-14.25	-17.99
1C	Transect line 1 - eastern side of silt flats - east side of river (Bio B)	2765040	6448520	2.02	34.80	16.96	5.53	0.119	3.34	1.17	-20.69	-9.80	-14.64
2A	Transect line 2 - gloopy mud in cleared mangroves (Bio A)	2764640	6449095	2.28	37.79	12.35	3.84	0.072	3.29	0.82	-24.38	-14.45	-20.15
2B	Transect line 2 - sandy mud by Tawatawa Stream (Bio B)	2764720	6448940	2.06	38.45	16.42	5.05	0.069	3.29	0.83	-24.47	-12.20	-18.66
2C	Transect line 2 - gloopy mud in tall mangroves (Bio C)	2764775	6448815	1.73	60.46	17.10	3.38	0.176	3.23	1.85	-24.39	-19.21	-20.52
3A	Transect line 3 - gloopy mud by Kapakapa Stream (Bio A)	2764970	6449855	1.23	52.88	15.15	3.57	0.137	3.80	2.05	-25.72	-15.16	-22.18
3B	Transect line 3 - sandy mud by Kapakapa Stream (Bio B)	2765005	6449775	2.10	36.38	13.99	4.45	0.074	3.58	0.85	-22.70	-13.41	-20.23
3C	Transect line 3 - silty mud across sediment delta (Bio C)	2765040	6449625	2.99	29.72	13.13	4.61	0.041	3.70	0.42	-20.60	-13.32	-18.78
4A	Transect line 4 - muddy seagrass bed	2765135	6450055	2.10	23.62	14.15	5.40	0.051	4.24	0.47	-19.47	-11.95	-17.86
4B	Transect line 4 - sandy mud (Bio A)	2765180	6450040	2.01	25.83	12.57	4.66	0.048	4.45	0.43	-20.22	-12.72	-19.10
4C	Transect line 4 - shelly sand confluence Wharekawa/Kapakapa [11 cockles] (Bio B)	2765270	6450010	2.13	25.00	11.76	4.41	0.016	3.86	0.12	-19.72	-13.99	-20.38
5A	Transect line 5 - gloopy mud in seagrass, west side of Wharekawa River.	2765695	6450480	1.94	44.58	17.22	4.77	0.161	4.21	1.74	-22.34	-16.82	-22.80
5B	Transect line 5 - shelly sand, east side of Wharekawa River. [8 cockles] (Bio B)	2765760	6450275	3.11	22.35	12.83	4.98	0.026	4.74	0.18	-16.29	-10.61	-16.09
5C	Transect line 5 - shelly mud in thick seagrass, east side of Wharekawa River.[1 cockle] (Bio C)	2765770	6450185	3.30	29.09	13.78	4.89	0.040	3.66	0.34	-16.23	-12.49	-16.62
6A	Transect line 6 - sandy mud by Wahitapu Stream (Bio A)	2766325	6450900	2.77	25.93	15.43	5.71	0.026	3.79	0.25	-17.44	-13.52	-20.25
6B	Transect line 6 - sandy mud by seagrass bed (Bio B)	2766275	6450910	1.91	23.70	14.47	5.52	0.026	3.30	0.22	-15.08	-10.91	-15.74
6C	Transect line 6 - sandy mud in sparse seagrass (Bio C)	2766205	6450910	1.88	20.40	15.31	6.09	0.025	1.88	0.20	-15.03	-11.17	-14.40
7A	Transect line 7 - sandy mud in sparse seagrass	2766370	6450790	2.29	21.90	11.76	4.59	0.019	4.20	0.15	-16.47	-12.35	-15.81
7B	Transect line 7 - shelly sandy mud - algal mat present [2 cockles] (Bio A)	2766330	6450690	2.27	24.19	13.54	5.13	0.025	4.74	0.19	-15.24	-9.11	-12.85
7C	Transect line 7 - shelly sandy mud - beside Wharekawa River [3 cockles] (Bio B)	2766305	6450610	2.21	30.72	14.13	4.89	0.038	4.98	0.27	-16.97	-10.04	-13.12
8A	Ocean Beach sand	2766890	6451060	2.48	0.15	10.99	5.49	0.007	4.42	0.07	-23.29	-24.27	-26.35
Sources													
9A	Mature pine surface soil on slope	2757820	6443410	0.70	29.01	18.34	6.51	0.175	2.52	4.20	-28.30	-27.52	-28.20
9B	Clear-felled pine active logging area surface soil on slope	2764060	6445615	0.92	41.89	20.99	6.10	0.217	5.57	5.12	-27.04	-26.54	-26.05
9C	Young pine 3-5 yr old surface soil on slope	2765260	6453585	1.16	26.92	18.58	6.79	0.190	6.19	3.21	-26.07	-25.36	-25.44
10A	Pasture low-level beside drain channels	2763780	6445870	1.05	39.81	17.54	5.28	0.712	4.30	10.22	-27.01	-25.83	-29.16
10B	Pasture flat land floodplain of Wharekawa River [Foster]	2762150	6446655	1.36	8.13	11.48	5.27	0.081	5.09	1.00	-27.30	-23.90	-25.01
10C	Pasture steep slip face topsoil	2761775	6446800	0.76	37.20	17.70	5.56	0.594	3.88	7.59	-26.55	-27.45	-26.41
11A	Slip face / cutting high level in pine/native forest	2757880	6443330	1.26	50.64	14.67	3.62	0.169	6.35	2.93	-25.57	-25.62	-25.51
12A	Native forest/scrub high level steep as patch in pine forest	2757935	6443255	1.03	46.68	22.20	5.92	0.437	2.22	9.63	-27.98	-27.61	-28.02
12B	Native forest low level sloping by stream (*Outside catchment*)	2760575	6435755	0.50	55.48	22.96	5.11	1.065	0.83	9.66	-28.32	-28.71	-25.99
13A	Wharekawa R. upstream silt deposit on river bank	2762880	6447795	0.99	18.89	16.58	6.72	0.112	1.53	1.64	-27.78	-29.91	-28.84
13B	Tawatawa Stm. upstream sandy silt deposit on stream bank	2763505	6448695	1.51	24.34	9.51	3.60	0.025	3.19	0.69	-27.09	-27.35	-29.06
13C	Kapakapa Stm. upstream muddy silt deposit on stream bank-mangroves	2764785	6449990	1.77	36.65	13.53	4.29	0.052	4.17	0.72	-25.62	-21.00	-26.88
13D	Wahitapu Stm. upstream sandy silt deposit on stream bank	2766255	6451080	2.49	20.05	8.76	3.50	0.015	3.78	0.13	-22.17	-22.34	-26.17
14A	Seagrass (roots, stems, and leaves combined)							1.159	4.89	27.22	-8.03	-10.86	-16.89
14B	Algal mat between lines 6 and 7 [layer 5 mm thick on top of the sandy mud]							0.137	3.08	1.15	-12.12	-10.42	-15.79
14C	Ulva							0.752	6.50	20.35	-17.87	-21.04	

Bio A, B, or C refer to the Bioresearches monitoring site as given in West (2006), Figures 17 to 23.
* acidified

8.2 Soil apportionments in the estuarine sediments by land use

Proportional contributions of soils to sediments by land-use

		Pine forest				Pasture			Native	Seagrass	Silt		
Site Code	Description	Mature (%)	Clear-felled (%)	Young (3-5yr) (%)	Total (%)	Low-slope (%)	Steep-slope (%)	Total (%)	(%)	(%)	Slip (%)	Flood-plain (%)	Total (%)
Estuary													
1A	transect 1	6.0	6.8	0.0	12.8	4.2	3.2	7.4	2.5	9.4	13.0	54.9	67.9
1B	transect 1	9.1	4.4	0.0	13.4	2.6	1.6	4.2	3.3	8.9	6.2	64.0	70.2
1C	transect 1	5.9	7.2	0.0	13.1	4.2	3.7	7.9	2.6	14.5	11.7	50.2	61.9
2A	transect 2	1.9	1.9	2.8	6.6	1.4	0.7	2.1	0.7	3.5	1.9	85.1	87.0
2B	transect 2	0.0	0.4	0.6	0.9	0.2	0.0	0.2	0.0	3.1	0.6	95.1	95.8
2C	transect 2	2.5	4.7	10.5	17.7	3.9	1.8	5.8	1.1	3.0	9.9	62.5	72.4
3A	transect 3	2.2	0.2	0.6	2.9	0.3	0.0	0.3	0.4	2.0	0.6	93.7	94.3
3B	transect 3	5.6	1.3	1.7	8.6	0.9	0.4	1.3	1.6	5.2	1.3	81.9	83.2
3C	transect 3	2.0	1.4	1.6	4.9	1.2	0.5	1.6	0.7	5.9	1.1	85.7	86.8
4A	transect 4	5.9	5.3	9.7	21.0	3.1	2.9	6.0	2.5	14.7	9.3	46.4	55.7
4B	transect 4	5.8	5.6	11.1	22.4	3.2	3.3	6.5	2.5	12.6	11.5	44.4	55.9
4C	transect 4	1.4	0.0	0.0	1.4	0.0	0.0	0.0	0.6	4.7	0.0	93.3	93.3
5A	transect 5	3.1	3.2	5.2	11.5	2.3	1.2	3.6	1.3	4.3	3.9	75.5	79.4
5B	transect 5	1.6	2.3	9.1	13.0	2.1	1.0	3.0	0.6	18.2	9.0	56.1	65.2
5C	transect 5	1.2	4.7	11.9	17.8	3.6	2.1	5.7	0.6	17.8	12.3	45.8	58.1
6A	transect 6	6.8	6.0	9.6	22.4	3.1	3.7	6.8	2.9	16.6	9.3	41.9	51.2
6B	transect 6	5.7	5.7	9.7	21.1	2.9	3.3	6.2	2.5	27.2	10.2	32.8	43.0
6C	transect 6	5.1	5.6	9.2	19.9	2.9	3.6	6.5	2.3	27.9	10.0	33.3	43.4
7A	transect 7	5.0	6.1	10.3	21.5	3.2	3.9	7.1	2.3	22.4	11.0	35.6	46.6
7B	transect 7	4.7	5.2	8.7	18.5	2.7	3.5	6.2	2.2	34.9	9.4	28.8	38.3
7C	transect 7	3.7	4.9	9.9	18.4	3.1	2.8	5.9	1.7	27.6	10.8	35.5	46.3
8A	Beach	40.7	3.4	5.7	49.8	1.0	8.2	9.2	16.0	3.9	14.7	6.5	21.1
Streams													
13A	Wharekawa R	30.0	10.6	0.0	40.6	3.4	15.4	18.8	14.0	0.0	10.7	15.9	26.6
13B	Tawatawa Stm	2.9	5.1	13.3	21.2	2.5	5.6	8.1	1.4	0.0	69.2		69.2
13C	Kapakapa Stm	17.9	15.5	27.7	61.1	0.0	0.0	0.0	7.5	3.4	28.0		28.0
13D	Wahitapu Stm	13.4	4.3	60.8	78.5	2.1	2.3	4.4	4.4	4.6	8.1		8.1
10B	Flood-plain silt	2.2	4.7	0.0	6.9	5.3	1.3	6.6	0.5		86.0		86.0

Data are from mean model results and hence values are not absolute

8.3 Soil apportionments in the estuarine sediments by sub-catchment

Proportional contributions of soils to sediments by sub-catchment

Site Code	Description	Wharekawa (%)	Tawatawa (%)	Kapakapa (%)	Wahitapu (%)	Estuary (%)
Estuary						
1A	transect 1	44.9	6.9	8.0	7.1	33.1
1B	transect 1	39.2	5.6	12.1	7.6	35.5
1C	transect 1	22.7	4.0	7.3	5.8	60.1
2A	transect 2	24.0	1.2	47.7	1.7	25.4
2B	transect 2	42.9	6.0	14.5	8.1	28.4
2C	transect 2	59.7	9.1	9.6	9.1	12.5
3A	transect 3	52.5	5.0	20.8	6.6	15.1
3B	transect 3	41.0	2.8	21.5	3.6	31.0
3C	transect 3	36.8	2.7	16.9	3.6	40.0
4A	transect 4	25.6	1.5	15.9	1.9	55.1
4B	transect 4	31.8	1.9	17.8	2.6	45.9
4C	transect 4	29.0	6.8	12.1	11.7	40.5
5A	transect 5	18.4	3.1	48.3	4.8	25.5
5B	transect 5	11.1	2.4	3.6	3.8	79.2
5C	transect 5	17.9	3.8	5.4	6.1	66.9
6A	transect 6	25.1	6.2	12.8	11.9	44.0
6B	transect 6	6.2	1.1	2.1	2.1	88.5
6C	transect 6	8.8	1.7	2.0	2.7	84.8
7A	transect 7	16.3	3.4	4.8	5.4	70.0
7B	transect 7	7.3	1.4	2.3	2.6	86.5
7C	transect 7	7.3	1.2	1.3	1.8	88.4

Data are from mean model results and hence values are not absolute