# Assessment of the Estuarine Ecological Monitoring Programme to 2010

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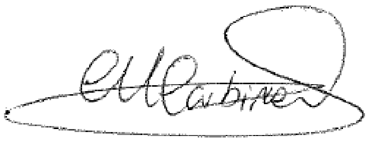

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# Assessment of the Estuarine Ecological Monitoring Programme to 2010

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# Executive Summary

Early in the 1990's, the potential threat associated with increased inputs of terrestrial sediment into estuaries and coastal zones as a result of changes in landuse (including urbanisation) was recognised by NIWA and the then Auckland Regional Council (ARC), now Auckland Council. Since then, the council has melded catchment modelling of likely sediment runoff under various development scenarios, with estuarine sediment transport models and results of experimental investigations of ecological effects to inform planning and development. Ecological experimental manipulations can only be conducted at small scales and a number of problems occur in trying to scale up from a one-off small scale experiment to a potentially large-scale, cumulative impacts. Thus, in 2000 the ARC began monitoring in Okura Estuary (conducted by Uniservices) with the intention of capturing potential changes in the ecology of the estuary associated with periods of pre-development, development and post-development phases. In August 2002, four other estuaries were added to the monitoring programme (Puhoi, Waiwera, Orewa and Mangemangeroa). In August 2004, Turanga and Waikopua estuaries were added to the regional monitoring programme.

Ten sites were located along the length of each estuary, with sites further up the estuary assumed most likely to be impacted by terrestrial sedimentation. The monitoring over time, in spring and autumn, within and between estuaries was designed to detect long-term effects driven by chronic increases in turbidity and in the proportion of fine muddy sediments in the estuary. Similar to other programmes monitoring the health of coastal and estuarine ecosystems, both in New Zealand and internationally, the focus was on the macrofauna living in the intertidal sediments. Environmental variables that may be affected by increased terrestrial sedimentation, such as sediment particle size and height of the seafloor, were also measured. To determine whether individual sediment depositional events resulted in changes to the benthic communities, sites were also monitored after a rainfall event and after a relatively dry period in both seasons. In 2007, this sampling was changed to target heavier rainfall events, regardless of when they might occur during the year. Due to the patchiness of heavy rainfall in the Auckland area, this sampling was limited to estuaries that had gauging stations situated in their catchments (namely, Okura, Orewa and Mangemangeroa).

In 2009, NIWA took over the monitoring, and, in line with many of the benthic ecological monitoring programmes run by the ARC, after 5 years of consistent monitoring, a spatially and temporally nested design was introduced. The number of sites continuously monitored in each estuary was reduced to 7 with the extra 3 sites being sampled on a rotational basis over 5 years. After 1 year of sampling, the data from all years was analysed to produce the following findings.

- No changes were observed coincident with the change in provider.
- Overall, the macrofaunal communities in the estuaries appear to be maintaining their status. However, some changes consistent with those predicted to occur as a result of increased sediment mud content or sedimentation were observed.

Trends over time in community composition consistent with increased sediment mud content were detected for two sites in Turanga, Puhoi and Orewa and one site in each of the other estuaries, with the exception of Mangemangeroa. Changes of concern in the abundance of taxa or diversity, consistent with ecological predictions of response to increased terrestrial sedimentation or mud content, were observed at 1 site in each of Orewa, Puhoi, Waikopua and Waiwera, and at 4 sites in Okura. While the changes observed do not indicate a large degree of change across these estuaries, they are sufficient to warrant continuation of the monitoring programme in its reduced state.

- The sampling regime for events based around rainfall trigger levels initiated in 2007 has proven more sensitive than the previous regime for detecting ecological responses to individual events. The observed responses are not usually consistent across sites or events; however, some of this inconsistency is explainable by the size of the event and the amount of rainfall falling in the 24 hrs prior to sampling. Importantly, sampling over a number of events occurring within a 6 week period revealed cumulative reponses by the benthic community. These results suggest that the event monitoring provides a valuable function in strengthening the causal link between macrofaunal change and terrestrial sedimentation, and between predictions generated from experimental manipulations of terrestrial sedimentation and from surveys of ambient sediment content.

- The recently initiated changes to the monitoring programme will not reduce the ability of the programme to detect changes associated with increased terrestrial sedimentation. Indeed monitoring the grainsize composition of the surficial (top 2–3 mm) sediment has proven to be a useful predictor of change in community composition.

- Monthly monitoring of environmental variables (volume and grainsize of sediment caught in the sediment traps and height of the bed) comprises a significant portion of the costs of this monitoring programme. However, this data has proven to be variable and not always useful. Our recommendation, therefore, is that the monitoring of the sediment traps is removed from the programme. Bed height can remain monitored, as it requires little effort, but only needs to occur when the macrofaunal community is monitored.

This monitoring programme provides a vital feedback to planning and policy conducted in the region, allowing assessment of urban development impacts, and thus the relative risks of differing management policies, on the estuaries that so many Aucklanders wish to utilise.

# 1 Introduction

Planning for growth of the Auckland region has for some time suggested that the estuaries on the fringes of the metropolitan area are prime candidates for residential expansion. Early in the 1990's, the significant threat of increased terrestrial sediment runoff into estuaries and coastal zones as a result of this development was recognised by NIWA and the ARC. Initially it was thought that muddy areas (e.g., tidal creeks and upper estuary areas) would be less affected than sandy areas, but a number of small-scale experimental studies, co- funded by FRST and ARC , found that all areas were potentially at risk (Norkko et al. 2002). Around the east coast of the Auckland Region, ecological responses were observed as a result of quite small experimental applications of terrestrial sediment onto the seafloor and into the water column. These responses ranged from changes in the feeding behaviour and health of individual species to complete eradication of whole macrofaunal communities (Ellis et al. 2002, Hewitt & Pilditch 2004, Lohrer et al. 2004, 2006, Norkko et al. 2006, Hewitt & Norkko 2007). To better manage the risks associated with this major contaminant, the ARC melded catchment modelling of likely sediment runoff under various development scenarios, with estuarine sediment transport models and results of experimental manipulations on ecology to inform planning and decision making.

Ecological experimental manipulations can only be conducted at small scales and a number of problems arise in trying to scale up from a one-off small-scale experiment to potentially large-scale and cumulative impacts (Thrush et al. 1999, Hewitt et al. 2007). A weight of evidence approach has been used to infer broader-scale effects by comparing the taxa shown to be sensitive in the experiments with those demonstrating relationships with sediment mud content or sediment accumulation rates from large-scale surveys (Lundquist et al. 2003, Gibbs & Hewitt 2004, Thrush et al. 2004, Anderson et al. 2007). However, stronger evidence is often required in a court of law. Thus, in 2000 the ARC began monitoring in Okura Estuary (conducted by Uniservices) with the intention of capturing potential changes in the ecology of the estuary associated with periods of pre-development, development and post-development phases.

In August 2002, four other estuaries were added to the monitoring programme (Puhoi, Waiwera, Orewa and Mangemangeroa). Mangemangeroa was added as the urbanisation beginning to occur around its catchment was planned to intensify over time. Orewa was included as an example of an estuary with an already developed catchment. Puhoi and Waiwera were included in order to place any potential changes through time in the other estuaries within a broader regional context. However, Mangemangeroa is spatially separated from the others (lying to the south of Auckland City and discharging into the Whitford Embayment). To enable useful comparisons to be made and to extend the number of reference estuaries, in August 2004, Turanga and Waikopua (also from the Whitford Embayment) were added to the regional monitoring programme.

The design of the monitoring centered around 3 phases of development that differed spatially between estuaries and, for some estuaries, varied over time. Ten sites were located along the length of each estuary. Sites further up the estuary were assumed to be most likely to be impacted by terrestrial sedimentation. The monitoring over time within and between estuaries was designed to detect long-term effects driven by chronic increases in turbidity and in the proportion of fine muddy sediments in the estuary.

To determine whether individual sediment depositional events resulted in changes to the benthic communities, the sites were monitored in spring and autumn in each year, once after a rainfall event and once after a relatively dry period. A report of the results from 2000 to 2007 found no effect of individual events and this lack of effect was suggested to be a result of the size of rainfall events that were being monitored (Anderson et al. 2007). At this time the definition of an event was > 15 mm in a 24-hour period. Unfortunately this sized event could be expected to occur at least twice in each of the seasons and therefore was unlikely to have a detectable effect in a system as physically dynamic as an estuary. Most of the studies investigating one-off events relate to sediment deposition events associated with much more severe storms (e.g., Norkko et al. 2002; Hewitt et al. 2003). After consultation with the ARC, the design of the monitoring programme was altered to target heavier rainfall events, regardless of when they might occur during the year. Due to the patchiness of heavy rainfall in the Auckland area, such monitoring was to be limited to estuaries that had gauging stations situated in their catchments (namely, Okura, Orewa and Mangemangeroa).

Unfortunately, since monitoring began, a number of the reference estuaries have either had urbanisation increase around their catchments or been subject to extensive road works within the catchments associated with the extension of the northern motorways. The present lack of real reference estuaries has necessitated a shift in the design and analysis of the monitoring programme.

Two further changes have occurred in the monitoring programme since the last report. Firstly, in line with many of the benthic ecological monitoring programmes run by the ARC, after 5 years of consistent monitoring the number of sites monitored in each harbour has been reduced. Secondly, the collection and analysis of data has also recently been shifted from Uniservices to NIWA.

This report therefore investigates a series of questions.

1. Have the recent changes in design or operation had any impact on the ability of the monitoring programme to detect changes over time?
    a. Are there any differences caused by the change in provider?
    b. Has the reduction in sites had a deleterious effect on our ability to detect change?
2. Can an ecological response to an individual storm event be detected and if so which measured variable best explains it?
3. Are there ecological changes over time in any of the estuaries that are associated with increased terrestrial sedimentation?
4. Are there any other cost-effective improvements that can be made to the monitoring programme now that over 6 years of data have been collected from all estuaries? This question is divided into two further questions:
    a. considerable effort is placed in this programme in the monitoring of traps that collect sediment passing over the sites, with the idea that

this information can provide a causal link to terrestrial sedimentation. How useful is this information? Is there other, more cheaply collected information that is better?

b. is the temporal variability caused by sampling within a 3 month window sufficient to confound detection of changes?

# 2 Sampling methods

## 2.1 Estuaries and sites

Seven small east coast estuaries are monitored: Puhoi, Waiwera, Orewa, Okura, Mangemangeroa, Turanga and Waikopua (Figure 2.1). These estuaries have been sampled for varying lengths of time: Okura from April 2000; Puhoi, Waiwera, Orewa and Mangemangeroa from August 2002; and Turanga and Waikopua from August 2004.

Initially 10 sites were sampled within each estuary with 1 being closest to and 10 being furthest from the mouth of the estuary (see Appendix 1 & 2 Anderson et al. 2008 for placements of the sites). Within the Whitford embayment, the sites were chosen to cover zones previously identified as being most vulnerable to potential impacts from sediment inputs, or as areas of high biodiversity (Senior et al. 2003). Sites are located at mid-tide (ranging from -0.6 to 1.6 m tidal height relative to mean sea level) and are 50 m (parallel to the waterline) x 25 m (perpendicular to the waterline).

Since August 2009, the number of sites in each estuary has changed. Following analysis of the Manukau Ecological Monitoring Programme (Hewitt et al. 1994, Hewitt and Thrush 2007), demonstrating the cost-effectiveness of temporally nested monitoring, the ARC has been establishing this technique throughout most of their ecological monitoring programmes once 5 years of data has been collected and analysed. Given the gradient nature of the within-estuary design, it was decided to continue sampling 7 of the sites across the gradient in each estuary as permanent sites (Table 2.1) and rotate sampling of the remaining sites over a 5 year period (i.e., 4 extra sites per year). In 2009-2010, all sites in Turanga were monitored as was a single extra site in Okura (7 continuous sites plus 1).

Moreover, as the analysis of the sediment trap data is a considerable component of the cost of the monitoring programme and yet was not identified as being very useful in the last report (Anderson et al. 2008), it was decided that while collection of the trap sediment would continue, analysis would only be done on 3 sites. The selection of these three sites was done in conjunction with the ARC and covered the established gradient of volume of sediment caught in the traps for each estuary (Table 2.1).

**Figure 2:1:**

Location of the 7 monitored estuaries.

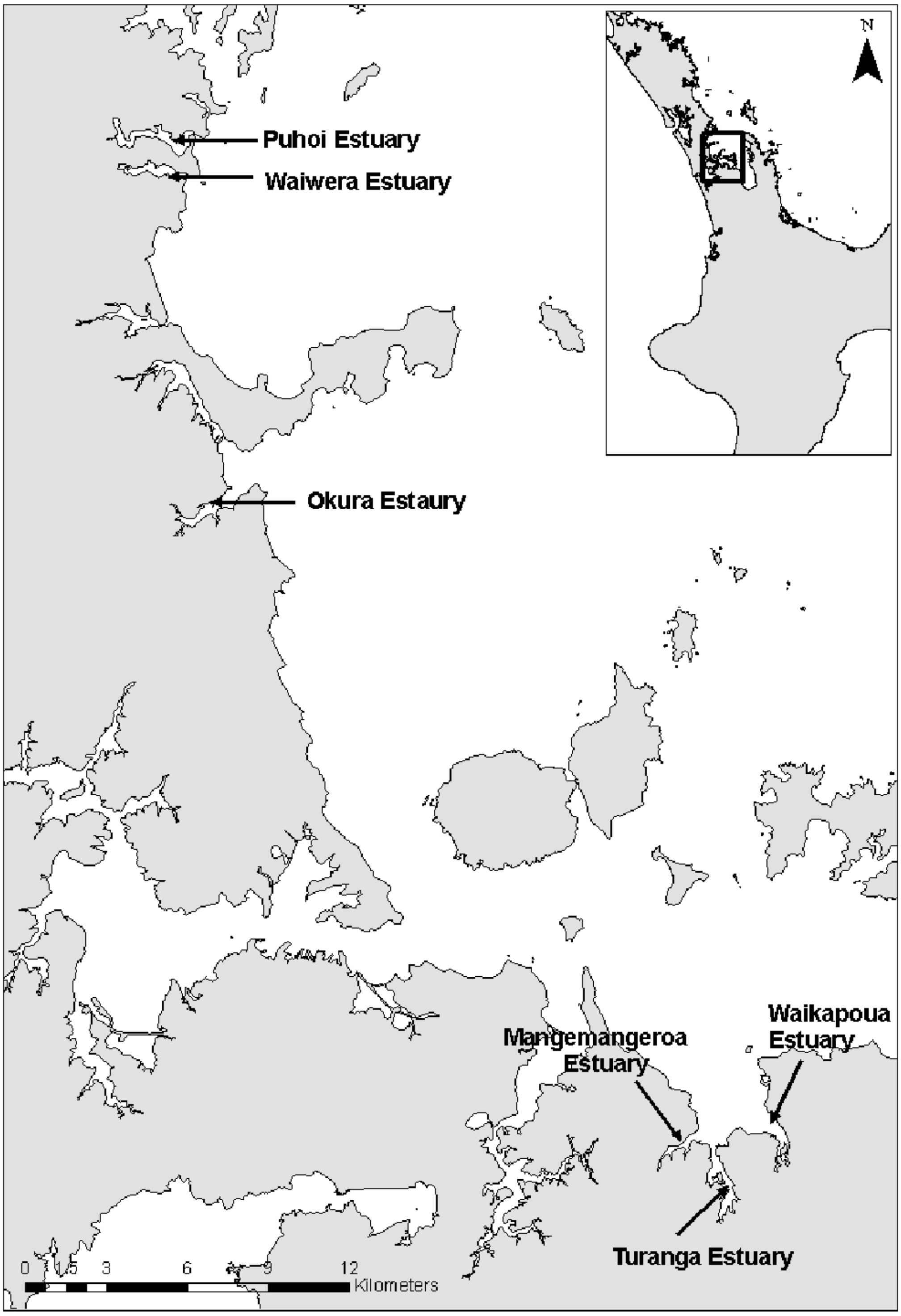

**Table 2.1:**

Sites retained as permanent sites in each estuary, sites for 5 yearly rotation and the sites used for sediment trap analysis.

| Estuary | Sites for rotation | Permanent sites | Trap sites |
|---|---|---|---|
| Puhoi | 5, 8, 10 | 1–4, 6,7, 9 | 9, 4, 1 |
| Waiwera | 4, 7, 10 | 1-3, 5, 6, 8, 9 | 8, 6, 2 |
| Orewa | 7, 9, 10 | 1–6, 8 | 8, 4, 1 |
| Okura | 5, 6, 10 | 1–4, 7–9 | 9, 7, 3 |
| Mangemangeroa | 1, 4, 8 | 2, 3, 5–7, 9, 10 | 9, 6, 3 |
| Turangi | 2, 5, 9 | 1, 3, 4, 6–8, 10 | 7, 4, 3 |
| Waikopua | 2, 5, 10 | 1, 3, 4, 6–9 | 8, 6, 3 |

## 2.2 Macrofauna

Initially, sampling occurred twice (after rain, and after a dry period) within each of two discrete seasonal three month blocks (winter/spring: August–October and summer/autumn: February–April), yielding four sampling times per year. In 2007, this was altered; the dry sampling was maintained, but the rainfall sampling was changed to being triggered by rainfall in excess of 60, 57.5 and 50.6 mm over a 24 hr period recorded at gauging stations in Orewa, Okura and Mangemangeroa respectively. Only estuaries where the trigger occurred were sampled and sampling occurred within 7 to 10 days of the trigger event.

At each site, six replicate faunal cores (130 mm in diameter x 150 mm deep) are taken from random positions at each site, excluding the area within 5 m of a core location for the previous 6 months. Cores are sieved on a 0.5 mm mesh and the material retained preserved in 70% isopropyl alcohol with 0.01% rose bengal. Later the fauna are identified to the lowest practical taxonomic level (usually species) and counted. Anderson et al. (2008) noted that the level of taxonomic resolution has increased markedly through time, and that community-level analyses use data only from August 2002 onwards. Throughout the analysis in this report the level of taxonomic resolution reported in Appendix 5 (Anderson et al. 2008) has been used.

Individuals from three bivalve species (the cockle *Austrovenus stutchburyi*, the wedge shell *Macomona liliana* and the pipi *Paphies* australis) were placed into size classes to allow some assessment of changes in the population structure of these large and long-lived animals.

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## 2.3 Sediment

### 2.3.1 Ambient sediment

Sampling of ambient sediment to determine changes in sediment grainsize is coincident with macrofaunal sampling. Initially, ambient sediment samples were obtained adjacent to each faunal core using a 38 mm diameter x 15 cm deep corer. This however dilutes any recent changes in sediment characteristics by the bulk of the material collected in the core. In August 2004, sampling changed to using a 20 ml syringe sampling to a depth of approximately 2 cm.

The six sediment cores from a single site were combined into a single sample which was frozen until grainsize analysis could occur. Prior to grainsize analysis, organic matter was removed using 9% hydrogen peroxide until fizzing ceased. Samples were then dried and weighed to obtain a total dry weight. They were then deflocculated for at least 4 hours (using Calgon 5g per litre) and wet-sieved on a stack of sieves (500, 250, 125 and 63µm). Each fraction (> 500, 250–499, 125–249, 63–124 and < 63µm) was dried, weighed and calculated as a percentage of the total weight. The fraction less than 63 µm was calculated by subtraction of all other dry weights from the initial dry weight. Due to the change in depth sampled and the sizes of the sieves used, only data from August 2004 onwards are used for subsequent analyses.

### 2.3.2 Terrestrial sediment inputs

Initially, sediment inputs were characterised by using a combination of a sediment trap and a depth-of-disturbance rod at each site:

1. A sediment trap (37 mm diameter by 500 mm deep) was placed at the lowest point of each site so that the opening was 200–250 mm above the sediment surface. These traps collect sediment passing over the mouth of the trap. Sediment traps are deployed continuously at each site and are sampled approximately after monthly. However, at some sites a shorter deployment period was necessary (e.g., a fortnight, or even less), because these sites have a greater turnover of sediments and, if left for a whole month, the traps would frequently overfill, or at least breach the desired aspect ratio (distance to top of trap from sediment within/diameter of trap > 10) that needs to be maintained to ensure that substantial resuspension of sediment out of the trap does not occur. Data from traps were excluded from subsequent analysis when aspect ratios were breached. Otherwise, the amount of sediment collected in the traps over each period was standardised across all sites by being expressed as a rate in grams per $cm^2$ per day. Sediment collected from traps was filtered (mesh size ~2 µm), dried and weighed. These sediments were then sub-sampled, pre-treated for organics, deflocculated and wet sieved as for ambient sediments to characterise their grainsize fractions.

2. Depth-of-disturbance rods were used to gauge relative change in the height of the bed using the poles that held the sediment traps. Measurements were taken between the top of the sediment trap holder and the ambient sediment surface at least once a month to measure the net erosion or accretion at a site. When scour was present at the base of the marker poles the height of the top of the holder

was estimated in relation to the ambient bed height at the pole independent of any local scouring using a ruler.

However, neither of these measures is considered an effective measure of the degree of terrestrial sediment being deposited at the site. Depth of disturbance rods only measure net accumulation, i.e., deposition–erosion, usually with large errors relative to the magnitude of change that might be expected. Traps do not precisely quantify sediment deposition because they integrate deposition from the water column and resuspension of material from the bed. Neither contain information about the source of the sediment: is it terrestrial sediment washed down the creek or site sediment resuspended by waves, or even marine sediment washed up on shore by waves and currents?

For this reason a new measure was instituted in August 2009. Recently, sediment tracking techniques have been developed that allow determination of sediment sources (e.g., separating land from marine or forest and farming from urban land use). Recent studies using 13C and 15N stable isotope analyses of organic matter (e.g., Cloern et al. 2003; Cook et al. 2004) were able to discriminate between terrigenous and estuarine sources. Different plants produce the same compounds (e.g., fatty acids) but with different compound specific isotopic signatures, allowing soils from different landuse to be separated (Gibbs 2008).Determining that the amount of sediment from urban landuse was increasing at the same time that the ecology was changing would enhance the ability of the programme to correctly attribute cause and effect and thus aid the ARC in developing and defending management strategies. In December, sediment samples were collected from the surface 3 – 5 mm at each site with sediment traps in place. At the same time, samples were taken from: stream inflows into the more estuarine environment; coastal areas; and, for some estuaries, different land uses. The latter were taken to add to information on specific signatures related to different landuses and catchments. Each bulk soil or sediment sample was mixed and sieved through a stainless steel 1-mm mesh to remove stones, shells, plant material, invertebrates, and benthic macrofauna before storing in the dark at 4 °C for analysis of carbon, nitrogen and fatty acid isotopes (as per Appendix 1 and Gibbs 2008).

Finally, on every sediment trap sampling occasion, sediment samples were collected from the surface 2–3 mm at each site with sediment traps, particularly focusing on the troughs of any ripples, as this is where recently transported fine sediment would accumulate. These samples were analysed for grainsize (as per section 2.3.1), with the intention of comparing these measurements with those of the trapped sediment.

## 2.4 Rainfall event sampling

Event sampling according to the new trigger values occurred a number of times in all three estuaries (Okura, Mangemangeroa, Orewa), although the number of rainfall events and the size of these differed (Table 2.2). Because of this, and due to differences in macrofaunal community composition between estuaries (e.g., not all estuaries have abundant pipi (*Paphies australis*) populations at their mid to outer sites), analyses of macrofaunal community responses to events were conducted on each estuary separately.

**Table 2.2:**

Dates of event sampling in each estuary, including information on rainfall (mm) preceding the sampling date both of the event and of the nearest dry sampling period.

| Sampling Date (days after event) | Rainfall (mm) | | Rainfall (mm) | | Rainfall (mm) | |
|---|---|---|---|---|---|---|
| | Event | Previous 2 weeks | Previous 24hrs | Dry sampling date | Previous 2 weeks | Previous 24hrs |
| **Okura** | | | | | | |
| 9th Oct 2007 (7) | 80 | 110 | 0 | 9th Aug | 180 | 2 |
| 3rd Mar 2008 (7) | 72 | 100 | 0 | 1st May | 75 | 12 |
| 6th Aug 2008 (11) | 55 | 31 | 0 | 16th Sep | 30 | 0 |
| 19th Jun 2009 (9) | 72 | 112 | 0 | 10th Feb | 9 | 6.7 |
| 6th Jul 2009 (7) | 90 | 113 | 20 | 21st Sep | 30 | 0 |
| 11th Dec 2009 (7) | 100 | 122 | 0 | 21st Sep | 30 | 0 |
| 28th May 2010 (7) | 123 | 180 | 10 | 14th Apr | 27.5 | 2 |
| **Mangemangeroa** | | | | | | |
| 8th May 2008 (4) | 58 | 155 | 0 | 2nd May | 98 | 5 |
| 15th May 2008 (6) | 45 | 80 | 2 | 2nd May | 98 | 5 |
| 6th Aug 2008 (9) | 65 | 172 | 3 | 16th Sep | 28 | 0 |
| 11th Dec 2009 (6) | 60 | 83 | 0 | 21st Sep | 7 | 0 |
| 28th May 2010 (7) | 50 | 95 | 5 | 14th Apr | 29 | 0 |
| **Orewa** | | | | | | |
| 11th Dec 2009 (7) | 80 | 105 | 0 | 21st Sep | 15 | 0 |
| 28th May 2010 (7) | 102 | 185 | 3 | 14th Apr | 18 | 0 |

# 3 Have the recent changes in monitoring design had any effect?

Initially 10 sites were sampled in each estuary by Uniservices. Since August 2009, sampling has been conducted by NIWA and the number of sites routinely sampled in each estuary has decreased to 7. Sites were selected for continuous monitoring based on 3 criteria. Firstly, the gradient in sediment mud content present in each estuary needed to be maintained. Secondly, good spatial coverage of each estuary was needed. Thirdly, sites should preferably be those exhibiting the least temporal variability in macrofaunal community composition.

This section answers two important questions:

1. Are there any differences caused by the change in provider?
2. Has the reduction in sites had a deleterious effect on the programme's ability to detect impacts?

## 3.1 Methods

While there is little reason to expect any differences in measurements made by the different providers, it is sensible to check this. Graphical analysis of time series of the different measures was used to check for any step changes in the data coincident with the change in provider. The taxon lists pre and posts August 2009 were also compared.

The effect of the reduction in sites on the relationship between sediment mud content and macrofaunal community composition in each estuary was investigated using canonical analysis of principal coordinates (CAP, Anderson and Robinson 2003, Anderson and Willis 2003). This and all subsequent multivariate analyses were conducted using the PRIMER v6 computer program (Clarke and Gorley 2006) on square root transformed Bray-Curtis similarities, as per Anderson et al. (2008).

For each estuary, a CAP analysis was conducted on all sites for dry sampling occasions occurring between August 2004 and 2009 and then using only the 7 sites in each estuary that were to be continuously monitored. The strength of these two relationships was then compared for each estuary.

## 3.2 Are there any differences caused by the change in provider?

The taxonomic resolution of the previous dataset was relatively low in some instances. While taxonomic resolution has increased in the last year, analyses involving past data can easily be accommodated by grouping species/genera to higher taxonomic levels. Appendix 2 lists the 20 taxonomic groups previously used together with the 44 new taxa they represent (mainly at species level). Two taxa new to this monitoring programme were also observed over the past year: an Onuphid worm; and a gastropod, *Zeacumantis subcarinatus*.

Thirty nine taxa that had previously been found were not observed in the past year (Appendix 3). Some of these are irresolvable, i.e., taxa previously labeled as unidentified Anemone, Bivalve, Crab, Crustacean or Polychaete. Others may be mistakes or are not true marine macrofauna. The previously identified Gnathiidae was most likely a crab in larval form as Gnathiidae are generally deep water fauna, Gnathostomulida is generally considered as meiofauna rather than macrofauna and mites are freshwater invertebrates that may be washed down in storms. The rest of these unobserved taxa were generally found only rarely so it is not surprising that they were not found on the 4 additional recent occasions.

Once the new taxa had been aggregated to the previous taxonomic resolution, no consistent changes to the macrofaunal communities coincident with the start of the new sampling provider were apparent (Figures 3.1 & 3.2). Some change did occur at Puhoi Site 7 with the last 2 sampling occasions being outside the previous ordination space (Figure 3.2), but this site has always been variable over time. Waiwera Site 1 continued to show a trend within the ordination space of moving away from that occupied by the other sites (Figure 3.2).

**Figure 3.1:**

Non-metric multidimensional scaling ordination showing tracks over time of all sites in Mangemangeroa, Okura and Orewa between August 2004 (open circle)–April 2010 (X), based on site averaged species composition (stress = 0.17). Time tracks not ending in X represent those sites not sampled since autumn 2009. Changes co-incident with the new provider would require the line ending in X point to lie outside the ambit of the previous sampling points at a site.

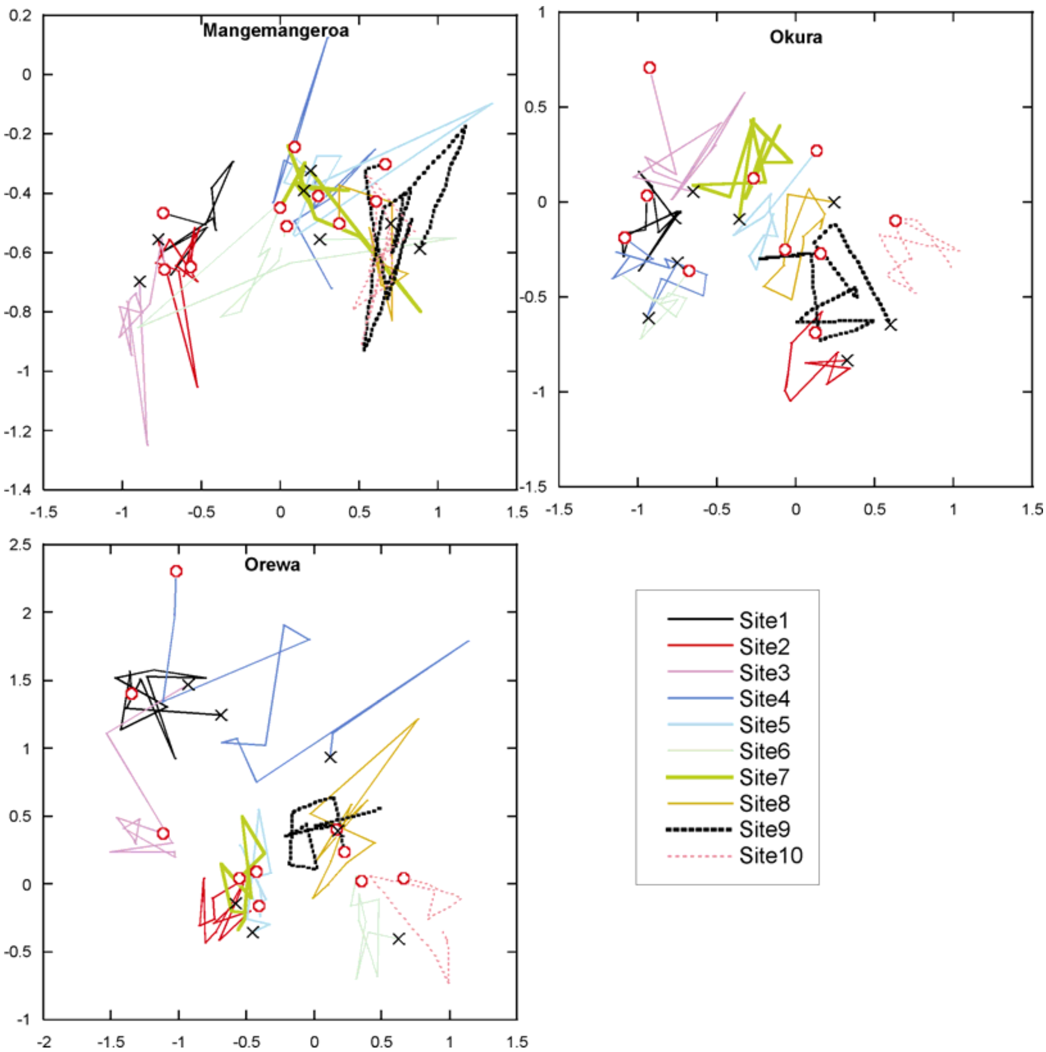
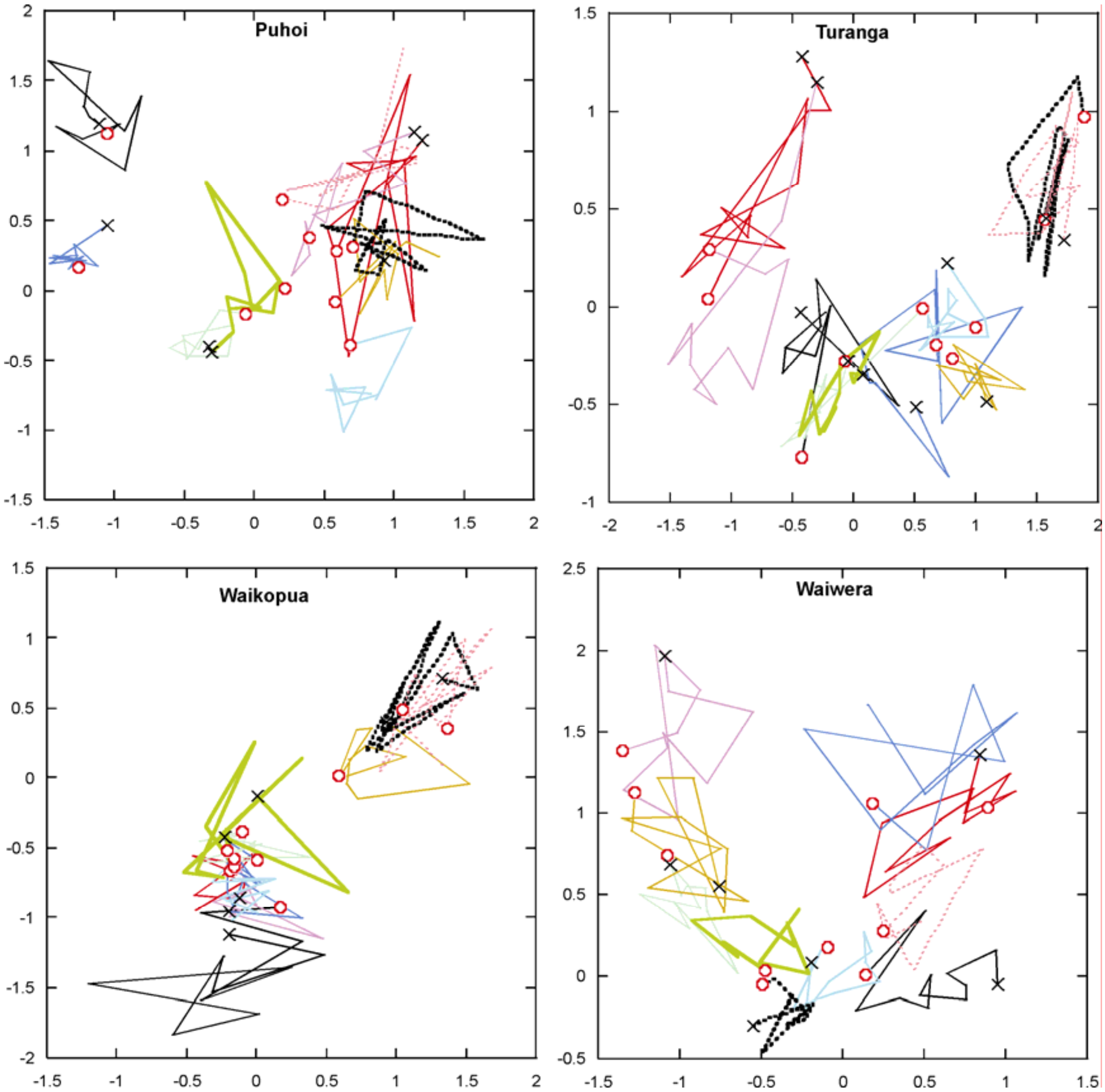


**Figure 3.2:**

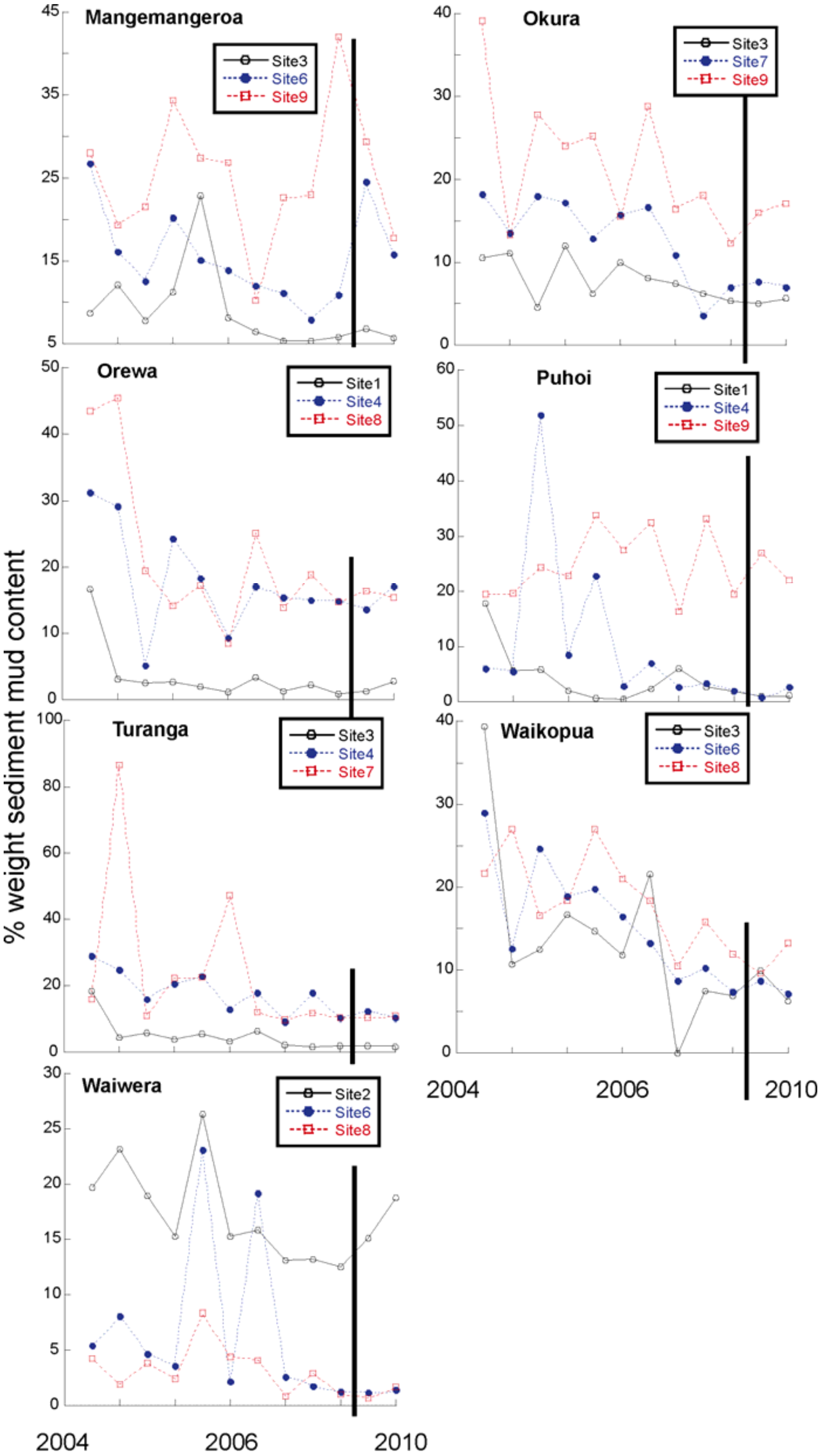
Non-metric multidimensional scaling ordination showing tracks over time of all sites in Puhoi, Turanga, Waikopua and Waiwera between August 2004 (open circle)–April 2010 (X), based on site averaged species composition (stress = 0.17). Time tracks not ending in X represent those sites not sampled since autumn 2009. Changes co-incident with the new provider would require the line ending in X point to lie outside the ambit of the previous sampling points at a site. Refer to Fig. 3.1 for legend.




Similarly, there were no obvious step changes in bed height, trapped volume of sediment, % content of mud in trapped sediment or ambient sediment grainsize (see Figure 3.3 and Appendix 4 for selected figures).

**Figure 3.3:**

Temporal pattern of ambient sediment mud content at 3 sites from each estuary. A black line marks the change in provider.



## 3.3 Has the reduction in the number of sites had a deleterious effect?

Reducing the number of sites in each estuary from 10 to a core of 7 generally had only small effects on the ability to find a relationship between macrofaunal community composition and sediment mud content (Table 3.1). Changes in the correlation between community composition and mud content determined by CAP were all under 10%. In fact, only for Puhoi and Mangemangeroa was there greater than a 5% decrease. For Waiwera there was no change, and for Waikopua and Orewa there was actually an increase in the strength of the correlation.

**Table 3.1:**

Correlation coefficients between community composition and mud content for all 10 sites or the 7 core sites, together with the %reduction in correlation. A negative reduction is an improvement in the correlation.

| | All 10 sites | Core 7 sites | % reduction |
|---|---|---|---|
| Mangemangeroa | 0.75 | 0.69 | 8 |
| Okura | 0.76 | 0.73 | 4 |
| Orewa | 0.71 | 0.74 | -4 |
| Puhoi | 0.65 | 0.59 | 9 |
| Turanga | 0.66 | 0.63 | 5 |
| Waikopua | 0.75 | 0.76 | -1 |
| Waiwera | 0.82 | 0.82 | 0 |

# 4 Are there ecological changes over time associated with increased terrestrial sedimentation?

Macrofaunal communities are not expected to remain consistent over time. There will always be some temporal shifts, for example, seasonal patterns and longer-term cyclic patterns associated with recruitment patterns of particular species or El Nino events. However, the ecological monitoring over time in the Manukau and Mahurangi Harbours, conducted by the Auckland Council, demonstrate that these natural changes are generally small and do not prevent detection of impacts associated with human use. So, it is not enough to describe changes in the communities at the different sites and estuaries; rather we need to know whether any observed changes are associated with increased terrestrial sedimentation.

## 4.1 Methods

CAP was used to model macrofaunal community composition along a gradient in the percentage mud of ambient sediments across the region. In 2007, a model was created using averages in both faunal abundances and percentage mud from time 20 (August 2004) onwards, on dry sampling occasions, at each of the 70 sites, thus integrating temporal variation. However, this averaging over time integrates any possible changes in community composition relating to increased terrestrial sedimentation occurring over time. While this may have had limited effect in 2007, the longer the time series included in producing the averages the more effects of increased terrestrial sedimentation may bias the results. For this reason, in the present report the averaging was undertaken on sampling conducted from spring 2004 (the earliest date that all estuaries were sampled) to autumn 2007 only. Once the model had been produced, temporal changes in macrofaunal community composition over time were mapped onto the canonical axis of the mud gradient model using the 'add samples' option available in Primer V6. The resultant scores (CAPmud) from each site were then analysed by regression to determine trends over time. The potential for temporal autocorrelation was investigated but proved not to be important within this short time period. Note that this analysis as reported in Anderson et al. (2008) did not incorporate any of the sediment trap information, presumably as it was not useful.

Anderson et al. (2008) also determined a number of dominant taxa that showed responses to mud content of sediment using quantile regression (Table 4.1). Five taxa (*Paphies australis, Colurostylis* spp., *Anthopleura aureoradiata, Waitangi brevirostris and Aonides oxycephala*) were found to strongly prefer low mud content and three taxa (crabs, Nereididae polychaetes and Corophidae amphipods) were found to prefer high mud content. The results were similar to those found by Thrush et al. (2003) using maximum density models and thus seem likely to be robust. However, the models developed in Thrush et al. (2003) were also developed from data sets gathered over different spatial scales, regional, estuary and sandflat (Thrush et al. 2005). In this analysis, at the estuary-scale, they report a strong positive relationship between % mud content and Nereididae abundance, and a much improved negative relationship for *Austrovenus* and *Macomona*. Therefore, changes in abundance of these taxa at each site over time were also analysed in this section to determine whether any changes were consistent with the predicted response to increasing mud content.

**Table 4.1:**

Results of analyses (TP384, Thrush et al. 2005) of the response of the 20 most dominant taxa at the sites to % sediment mud content, showing optimum mud content (range given if differences are observed between studies) and categories used in analyses. S = taxa that have optimal abundances at < 10% mud; M = taxa that have optimal abundances at > 30% mud. Taxa not designated as preferring either mud or sand are those that either prefer intermediate levels of mud, or have optima that occur over a large range of mud content.

| Taxa | Optimum mud content (%) | Analysis category |
|---|---|---|
| *Paphies australis* | 3.4 | S |
| *Colurostylis* spp. | 3.4 | S |
| *Anthopleura aureoradiata* | 3.4 | S |
| *Waitangi brevirostris* | 7.5 | S |
| *Aonides trifida (oxycephala)* | 8.1 | S |
| *Austrovenus stutchburyi* | 0–10 | S |
| *Macomona liliana* | 0–10 | S |
| *Nucula hartvigiana* | 12.0 | |
| *Prionospio (Aquilaspio) aucklandica* | 12.0 | |
| Barnacles | 13.4 | |
| Exogoninae | 14.2 | |
| *Arthritica bifurcata* | 17.4 15–25 | |
| *Heteromastus filiformis* | 23.2 20–25 | |
| Orbinids | 23.2 20–30 | |
| *Capitella* spp. and Oligochaetes | 28.5 20–40 | |
| Polydorid complex | 29.2 | |
| Corophidae | 41.2 | M |
| *Austrohelice (Helice), Hemigrapsus, Hemiplax (Macrophthalmus)* | 41.2 | M |
| Nereididae (Nereidae) | 40 | M |
| *Paracalliope* spp. | NA | |

Analyses were also conducted on different size classes of the measured bivalves (*Austrovenus, Macomona* and *Paphies*). Where a significant change to the overall abundance of these bivalves was found, analyses were also conducted on the different size classes to determine whether the population as a whole was showing a change or whether it was confined to specific size classes.

We also incorporated number of taxa into this analysis. Experiments manipulating terrestrial sedimentation events conducted in Okura, Mahurangi and Whitford, all observed decreases in number of taxa. A survey conducted across a number of Auckland estuaries, measuring rates of sediment accumulation over the last 50 years, observed that muddy sites were not necessarily less diverse than sandy sites, but that higher rates of sediment accumulation were associated with decreased number of taxa (Lundquist et al. 2003). That both the short term manipulative studies and the time-integrative survey found similar results emphasizes that decreases in species diversity is linked with increased terrestrial sedimentation.

All these analyses assume that the sediment mud content at a site is associated with terrestrial sediment inputs. Compound specific isotope data was used to determine whether the majority of sediment from 3 sites in each estuary was more strongly associated with terrestrial or coastal sediments. Associations between sediment source and sediment mud content were analysed by Pearson and Spearman correlations.

## 4.2 Results

Cyclic patterns in community composition (represented by CAP scores) over time were common, varying from relatively long cycles (e.g., 4 years Figure 4.1. Mangemangeroa) to well-defined 2–3 year cycles (e.g., Figure 4.1 Waikopua Site 2 and Waiwera Site 8). However, trends over time in community composition consistent with increased sediment mud content were detected in at least one site within each estuary, except for Mangemangeroa and Waikopua (Table 4.2, Figure 4.1). These two estuaries have much higher variability over time in sediment mud content (average standard deviation per site of 7.75 and 9.97 for Mangemangeroa and Waikopua respectively). Trends over time in the CAP scores consistent with increased sediment mud content were detected for two sites in Turanga (sites 8 and 10), Puhoi (sites 1 and 3) and Orewa (sites 2 and 7). Sites most likely to be affected were those in the outer estuary (sites 1–3) and those in the upper estuary (sites 7–10). These results highlight that overall responses are driven by both changes in the physical threat and in the ecological response.

Cyclic patterns in abundance of many taxa were also observed at all sites. However, Puhoi, Waiwera, Waikopua and Orewa also showed trends of concern (i.e., decreases in abundance of taxa that are expected to show optimal abundances at < 10% mud content) in more than 1 taxa at a site (e.g., Figure 4.2). Decreases in abundance were observed in *Colurostylis* and *Aonides* at Waiwera Site 9 (Appendix 5), in number of taxa and *Colurostylis* at Puhoi Site 10 and in *Paphies* and Waitangi at Orewa Site 4. Okura showed trends in abundance of concern at 3 sites, decreases in abundance of *Aonides* and *Austrovenus* at Site 1, in *Aonides* and Waitangi at Site 6 and in number of taxa and *Colurostylis* at Site 9. Waikopua showed trends in abundance of concern at site 5, decreases in abundance of *Aonides* and *Macomona*. Note that for all these trend analyses, screening removed any trends that were driven by one or 2 high points at the beginning or end of the time series, or where abundances were generally very low (< 2 individuals per 6 cores).

**Table 4.2:**

Sites where trends over time are consistent with increased sediment mud content ($p < 0.05$) (see Appendix 5 for statistical results). Y = trends of concern for most of community indicated by a significant trend for CAPmud scores. S = Taxa predicted to decrease in abundance with increased mud that show that trend, followed by the number showing the trend. M = Taxa predicted to increase in abundance with increased mud that show that trend, followed by the number showing the trend. Yellow highlights indicate sites with at least 2 trends of concern.

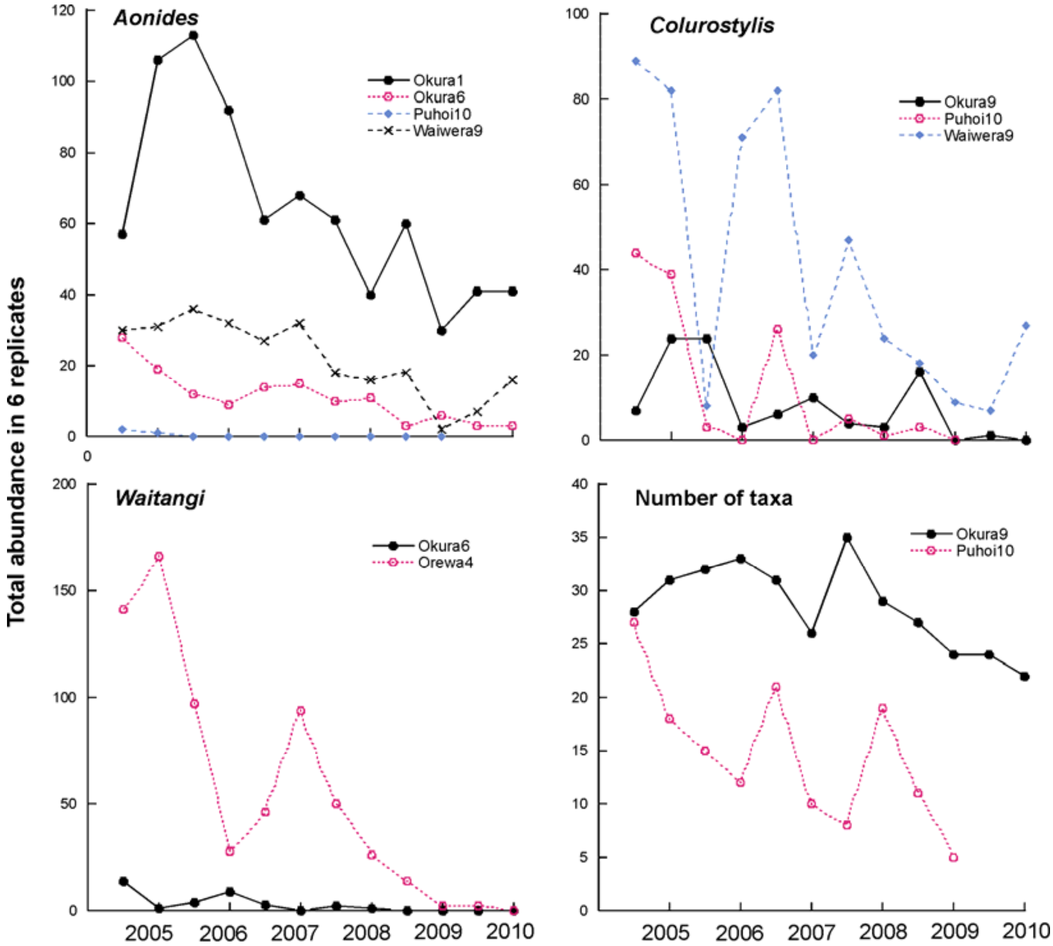
| Site | Mangemangeroa | Okura | Orewa | Puhoi | Turanga | Waikopua | Waiwera |
|---|---|---|---|---|---|---|---|
| 1 | | S2, M2 | | Y | S1 | | Y |
| 2 | S1 | Y | Y | S1 | | S1 | |
| 3 | S1 | | | Y | S1 | | S1 |
| 4 | | M1 | S2, M1 | | | | |
| 5 | | | | | S1 | S2 | S1 |
| 6 | | S2 | | | | S1 | |
| 7 | | | Y | S1 | S1 | S1 | |
| 8 | | | S1 | S1 | Y | | |
| 9 | | S2 | | | | | S2 |
| 10 | | S1 | S1 | S2 | Y | | |

**Figure 4.1:**

Temporal patterns observed in CAP scores related to mud (CAPmud) at 3 sites from each estuary. Decreasing CAPmud scores represent a community related to increasing muddiness. The sites have been selected to show not only the decreasing trends detected and recorded in Table 4.2, but also cyclic patterns (e.g., site 9 Orewa and site 2 Waikopua) and random variation.

**Figure 4.2:**

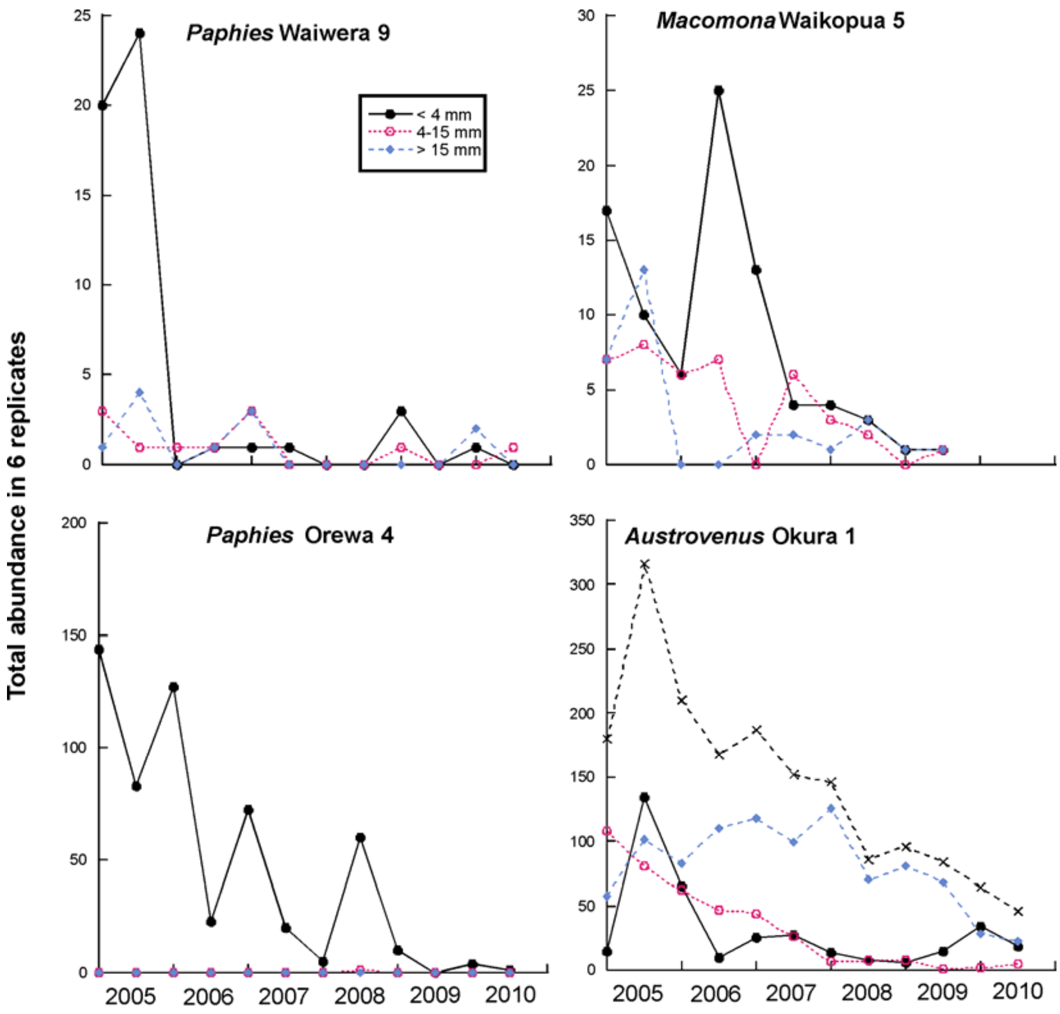
Selected trends in abundance consistent in direction with those predicted to occur as a result of increased sediment mud content.




Size-class based analysis of the significant trends observed in *Austrovenus*, *Macomona* and *Paphies australis* showed some strong recruitment patterns. The significant decrease observed in the overall population of *Paphies* at Waiwera Site 9 was driven by a single high recruitment peak (Figure 4.3). Only juvenile *Paphies* were found at Orewa Site 4 and the abundance of these exhibited a strong decline from 2004 to 2010 (Figure 4.3). At Okura, the steep decline in *Austrovenus* at Site 1 initially appears driven by strong juvenile recruitment in 2005. While the adults have been maintaining good abundances, the ongoing lack of juvenile recruitment appears to be affecting the adult population in the last 2 years (Figure 4.3). In Waikopua at Site 5 a significant decrease in *Macomona* sized < 15mm can be seen (Figure 4.3).

**Figure 4.3:**

Temporal patterns in bivalve size classes for those species/sites for which significant trends in the species abundances were detected. In the figure for *Austrovenus* at Okura S1, the overall species abundances are also plotted, using a cross and dashed line.




The three taxa that were predicted to increase in abundance with mud content generally did not demonstrate significant trends over time. Frequently, the direction of the change in abundances observed for a taxon was consistent across sites and estuaries, even when not significant, e.g., *Aonides* (Appendix 5). In two cases, these directions were not consistent with those predicted by abundance-mud models e.g., *Anthopleura* generally demonstrated increases in abundance over time and Corophids generally decreased.

No significant increases in mud content over time were observed at any of the sites. However, significant decreases in ambient sediment mud content were found at some sites in all estuaries, except Mangemangeroa. These were mainly driven by one (or occasionally two) high point(s) at the beginning of the series (August 2004), or by multiyear cycles (see Figure 3.3 for examples). Only at 2 sites in Okura (Sites 7 and 9), 2 sites in Turanga (Sites 1 and 4) and 3 sites in Waikopua (sites 2, 6 & 8) were negative trends really apparent. However, these decreases seemed more driven by a slight change in sediment grainsize around the 63 $\mu$m size fraction, as when the very fine silt fraction (which also is often a part of the terrestrial sediment load in the

Auckland region (Lohrer et al. 2004) was amalgamated with the mud fraction, only one trend was observed (Site 2 at Waikopua). At this site it appeared as if something had happened between Spring 2007 and Autumn 2008.

Isotopic signatures of the top few millimetres of sediment at the sites sampled closest to the coast unsurprisingly suggested that, for most estuaries, this sediment predominantly was sourced from marine sediments (Table 4.3). High certainty in these results is indicated by their low standard deviations (see Appendix 6).

**Table 4.3:**

Summary of % contribution of likely source sediments to the sediment found at each site in September 2009. Delta = combination of % contribution from samples taken in the uppermost portion of the estuary. Upper = combination of % contribution from samples taken at site(s) further up the estuary from the present one. Lower = combination of % contribution from samples taken at site(s) lower down the estuary from the present one. Coast = marine sediment from nearby coast. Full results, given in Appendix 6, suggest that certainty is lower for values < 30 (high standard deviations relative to average) and is high for values > 75.

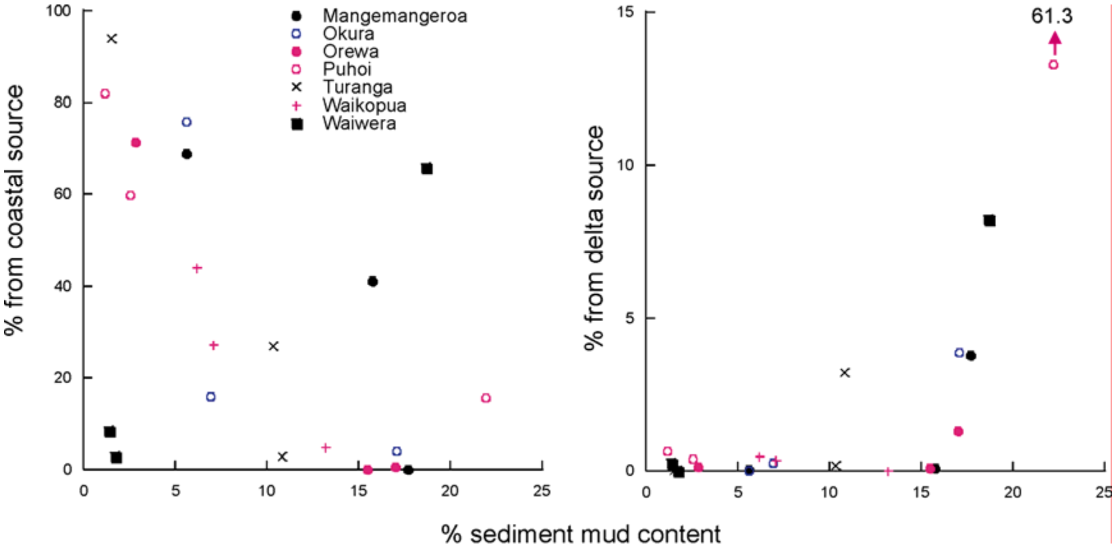
| Estuary | site | delta | upper | lower | coast |
|---|---|---|---|---|---|
| Mangemangeroa | s3 | 0.02 | 31.14 | | 68.84 |
| Mangemangeroa | s6 | 0.08 | 41.00 | 17.86 | 41.06 |
| Mangemangeroa | s9 | 3.81 | | 96.19 | 0.00 |
| Okura | s3 | 0.00 | 24.07 | | 75.93 |
| Okura | s6 | 0.27 | 40.29 | 43.71 | 15.73 |
| Okura | s9 | 3.90 | | 92.17 | 3.93 |
| Orewa | s1 | 0.14 | 28.37 | | 71.49 |
| Orewa | s4 | 1.31 | 11.05 | 87.16 | 0.48 |
| Orewa | s8 | 0.10 | | 99.90 | 0.00 |
| Puhoi | s1 | 0.64 | 17.54 | | 81.83 |
| Puhoi | s4 | 0.38 | 6.78 | 33.01 | 59.83 |
| Puhoi | s9 | 61.30 | | 23.21 | 15.49 |
| Turanga | s3 | 0.00 | 6.18 | | 93.82 |
| Turanga | s4 | 0.17 | 53.12 | 19.68 | 27.03 |
| Turanga | s7 | 3.22 | | 94.03 | 2.75 |
| Waikopua | s3 | 0.47 | 55.70 | | 43.83 |
| Waikopua | s6 | 0.32 | 64.04 | 8.50 | 27.14 |
| Waikopua | s8 | 0.00 | | 95.23 | 4.76 |
| Waiwera | s2 | 8.23 | 25.86 | | 65.91 |
| Waiwera | s6 | 0.26 | 0.18 | 91.29 | 8.28 |
| Waiwera | s8 | 0.00 | | 97.21 | 2.79 |

The only estuary for which this was not the case was Waikopua. In Waikopua, the similarity between the three sampled sites suggested that sediment was being resuspended and moved around the tidal flats, between the sites. Sites highest up the estuary showed much less consistency between estuaries in sediment source. Only for Puhoi was the most likely source for the upper site predominantly the delta sample (the delta sample is a sample of sediment taken in the uppermost portion of each estuary, well above all the monitored sites). For the other estuaries a mix of sediment from lower down the estuary was important. For the site in the middle of the estuary, again there was little consistency in likely source of sediment.

In order for percent mud content at each site to be a good predictor of the degree of stress that terrestrial sediment inputs are having on the community, mud content should be strongly positively correlated with the amount of delta source sediment and negatively correlated with the amount of coastal sourced sediment. Samples taken in September 2009 observed only poor correlation for these variables, Pearsons r = 0.49 and -0.49 from delta and coastal source sediment respectively (Figure 4.4). Correlations between the likely proportion of delta source sediment and sediment trap information (i.e., total sediment trapped, amount of sediment and sediment trapping rate) exhibited weak to no correlations (correlation coefficients < 0.28). A slightly better correlation (Spearman $\rho = 0.31$) was found for the relationships between the proportion of delta source sediment and the % mud content of the sediment scrapes.

**Figure 4.4:**

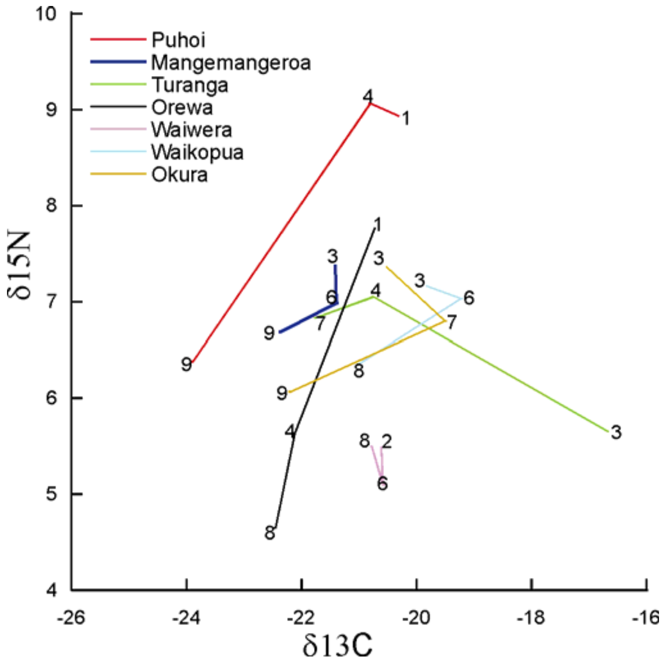
Relationships between percent sediment mud content and % source sediment of delta and coastal sediment in September 2009. There is one outlier in the delta plot shown as an arrow with actual value above it.




Plots of $\delta^{15}N$ vs. $\delta^{13}C$ show movement from upper right to lower left from sites near the mouth to the upper estuary sites, for all estuaries (Figure 4.5). Sediments closer to terrestrial source are expected to be less enriched as there has been less time for digenesis and animal reworking to enrich the sediments. The amount of $\delta^{13}C$ was well correlated with the sediment mud content at a site (Pearsons r = -0.68) while the ratio of $\delta^{15}N$ to $\delta^{13}C$ was well correlated with the mud content found in the sediment traps (Pearsons r = 0.69).

**Figure 4.5**

Relationship between δ$^{15}$N vs. δ$^{13}$C observed across the sites within estuaries observed in September 2009.



# 5 Ecological responses to individual storm events

Increased terrestrial sediment is most likely to have a cumulative impact on estuarine systems. That is, a number of small rainfall events bringing in small amounts of sediment which will be deposited in various places around the estuary and, probably, resuspended, moved and deposited elsewhere. These small amounts of sediment will gradually increase turbidity in the estuary, increase the muddiness of the sediment and extend muddy areas to the detriment of sandy areas. But heavy rainfall events, particularly falling on cleared ground, are likely to wash much more sediment into the estuary and, consequently, an effect large enough to be measured may result from a single storm. Information on the size of individual events that have measurable effects, and whether or not the effect lasts past the next sampling occasion, would be very useful to environmental managers and development planners. This information would also be useful to supplement previous short-term experimental studies that have added terrestrial sediment to intertidal areas. Such studies, while providing robust evidence of decreased abundances of several taxa, and decreased overall biodiversity, associated with terrestrial sediment inputs, have a number of limitations (Senior et al. 2003). Specifically, they are limited in the size of area disturbed (with the largest studies only covering 6.6 $m^2$, recovery may be enhanced as species quickly move in from non-manipulated areas) and the sediment is not necessarily similar to the sediment that may arrive with a natural event, as this may be a mix of new terrestrial sediment and sediment that has been held in streams and higher in the estuary.

In 2007, the monitoring programme began to target heavy rainfall events, in an effort to gather information specific to individual rainfall events. This report is the first to analyse this rainfall event sampling.

## 5.1 Methods

Due to the patchiness of heavy rainfall in the Auckland area, rainfall event monitoring was limited to estuaries that had gauging stations situated in their catchments (Okura, Orewa and Mangemangeroa) and sampling only occurred in the estuary for which the rainfall trigger was exceeded. Separate multivariate analyses were conducted for each estuary (PERMANOVA+ add-on package; Anderson and Gorley 2008), similar to that performed on the previous data and reported in Anderson et al. (2008). Site, event and season were fixed factors while year was included as a random factor.

However, we may not detect a single response in macrofaunal community composition across all sites in an estuary and across all events, for a number of reasons:

1. The dry sampling occasion may be temporally separated from the rain event sampling by such a long period that seasonal changes in community composition may preclude detection of the response.
2. Sediment deposition triggered by rainfall may occur too frequently to allow the community to recover between depositional events. The long-term monitoring of

the dry sampling is predicated upon this concept and the work by Lohrer et al. (2004) demonstrated that sediment deposition as low as 3 mm per month could result in a cumulative change in community composition over a year. However, the rainfall triggers could potentially result in larger sediment deposition and thus responses to multiple events may be able to be detected over smaller time frames.

3. Rainfall below the trigger level may elicit a small response and rainfall events well above the trigger may elicit a greater response than those just above the trigger. Moreover, the macrofaunal community may be affected by event duration as well as intensity, indicating that cumulative rainfall over a 2 week period preceding event sampling may be important. Similarly, the amount of rainfall occurring between the event and the sampling date may also be important, controlling the ability of individual taxa (and thus the community) to recover from the event.

4. Rainfall is used here as a proxy for terrestrial sedimentation. However, within an estuary, the amount of terrestrial sedimentation that occurs at a site as a result of a specific rainfall will not always be consistent. Leaving aside that similar intensity rainfall events will generate differing amounts of sediment entering the estuary, sediment deposition at a site is dependent on estuarine characteristics (e.g., wave exposure, water velocity, depth and salinity) and temporal characteristics (e.g., tidal state, wind direction, wave height and period). In the initial design of this monitoring programme, terrestrial sediment inputs at each site were to be characterized by the amount of sediment caught in the traps. This, in conjunction with net accumulation/removal measured by bed height, was expected to explain site dependent responses. However, previous analyses of community structure in rain vs. dry periods found no significant differences even when using the amount of sediment caught in sediment traps as an explanatory variable (Anderson et al. 2008).

5. The type of macrofaunal taxa (and therefore the macrofaunal community) at a site might determine the response to an event. Macrofauna living in places with a history of frequent deposition (whether terrestrial or marine) are likely to be tolerant of the prevailing conditions. For example, taxa that live closer to the open coast may be less able to cope with high sediment deposition and suspended sediment loads in the water column sediment (Lohrer et al. 2004, Hewitt et al. 2001, Hewitt and Norkko 2007).

To investigate point 1, events where the preceding dry sampling was conducted within 6 weeks were analysed by pairwise comparisons. Okura August 2008, Mangemangeroa May 2008 and all estuaries May 2010 were used.

To investigate point 2, multiple events occurring within a 3 week period were analysed by replacing the factor event (y or n) with a cumulative factor (event1, event2, dry). Two of these occurred. Mangemangeroa was sampled on the 2$^{nd}$ May 2008 after a dry period, then again on 8$^{th}$ May and 15$^{th}$ May following events. Okura was sampled for an event on the 19$^{th}$ June 2009 and then again on the 6th July. Unfortunately the nearest preceding dry sampling was in February (summer versus winter), so the following sampling on the 21$^{st}$ September was used as the dry sampling comparison.

To investigate points 3–5, the relationship between the size of the rainfall event and the macrofaunal community composition for each estuary was determined using CAP on pre-event and event sampling data averaged for each site/sampling occasion. The difference in CAP scores between each pre-event and event sampling was calculated and a multiple regression was used to determine environmental variables most useful in predicting variability. Environmental variables (Table 5.1) were related to rainfall intensity and duration, sediment trap data and site information. Rainfall information was collected from the Auckland Council HydWebserver from sites Awohunui (Okura), Orewa and Mangemangeroa. Sediment trap data was included as the previous report did find that the amount of sediment caught in the traps and the amount of fine sediment helped explain a small percentage of the variation in macrofaunal community composition across all estuaries and sites. Site information included the net sediment accretion/erosion prior to sampling and the % mud content of the surficial sediment scrapes. This analysis was only conducted on the August 2007 to 2009 data, as post July 2009 not all sites had sediment trap information.

**Table 5.1:**

Environmental variables used as potential predictors of changes in community composition in response to rainfall events.

| **Rainfall associated statistics** |
| --- |
| Maximum depth over a 24 hr period in preceding week |
| Total depth over the 24hrs prior to sampling |
| Total depth over the 2 week period prior to sampling |
| **Sediment trap data** |
| Weight of sediment collected in trap prior to sampling |
| % mud content of sediment collected in trap prior to sampling |
| **Site information** |
| Net sediment accretion/erosion prior to sampling |
| % mud content of top 3mm of sediment |

Finally the $\delta^{15}N$ and $\delta^{13}C$ isotope values were plotted and correlated with sediment mud content in both the core and scrape samples collected from the December event sampling.

## 5.2 Can ecological responses to individual storm events be detected?

Analysis over the full 4 years of event sampling revealed that for Okura and Mangemangeroa, there was a significant interaction between event and year (Table 5.2), which was driven mainly by differences in the strength of the response between years (Table 5.3). No overall effect of the events sampled could be detected (Table 5.2, Figure 5.1). For Orewa, a significant interaction between site and event was found (Table 5.2, with a response to the two sampled events only occurring at Site 3 (Table 5.4, Figure 5.2).

**Table 5.2:**

PERMANOVA conducted for each estuary using site (Si), year (yr), season (se) and event (ev) as factors. Degrees of freedom and per mutational p-values are presented for all main and 2 way-interaction terms. Terms involving event are shaded and p-values < 0.05 for these terms are bolded.

| | Okura | | Mangemangeroa | | Orewa | |
|---|---|---|---|---|---|---|
| | df | p | df | p | df | p |
| Si | 9 | 0.001 | 3 | 0.012 | 6 | 0.001 |
| se | 1 | 0.2327 | 1 | 0.001 | 2 | 0.001 |
| ye | 3 | 0.001 | 1 | 0.001 | | |
| ev | 1 | 0.876 | 1 | 0.619 | 1 | **0.03** |
| Sixse | 9 | 0.024 | 9 | 0.794 | 12 | 0.001 |
| Sixye | 25 | 0.001 | 6 | 0.001 | | |
| Sixev | 9 | 0.974 | 12 | 0.438 | 6 | **0.001** |
| sexye | 1 | 0.001 | 1 | 0.001 | | |
| sexev | 1 | 0.6354 | 1 | 0.106 | | |
| yexev | 3 | **0.001** | 1 | **0.001** | | |

**Table 5.3:**

Results of pairwise comparisons for response to events in different years in Okura and Mangemangeroa. Avdiss = average Bray-Curtis dissimilarity (%)

| | Year | t | p | avdiss |
|---|---|---|---|---|
| **Okura** | **2007** | **2.9328** | **0.001** | **65** |
| | 2008 | 2.3001 | 0.001 | 62 |
| | 2009 | 4.0379 | 0.001 | 64 |
| | 2010 | 1.5789 | 0.003 | 61 |
| **Mangemangeroa** | **2008** | **2.1616** | **0.001** | **61** |
| | 2010 | 1.9219 | 0.001 | 55 |

**Figure 5.1:**

Non-metric multidimensional scaling ordination of event and dry sampling in Mangemangeroa and Okura.  Site numbers are given.

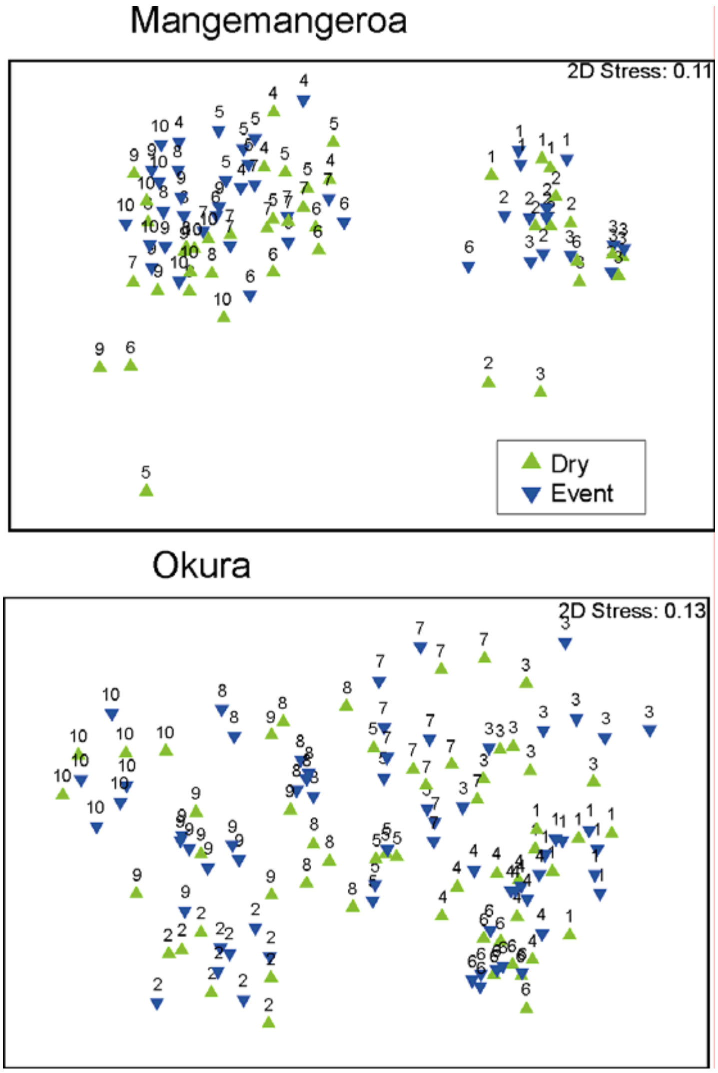
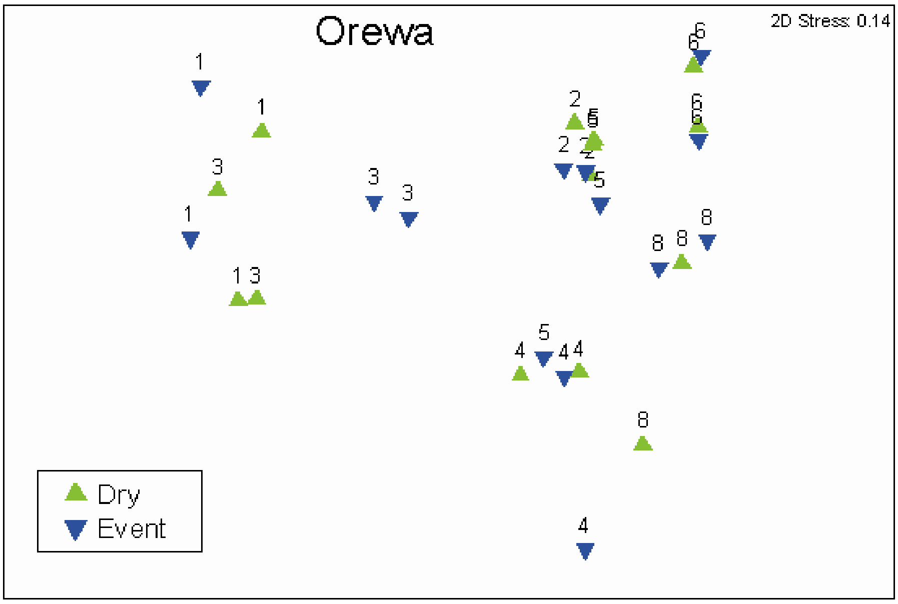


**Table 5.4:**

Results of pairwise comparisons for response to events in different sites in Orewa. Avdiss = average Bray-Curtis dissimilarity (%). Significant p values are in bold text.

| Orewa | Site | t-value | p-value | Avdiss |
|---|---|---|---|---|
| | 1 | 1.3288 | 0.085 | 53 |
| | 2 | 0.76715 | 0.701 | 53 |
| | 3 | 2.1531 | **0.002** | 60 |
| | 4 | 1.2559 | 0.158 | 58 |
| | 5 | 1.0755 | 0.321 | 59 |
| | 6 | 1.0667 | 0.332 | 44 |
| | 8 | 1.3253 | 0.115 | 60 |

**Figure 5.2:**
Non-metric multidimensional scaling ordination of event and dry sampling in Orewa. Site numbers are given.




Analysis of those events where a dry sampling had preceded the event by less than 6 weeks only occurred once for both Orewa and Okura. For Orewa, PERMANOVA analysis again revealed a significant site*event interaction (p = 0.038) with a detectable response occurring only at site 3. For Okura in year 2010 a significant site*event interaction was also found, with responses detected at all but 3 sites (1, 3 and 4). For Mangemangeroa, 2 events were available for analysis and significant site*event and year*event interactions were observed. A significant response was detected for sites 5 and 8 in autumn of 2008 and for sites 2, 5, 6, 9 and 10 in May 2010.

Multiple events occurred over the winter of 2009 for Okura and 2008 for Mangemangeroa. For Okura, a response to the first event was detected at all but three of the sites (Table 5.5). While a significant difference in community composition between event 1 and 2 was only detected at two sites, significant differences between the dry sampling and the second event sampling were detected at all but one site, and even at that site the p value was < 0.10. In all cases the significance level of event and the dry sampling contrasts decreased with the second event. For Mangemangeroa, the results were not so clear cut, with significant differences between dry sampling and the first event only being detected at only 2 sites. However, again the significance level decreased with the second event, resulting in significant responses being detected at 6 of the sites.

**Table 5.5:**

Significance levels of pairwise comparisons between community composition found in dry sampling, sampling after one event and sampling after two events in Mangemangeroa and Okura. Between = comparison between the first and second events, Event 1 = comparison between dry sampling and the first event, Event 2 = comparison between dry sampling and the first event. Significant p values are in bold text.

| | | Between | Event 1 | Event 2 |
|---|---|---|---|---|
| **Okura** | site 1 | 0.668 | 0.053 | **0.037** |
| | site 2 | **0.002** | **0.003** | **0.002** |
| | site 3 | 0.841 | 0.125 | 0.099 |
| | site 4 | 0.162 | **0.048** | **0.006** |
| | site 6 | 0.199 | **0.003** | **0.002** |
| | site 7 | 0.350 | 0.180 | **0.010** |
| | site 8 | 0.916 | **0.003** | **0.001** |
| | site 9 | **0.034** | **0.006** | **0.003** |
| **Mangemangeroa** | site 1 | 0.817 | 0.189 | **0.002** |
| | site 2 | 0.556 | 0.351 | **0.009** |
| | site 3 | 0.998 | 0.887 | 0.762 |
| | site 4 | 0.951 | 0.519 | 0.121 |
| | site 5 | 0.577 | **0.101** | **0.012** |
| | site 6 | 0.403 | 0.142 | **0.005** |
| | site 7 | 0.547 | 0.338 | 0.240 |
| | site 8 | 0.128 | **0.031** | **0.006** |
| | site 9 | 0.377 | 0.289 | 0.220 |
| | site 10 | 0.583 | **0.036** | **0.018** |

## 5.3 Which measured explanatory variables best predict event responses?

The effectiveness of environmental variables in explaining changes in community varied between estuaries. For Mangemangeroa, our regression analysis explained 45% of the variability of the change in CAP scores related to event-based changes in community composition. Important predictor variables were site sediment mud content, site sediment coarse particles content and the amount of rainfall in the preceding 24 hrs (Table 5.6). For Okura, the regression analysis explained 35% of the variability. Important predictor variables again included site sediment mud content and the amount of rainfall in the preceding 24 hrs, although for this estuary the change in bed load height since the preceding dry sampling was also important. Note that this analysis incorporates the intensity of the rainfall event implicitly as this is included in the CAP analysis.

**Table 5.6:**

Regression statistics associated with the analysis of changes in CAP scores driven by rainfall event size. Mud = site sediment mud content, Coarse = site sediment content > 500µm, R24 = amount of rainfall collected in 24 hrs preceding sampling, ∆bedht = change in bed height since previous dry sampling. MS = mean square, DF = degrees of freedom.

| **Mangemangeroa** | **DF** | **MS** | **F-value** | **P-value** |
|---|---|---|---|---|
| Model | 3 | 0.0314 | 7.27 | 0.0011 |
| Error | 26 | 0.0043 | . | . |
| | | **Parameter** | **t-value** | **P-value** |
| Mud | 1 | 0.0038 | 2.60 | 0.0151 |
| Coarse | 1 | -0.0016 | -1.80 | 0.0811 |
| R24 | 1 | 0.0147 | 1.70 | 0.1012 |
| **Okura** | **DF** | **MS** | **F-value** | **P-value** |
| Model | 3 | 0.0062 | 7.76 | 0.0003 |
| Error | 44 | 0.008 | | |
| | | **Parameter** | **t-value** | **P-value** |
| Mud | 1 | 0.0008 | 1.72 | 0.0926 |
| R24 | 1 | 0.0020 | 3.56 | 0.0007 |
| ∆bedht | 1 | 0.0069 | 2.11 | 0.0409 |

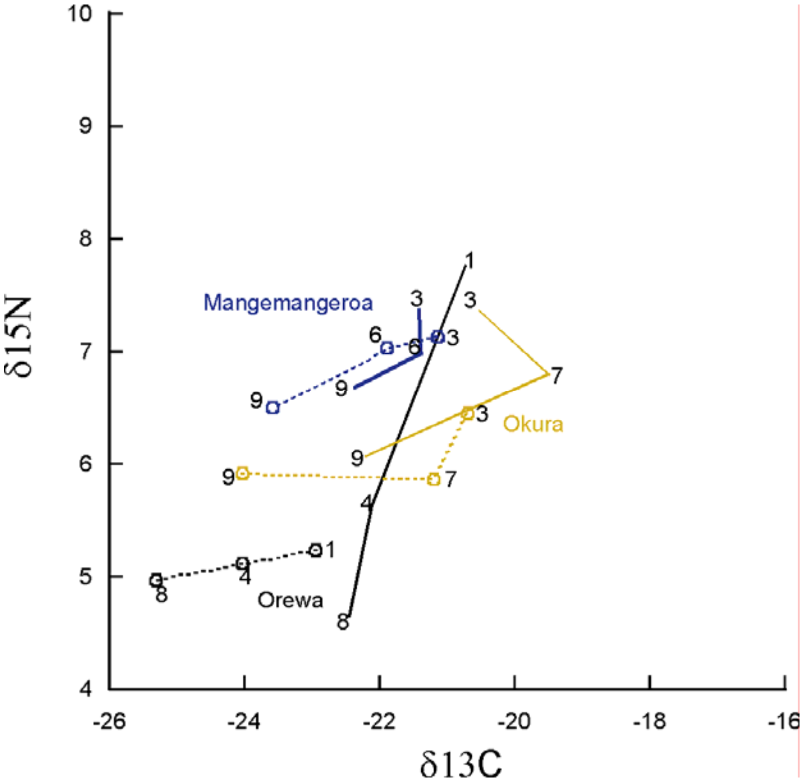
## 5.4 Isotopic signatures in ambient sediments

Comparison of isotopic signatures in ambient sediments in September 2009 with the samples taken after the December event showed that, at Mangemangeroa little change had occurred (Figure 5.3). What change there was occurred at site 9 (and was in the direction that would be expected if an increase in terrestrial sediment had occurred (i.e., the site value moved further to the left and down). More change had occurred in Okura, with site 3 (the site nearest the coast) decreasing in $\delta^{15}N$ and both the other sites decreasing in both $\delta^{15}N$ and $\delta^{13}C$. The greatest change occurred in Orewa, with both sites 1 and 4 showing marked decreases in both $\delta^{15}N$ and $\delta^{13}C$, while site 8 (furtherest up the estuary) showed a slight increase $\delta^{15}N$ but a marked decrease in $\delta^{13}C$.

$\delta^{15}N$ concentrations in the sediment post the event were well correlated with the sediment mud content obtained in the surficial sediment scrapes (Spearmans $\rho$ = 0.63).

**Figure 5.3:**

Comparison of isotopic signatures in ambient sediments in September 2009 (solid lines) with the samples taken after the December event (dotted lines).



# 6 Are there any other cost-effective improvements to the monitoring design that can be made?

Here we answer 2 questions: how useful is the sediment trap information, and does temporal variability within a 3 month window confound detection of changes?

## 6.1 Methods

The only analysis reported in Anderson et al. (2008) as finding sediment trap information to be a useful predictor was an assessment of the relationship between the collected environmental variables and the biotic data across space. For that analysis, data (averaged for each site from time 20 onwards) was examined using a distance-based linear model (DISTLM, Legendre and Anderson 1999; McArdle and Anderson 2001) on the Bray-Curtis dissimilarity matrix of square-root transformed abundances, using forward selection, based on the corrected AIC, simply to determine how much of the biotic variability could be explained overall.

In this report, we have included sediment trap information in the analysis of the response to rainfall events, but we also include an assessment of the relationship between the environmental variables and the biotic data across space and time. This analysis, using a distance based linear model as detailed above, was conducted on the non-event data collected during 2009–2010, data from all sites and from each sampling occasions were used, and environmental variables included those determined as important in Anderson et al. (2008) (explaining > 1% of variation) and other recently collected variables (Table 6.1).

Community composition information is available at 2 monthly intervals from sites in the Manukau and the Central Waitemata in their first year of sampling (1987–8 and 2000–1 respectively). Data from the first year of sampling Okura is also available, although the time intervals are longer and more variable. The average percent dissimilarity between sampling periods for these locations gives some indication of the degree of seasonal variability that may be expected to occur in estuaries and is compared with the average percent dissimilarity between nearest neighbor sites and between dry and event sampling for Okura. If the average percent dissimilarity between sampling is less than that observed between nearest neighbor sites or between dry and event sampling periods, then temporal variability within a 3 month window does not confound detection of changes.

**Table 6.1:**

Environmental variables tested for being important predictors of differences in macrofaunal communities.

| **Ambient sediment** |
|---|
| Average percent mud |
| Average percent fine sand |
| Average percent medium sand |
| Average percent coarse particles (shell hash) |
| %mud in sediment scrapes |
| **Sediment trap data** |
| Rate of accumulation of mud (< 63 μm) in traps ($g.cm^{-2}.day^{-1}$) |

## 6.2 How useful is the sediment trap information?

Sediment trap information collected over the time period prior to an event or over the preceding 3 months did not help determine the magnitude of response to a rainfall event (Section 5, Table 4.6). Instead, important predictor variables were site sediment mud content, site sediment coarse particles content and the amount of rainfall in the preceding 24 hrs.

Environmental variables chosen by distance-based linear model as useful for predicting spatial and temporal variation in community composition also did not include any sediment trap or bed height data (Table 6.2). Instead the most important variable was the average mud content (<63 μm) found at a site which explained 19.8% of the variability in macrofaunal community composition. The average content of coarse sediment (> 500 μm) and total fine sediment (63–250 μm) also explained small amounts of variability (4.4 and 4.2 % respectively). As these variables were all averages over time they were explaining variation in space. The only predictor related to temporal variability was the % mud content of the surficial sediment scrapes which explained 11.2% of the variability in community composition. Altogether, 40% of the variability in community composition in space and time was explainable by these four variables.

Note that there are differences between the results of this analysis and one reported by Anderson et al. (2008). The previous analysis also explained 40% of the spatial and temporal variation in community composition based on 4 variables: site sediment mud content (20.5%), site sediment fine sand (8.4%) and then the mud content in the sediment traps and tidal height (5.6% each). For the analysis reported here, tidal height was not available, if it had been we could have expected to explain more than 40%. More importantly, % mud content of the surficial sediment scrapes replaced the mud content from the traps as an explanatory factor and explained more of the variability (11.2 vs 5.6).

**Table 6.2:**

Variables selected as important predictors of variation in community composition across space and time.

| | Pseudo-F | P | % explained | Cumulative % explained |
|---|---|---|---|---|
| Average mud content | 9.9009 | 0.001 | 19.8 | 19.8 |
| % mud content of surficial sediment scrape | 6.1969 | 0.001 | 11.2 | 30.8 |
| Average coarse sediment content | 2.327 | 0.006 | 4.4 | 34.8 |
| Average fine sediment content | 2.5397 | 0.005 | 4.2 | 40.0 |

These results suggest that the ongoing monthly monitoring of sediment traps and bed height is not particularly helpful to the monitoring programme.

## 6.3 Does temporal variability over 3 months confound detection of changes?

Average % dissimilarity between dry sampling occasions in the first year of sampling in Okura was 55.7 for autumn and 60 in spring. These differences are only slightly higher than those observed between 2 monthly sampling occasions in the Manukau in 1987–1988 (average = 54.9). The average difference between adjacent sites in Okura, calculated from the same time period was higher, but the average difference between dry and event sampling occasions (2007–2010) was much lower (i.e., 45.7 (Table 6.3)). This suggests that within season variation is definitely compromising the ability of the programme to detect the effect of rainfall events on community composition, and, possibly, the ability to detect changes in community composition in response to increasing sediment mud content.

**Table 6.3:**

Average % Bray-Curtis dissimilarity within the three month seasonal sampling window, between adjacent sites in Okura Estuary and between dry and event sampling (2007–2010).

| | % dissimilarity | Difference (Minus within season) | % Difference |
|---|---|---|---|
| within season | 57.6 | | |
| between adjacent sites | 64.3 | 6.6 | 10.3 |
| between events and dry | 45.7 | -11.9 | -26.1 |

# 7 Summary and Recommendations

## 7.1 Observed changes in benthic macrofauna

The majority of temporal patterns observed in macrofaunal community composition and the abundance of dominant taxa were associated with seasonal or multiyear cycles. These types of patterns are expected and have been observed in other macrofaunal monitoring programmes conducted in the region. It is important that we understand these natural fluctuations if we are to tease apart the effects of human activities in our estuaries.

Some changes consistent with those predicted to occur as a result of increased sediment mud content or sedimentation were observed. Trends over time in community composition consistent with increased sediment mud content were detected for two sites in Turanga, Puhoi and Orewa and one site in each of the other estuaries, with the exception of Mangemangeroa. Mangemangeroa has had, for a number of years, a high sediment input, and therefore it is possible that many changes have already occurred (Oldman & Swales 1999). Changes in the abundance of taxa or diversity consistent with predictions of response to increased terrestrial sedimentation or mud content, derived from experimental studies and large surveys, were also observed at varying numbers of sites in all estuaries. While we can reasonably assume that a change of a single variable could occur as a matter of chance, 2 or more changes were observed at 1 site in each of Orewa, Puhoi, Waikopua and Waiwera, and at 3 sites in Okura.

Interestingly, the three taxa that were predicted to increase in abundance with mud content were much less likely to demonstrate significant trends over time. This may be because the predicted preferred mud content for these taxa is at the high end of that observed in this study, i.e., they may need a much larger change in mud content before they respond.

These changes have been observed despite no detectable increase in ambient sediment content at the sites. This is not surprising, as we would expect to observe changes to macrofauna in advance of measurable changes in the sediment mud content. Many macrofauna feed either in the water column, or the very surficial layer of the sediment. Increased amounts of sediment passing over the site in the water column, or changes to the surficial layer are unlikely to be measured by ambient sediment mud content in the top 2 cm until sedimentation becomes extreme. This is one of the reasons that benthic macrofauna are an ideal monitoring tool. It is also the reason that a review of the monitoring programme suggested monitoring the sediment content of 2–3 mm surface scrapes, such as has now been instituted (September 2009).

The changes we have observed do not indicate a large degree of change across these estuaries. However, some changes in a direction consistent with those predicted to occur from increased terrestrial sedimentation have occurred. While these changes are not accompanied by corresponding increases in sediment mud content, the compound specific isotope information did not find a strong correlation between the sediment mud content at a site and the percentage of terrestrially sourced sediment. We feel that sufficient changes in a direction consistent with those predicted to occur from increased terrestrial sedimentation have occurred to warrant continuation of the monitoring programme in its reduced state.

## 7.2 Event sampling

The sampling regime for events based around rainfall trigger levels initiated in 2007, has proven much more sensitive than the previous regime for detecting some ecological responses to individuals events, in that responses were detected. These responses are not consistent across sites or events and, unsurprisingly, the response is generally affected by the size of the event (amount of rainfall falling in the 24hr period) and the amount of rainfall falling in the 24 hrs previous to sampling. The response is also affected by the average ambient sediment mud content at the site. This was also anticipated by us, as muddy sites may be more likely to have sediment deposition events, while taxa living at sites in the outer sandy parts of the estuary may be more sensitive to any deposition, or muddy water passing over the site.

Importantly, sampling over a number of events occurring within a 6 week period in Mangemangeroa and Okura, reveal cumulative responses to the individual events. This suggests that the time that the macrofaunal community takes to recover between events can be longer than this, and thus that long-term cumulative responses are likely. This is important as, so far, only one experimental study on cumulative effects has been conducted (Lohrer et al. 2004) due mainly to the difficulty and expense in maintaining such experiments.

These results suggest that ongoing event monitoring is worthwhile. It provides a valuable function in strengthening the causal link between macrofaunal change and terrestrial sedimentation, and between predictions generated from experimental manipulations of terrestrial sedimentation and from surveys of ambient sediment content. At present, there are no rules for what to do when another event is forecast to occur within the sampling window of the previous event, yet this could be handled in 2 contrary ways. (1) Sampling should be rushed through to ensure both events are sampled. (2) Sampling should be delayed to sample the combined effect. The second option fits well within the analyses conducted for this report, as the magnitude of rainfall over the preceding 14 days will include both events and thus be very high. Using the first option instead would potentially confound the analyses. However the first option could provide a useful measure of how frequency of events is likely to constrain recovery and increase the community response to increased sedimentation. But in order for this analysis to be robust, such a series of events would need to occur in more than one estuary and, preferably, be followed by another sampling 7–10 days after the final event sampling.

## 7.3 Monthly monitoring of environmental variables

Monthly monitoring of environmental variables (volume and grainsize of sediment caught in the sediment traps and height of the bed) comprises a significant portion of the costs of this monitoring programme. This monitoring was initiated in the hope that it would provide (a) a direct measure of terrestrial sediment inputs at a site and thus strengthen the causal component to the monitoring and (b) integrate sedimentation with water-borne sediment passing over the sites that affects animals that feed in the water column. Monitoring had to be at least monthly because sediment traps need to maintain an at least 10:1 aspect ratio to avoid resuspension of sediment caught in the trap in laminar flow conditions.

Unfortunately, as pointed out by the 2005 review of the programme, sediment traps deployed inter-tidally in energetic systems do not provide a direct measure of sedimentation, because flow is not laminar and waves may resuspend sediment caught in the traps at any time. Moreover there is no way of determining whether sediment caught is terrestrial sediment, sediment from further up the estuary (which is at least likely to have been the result of terrestrial sediment inputs at some time), sediment resuspended on site either by waves or by boat propellers, or sediment resuspended off shore and moved onshore by waves. The causal link therefore is tenuous.

A number of other problems have been observed since trap placement occurred. Traps are frequently found askew, having been hit by boats or used as anchors for nets. Sometimes they have been pulled up by curious people and either not replaced at all or poorly replaced. Both of these affect not only the sediment traps ability to trap sediment but also the estimates of bed height made from them. Traps are also often found full of snails or crabs. These animals climb in and out of the traps, resuspending, or in the case of the crabs actively excavating sediment from the traps.

All of these problems may be why the sediment trap and bed load height information has proven of variable use in making predictions about what is happening to the macrofaunal communities at the sites. For example, Ford & Anderson (2005) found the trap data (grainsize, variation in grainsize and total weight trapped) explained a significant proportion of the variation in community composition and was more useful than ambient grainsize, when analyzing data from Okura, Orewa, Puhoi and Waiwera. Whereas, Anderson et al. (2007) found ambient sediment grainsize to be the most useful predictor and trap data to explain only 7.7% of the variability in macrofaunal community composition, when analyzing data from all 7 estuaries. In the analyses conducted for this report, we did not find trap data to be useful for predicting community composition changes related to rainfall events, or for describing differences between the core monitored sites over time and across estuaries. In the former comparison, the change in bed height from the previous dry sampling occasion was a useful predictor in Okura data, though not Mangemangeroa. In the latter comparison, trap data would have been useful had we not had the sediment grainsize data based on the surficial sediment scrapes.

Our recommendation, therefore, is that the monitoring of the sediment traps be removed from the programme. Bed height can remain monitored but only needs to occur when the macrofaunal community is monitored. Similarly, the grainsize composition of the surficial (top 2–3 mm) sediment should be monitored on those occasions.

## 7.4 Collection of other information

In the analyses conducted for this report, rainfall statistics proved useful in helping explain variation. We suggest that information from the relevant catchment on the rainfall over the 2 weeks and 24 hrs prior to sampling and the maximum rainfall in any 24 hrs prior to the week of sampling should be recorded and used in as much of the analyses as possible. We realize that this information is only available for 3 estuaries, but analysis could reveal whether it would be possible to use the Orewa data for Waiwera, and the Mangemangeroa data for Waikopua and Turanga.

Analyses conducted for the Manukau (Hewitt & Thrush 2009) found measures related to ENSO to be useful in explaining variability in species abundances. Another 2 years of data should be sufficient to allow these variables to be incorporated into analysis of the 7 estuaries data. Hewitt & Thrush (2009) also utilised measures of wave exposure calculated from wind and bathymetric data. Appropriate wind and bathymetric data are also available for these estuaries and thus wave exposure measures could be calculated.

The compound specific isotope (CSI) information suggests that the sediment mud content at a site is not an indicator of terrestrial sediment input. However, this may be a result of history (i.e., at least some proportion of the mud is marine sediment). Certainly the $\delta^{15}N$ and $\delta^{13}C$ signatures indicate a change up the estuary consistent with an increase in terrestrial source. Furthermore, the post event sampling showed a trend at most sites consistent with increased terrestrial sediment. This technique is therefore worthy of future investigation, the first step of which should be to determine how temporally consistent these findings are, by analyzing a similar set of samples taken in 2010–2011.

## 7.5 Other considerations

Some consideration should be given as to whether sampling within a 3 month window in spring and autumn is the most cost-effective method for sampling. Significant temporal variation appears to be occurring within this window. It may be that locating the sampling date within a month period (e.g., October and April) similar to that done in other Auckland Council Ecological Monitoring programmes would decrease this variation. In this case, it would be vital to collect rainfall statistics for the period prior to sampling and not to sample within 2 weeks of an event.

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# 10 Appendices

## 10.1 Appendix 1: Isotopic analysis methodology

Each sample was dried at 60 °C and then ground to a fine powder using a heavy duty stainless steel coffee grinder. A small aliquot (2–5 g) of each sample was acidified to remove inorganic carbonates by shaking the sample with 2 ml of 1 N hydrochloric acid (HCl) and allowing the suspension to stand overnight. Further HCl was added as required until no further effervescence occurred. The acid was then removed by decanting after centrifuging at 3,000 rpm and the sample rinsed twice with deionized water (Milli-RQ) by shaking and then centrifuging, before drying at 60 °C and hand-grinding to a fine powder in a mortar and pestle.

The C and N stable isotope composition of each acidified sample was determined by isotope ratio mass spectrometry (IRMS) as follows:

- About 20 mg of sample was weighed into a pure tin (Sn) capsule which was combusted at 1,020 °C in a NR1500 elemental analyzer (Fisons Instruments, Radano, Italy) with a pulse of oxygen in a helium carrier gas. The carbon combustion products were converted to $CO_2$ in a copper reduction furnace at 600 °C before the gas stream was coupled via a Finnigan Con-flo II gas injection interface to a DeltaPlus (Thermo Finnigan, Bremen, Germany) continuous flow, IRMS.
- Pulses of working standard $CO_2$ gas were injected at the beginning and end of each sample run to correct for intra-sample drift. Stable isotope ratios are reported in standard delta (δ) notation per mil (%) as: δX ¼ Rsample Rstandard 1 - 103 where X is $^{13}C$ or $^{15}N$ and R=$^{13}C/^{12}C$ or $^{15}N/^{14}N$, respectively. Standard reference materials were 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.

Organic Compounds

Because the fatty acid biomarkers were likely to be at low concentrations in the soil and sediment samples and acidification may reduce the organic carbon concentration in sediments, soil samples for FAME (fatty acid methyl ester) analyses were not acidified.

An aliquot (20 g) of each sample was extracted in a Dionex ASE 200 accelerated solvent extractor. The soil extraction method used double distilled DCM as the solvent, heated to 100 °C and raised to a pressure of 2,000 psi for 10 min. The extraction solvent was drained and flushed with clean solvent into a collection vial, and the extraction cycle was then repeated. A rinse cycle was used between each sample to prevent cross-contamination. The DCM extract from each sample was reduced to near dryness by rotary evaporation at 30 °C and then transferred to a 2-ml vial (Argilent wide-mouth screw-cap). The sample was allowed to evaporate to dryness at room temperature in a gentle nitrogen gas flow before the vial was sealed.

The free fatty acids were methylated with 5% concentrated HCl in methanol or 5% BF3 in methanol to form FAMEs which were extracted into hexane. Stable isotope ratios of FAMEs were analyzed using a Trace GC (Thermo Finnigan, Milan, Italy) coupled to a DeltaplusXP IRMS (Thermo Finnigan, Bremen, Germany). Samples were injected into a split/splitless injector at 300 °C and separated using a BP225 GC column. The GC oven was held at 50 °C for 5 min before being ramped to 230 °C at 7 °C/min where it was held for 10 min. The carrier gas was helium at a flow rate of 1.8 ml/min). Pulses of working standard $CO_2$ gas were injected at the beginning and end of each sample to correct for intrasample drift. A mixture of standardized FAMEs were analyzed every six samples and used to correct for instrumental drift during batch analysis and to standardize FAMEs to the PDB scale. The CSIA values of FAMEs were corrected for the methylation carbon added during derivatization by co-methylating three standard fatty acids (C16:0, C19:0, and C22:0) and using a mass balance equation: $\delta^{13}$CFA ¼ $\delta^{13}$CFAME ð1 XÞ$\delta^{13}$CMethanol X where X is the fractional contribution of the free fatty acid to the methyl ester. Analytical precision for standard fatty acids was below 0.5%. Another aliquot (5 g) was similarly extracted, methylated, and analysed for fatty and resin acid concentrations.

## 10.2 Appendix 2: Taxonomic changes

**Table 10.2.1:**

Taxonomic groups for which a lower taxonomic resolution is now available.

| Previous taxonomic level | Present taxonomic level |
|---|---|
| *Xymene sp.* | *X. ambiguous, X plebius* |
| Unidentified Gastropod | *Eatoniella abscindostoma* |
| Spionidae | *Spionid spA, Spiophanes bombyx* |
| Sipunculid | *Paracaudina chilensis, Sipunculid sp2* |
| Polydora complex | *Boccardia syrtis, Polydora cornuta, Pseudopolydora paucibranchiata* |
| Phoxocephalidae | *Phoxocephalidae, Torridoharpinia sp.* |
| Paraonid other | *Levinsenia gracilis, Paradoneis lyra* |
| Orbiniidae | *Orbinia papillosa, Scoloplos cylindifera* |
| Nuculidae | *Lasea parenganensis* |
| Nereididae | *Ceratonereis sp, Nicon aestuarenisis, Perenereis vallata, Platynereis sp.* |
| *Neoguraleus sp.* | *N. manukauensis, N. sinclairi* |
| Isopod other | Valifera |

Appendix 2: (cont.)

| Previous taxonomic level | Present taxonomic level |
|---|---|
| *Halicarcinus spp.* | *Halicarcinus whitei* |
| Goniadidiae | *Glycinde trifida, Goniada grahami* |

| | |
|---|---|
| *Exosphaeroma spp.* | *E. chilensis, E. falcatum, E. planum* |
| CapOlig | *Capitella spp, Oligochaete* |
| Crabs | *Austrohelice crassa, Hemiplax hirtipes, Hemigrapsus crenulatus* |
| Amphipod other | *Melita awa, Dexaminidae, Gammaropsis spp.,* Lljeborgidae, *Methlimedon sp, Paramoera cheveraux, Urothidae* |
| Stomatopoda | *Heterosquilla sp.* |
| Sabellidae | *Pseudopontamilla sp.* |

**Table 10.2.2:**

Taxa not observed over the last years sampling.

| *Bulla quoyi* | *Ligia novaezelandiae* | *Priapulopsis australis* |
|---|---|---|
| *Caecum digitulum* | *Lysidice ninetta* | Pycnogonidae |
| *Chaetognatha* | *Melanochlamys cylindrica* | *Rissoidae* |
| *Charybdis japonica* | *Modiolarca impacta* | *Scalibregmatidae* |
| *Cirsonella sp.* | Munnidae | *Sphaeroma guoyanum* |
| *Cominella maculosa* | *Mytilus galloprovinciallis* | Tanaidacea |
| *Cominella quoyana quoyana* | *Odostomia spp.* | Thalassinoidia |
| *Dorvilleidae* | *Onchidella nigricans* | *Zegalerus tenuis* |
| *Dosinia spp.* | *Pagurus sp.* | *Zenatia sp.* |
| *Felaniella zelandica* | *Paphies subtriangulata* | |
| Holothuroidia other | *Perna cannaliculus* | . |

# 10.3 Appendix 3: Temporal patterns in measured environmental variables

**Figure 11.4.1:**

Plots of % mud content found in the sediment traps over time from sites monitored in 2009–2010.

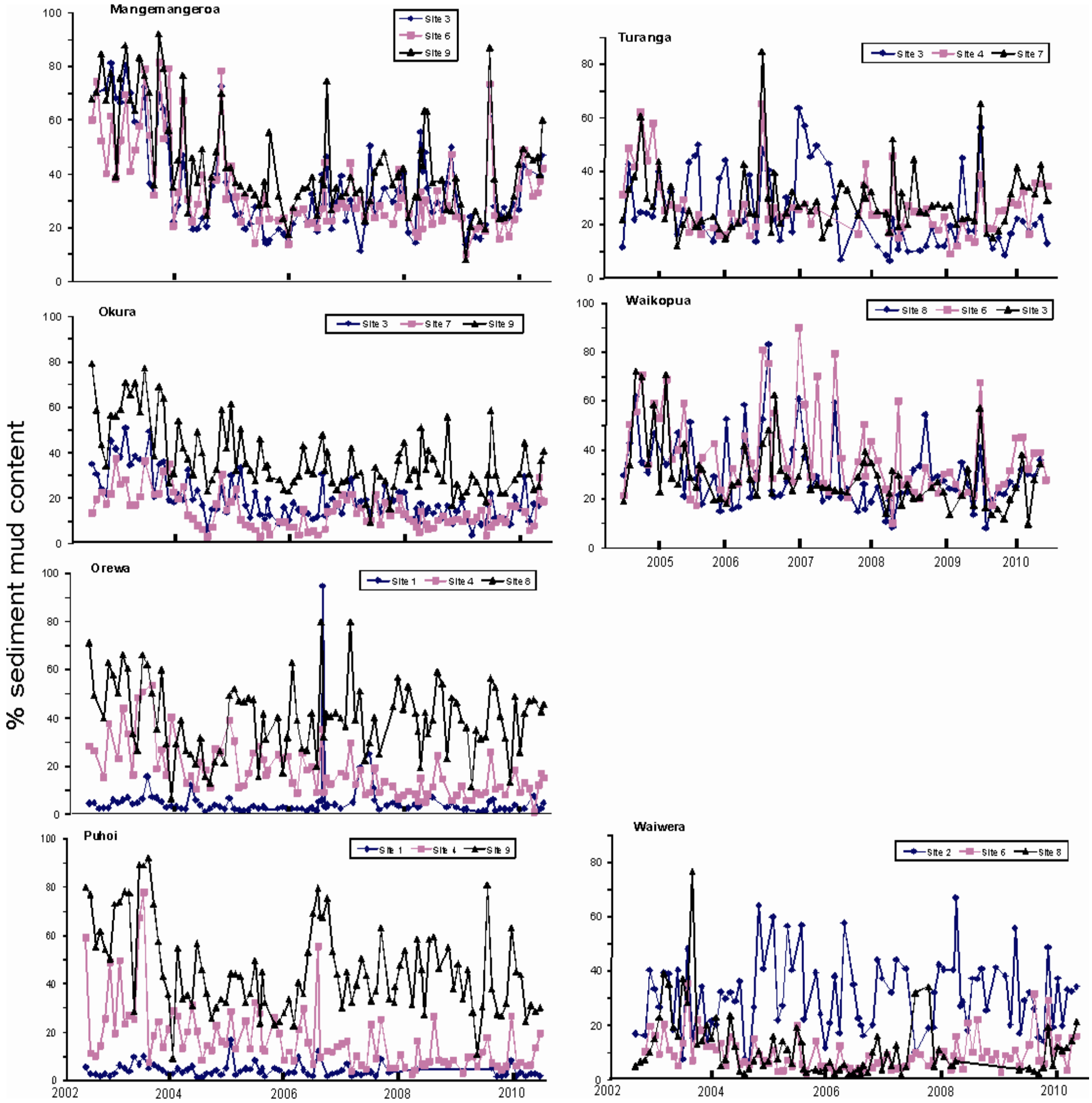


**Figure 10.4.2:**

Selected plo•ı ±ı volume of sediment fround in the sediment traps over time.

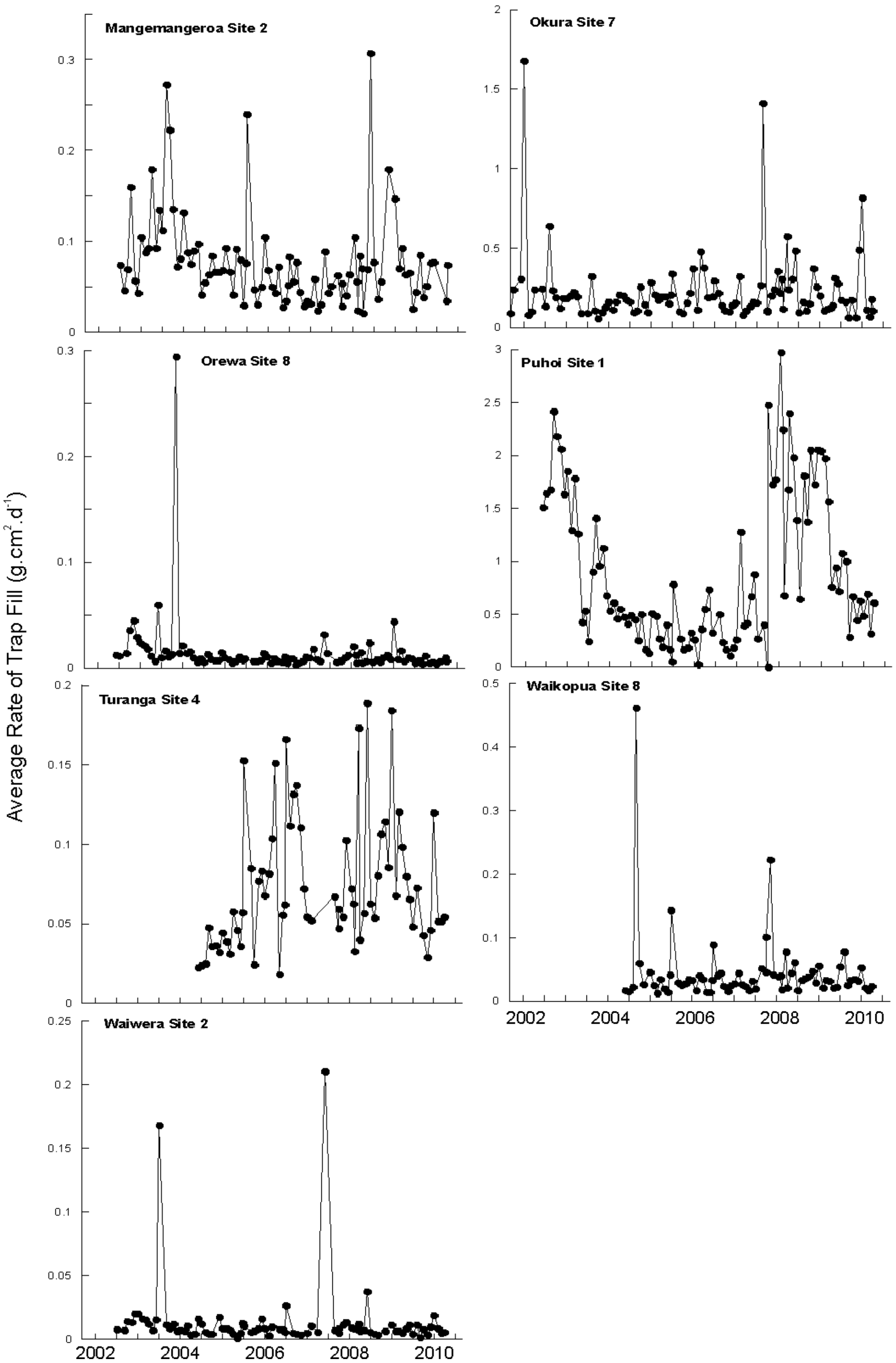
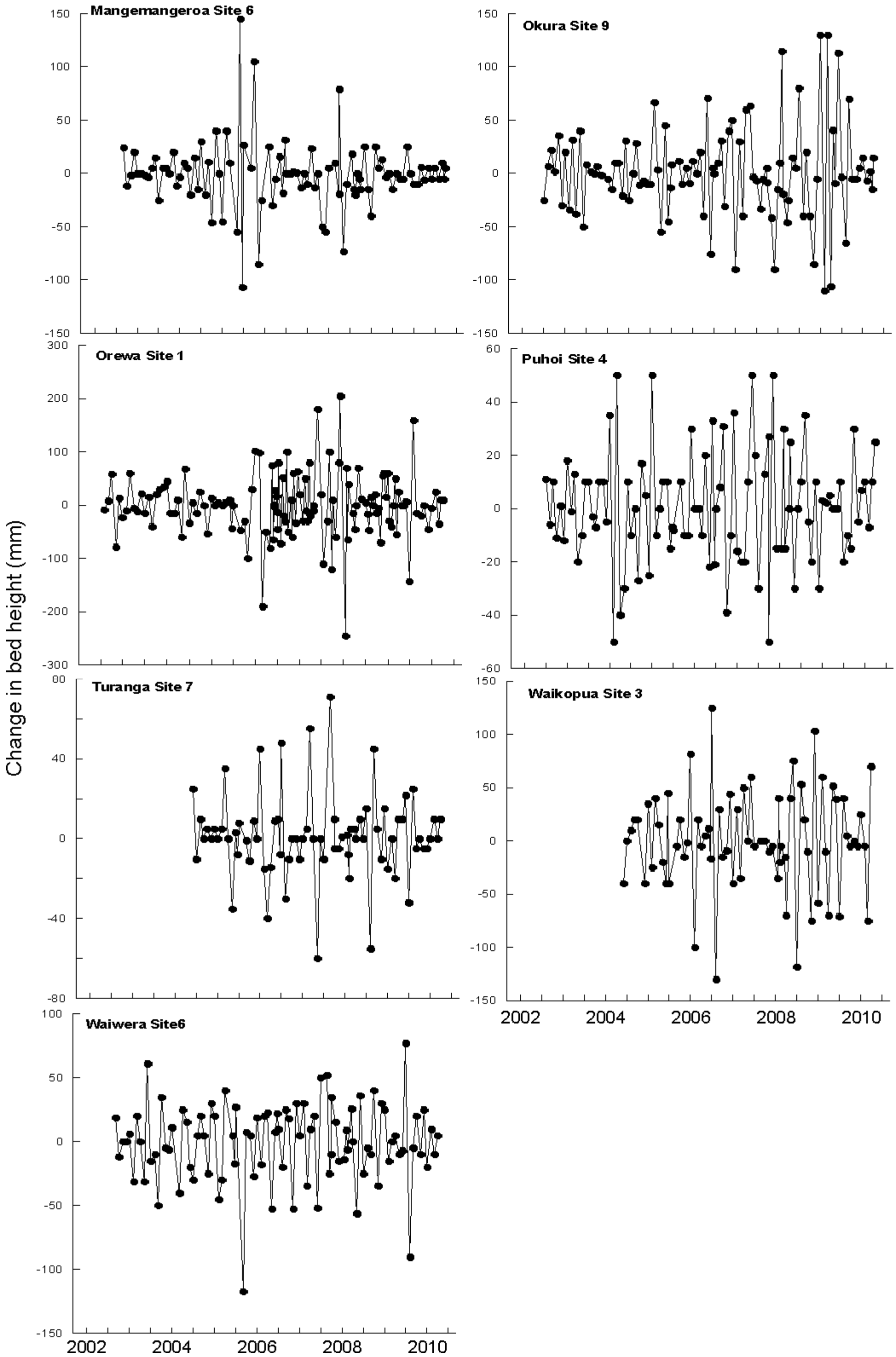


**Figure 10.4.3:**

Selected plots of changes in bed height fround in the sediment traps over time.



## 10.4 Appendix 4: Statistical results of trend analysis with %mud content across time at each site/estuary.

| | Mangemangeroa | | Okura | | Orewa | | Puhoi | | Turanga | | Waikopua | | Waiwera | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| site | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value |
| Capmud | | | | | | | | | | | | | | |
| 1 | 0.00 | 0.8816 | 0.00 | 0.4476 | 0.00 | 0.1452 | -0.01 | 0.0070 | 0.00 | 0.8412 | 0.00 | 0.8817 | -0.01 | 0.0002 |
| 2 | 0.00 | 0.3617 | -0.01 | 0.0239 | -0.01 | 0.0065 | 0.00 | 0.3685 | 0.00 | 0.8704 | 0.00 | 0.8369 | 0.00 | 0.3815 |
| 3 | 0.00 | 0.6052 | 0.00 | 0.7764 | 0.00 | 0.5177 | 0.00 | 0.0423 | 0.00 | 0.7372 | 0.00 | 0.3628 | 0.00 | 0.3179 |
| 4 | -0.01 | 0.1589 | -0.01 | 0.0533 | -0.01 | 0.1793 | 0.00 | 0.2411 | 0.00 | 0.5195 | 0.00 | 0.7299 | 0.00 | 0.9180 |
| 5 | 0.00 | 0.5524 | 0.00 | 0.9831 | 0.00 | 0.0943 | 0.00 | 0.7028 | 0.00 | 0.6411 | 0.00 | 0.8354 | 0.00 | 0.6900 |
| 6 | -0.01 | 0.1970 | 0.00 | 0.5873 | 0.00 | 0.0837 | 0.01 | 0.1673 | 0.00 | 0.5498 | 0.00 | 0.5194 | 0.00 | 0.5194 |
| 7 | 0.00 | 0.5152 | 0.00 | 0.4948 | -0.02 | 0.0023 | 0.00 | 0.5111 | 0.00 | 0.3758 | -0.01 | 0.2350 | 0.00 | 0.3160 |
| 8 | -0.01 | 0.0582 | 0.00 | 0.9333 | 0.00 | 0.6043 | 0.00 | 0.6167 | 0.00 | 0.0369 | -0.01 | 0.0059 | 0.00 | 0.9208 |
| 9 | -0.01 | 0.0677 | -0.01 | 0.1069 | 0.00 | 0.8586 | 0.00 | 0.8427 | 0.00 | 0.2399 | 0.00 | 0.1026 | 0.00 | 0.8746 |
| 10 | 0.00 | 0.4635 | 0.00 | 0.0941 | 0.00 | 0.4396 | -0.01 | 0.1087 | 0.00 | 0.0111 | 0.00 | 0.4352 | 0.00 | 0.5203 |
| # taxa | | | | | | | | | | | | | | |
| 1 | -0.38 | 0.1158 | 0.00 | 1.0000 | 0.35 | 0.1046 | -0.21 | 0.4355 | -0.17 | 0.4482 | -0.49 | 0.2545 | -0.99 | 0.0017 |
| 2 | -0.19 | 0.5628 | -0.19 | 0.7055 | -0.57 | 0.0316 | -0.94 | 0.0356 | 0.03 | 0.9114 | -1.02 | 0.1179 | -0.19 | 0.5912 |
| 3 | -0.62 | 0.1179 | 0.39 | 0.2713 | -0.66 | 0.1438 | -1.26 | 0.0041 | -0.16 | 0.6019 | -0.12 | 0.7531 | -0.66 | 0.1464 |
| 4 | 0.02 | 0.9704 | 0.55 | 0.2442 | 0.38 | 0.3774 | -0.33 | 0.2718 | 0.28 | 0.5682 | -0.50 | 0.2162 | -0.45 | 0.2952 |
| 5 | -0.57 | 0.1403 | 0.29 | 0.6768 | -0.23 | 0.4897 | -0.49 | 0.2407 | -0.57 | 0.0417 | -0.69 | 0.0576 | -0.52 | 0.0256 |
| 6 | -1.00 | 0.1498 | 0.00 | 0.9940 | -0.63 | 0.0909 | -0.11 | 0.7283 | -0.58 | 0.2150 | -0.26 | 0.2851 | -0.14 | 0.7038 |
| 7 | -0.34 | 0.4214 | -0.11 | 0.7172 | 0.08 | 0.8195 | -0.10 | 0.7551 | -0.89 | 0.0221 | -0.79 | 0.1025 | -0.43 | 0.3703 |
| 8 | -0.61 | 0.1307 | -0.45 | 0.2280 | -1.05 | 0.0321 | -1.34 | 0.0218 | -0.55 | 0.2145 | -0.35 | 0.3048 | 0.03 | 0.9234 |

| | Mangemangeroa | | Okura | | Orewa | | Puhoi | | Turanga | | Waikopua | | Waiwera | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| site | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value |
| 9 | -0.55 | 0.0849 | -0.74 | 0.0189 | -0.47 | 0.2959 | -0.32 | 0.3606 | 0.01 | 0.9748 | -0.30 | 0.3083 | -0.28 | 0.2987 |
| 10 | -0.14 | 0.6200 | -0.45 | 0.1271 | -0.97 | 0.0349 | -1.52 | 0.0285 | -0.40 | 0.1833 | 0.14 | 0.7989 | -0.04 | 0.9399 |
| *Anthopleura* | | | | | | | | | | | | | | |
| 1 | 7.38 | 0.0200 | -1.62 | 0.5302 | 0.00 | . | 0.47 | 0.2023 | 0.58 | 0.4657 | 0.20 | 0.3992 | -0.05 | 0.4954 |
| 2 | 4.74 | 0.0091 | -0.01 | 0.9038 | 2.63 | 0.0324 | 0.00 | . | 0.09 | 0.3164 | 2.91 | 0.0802 | -0.01 | 0.8928 |
| 3 | 13.02 | 0.0028 | 1.69 | 0.1450 | -0.04 | 0.9362 | -0.16 | 0.1082 | -0.08 | 0.7762 | 0.22 | 0.5062 | -0.02 | 0.6657 |
| 4 | -0.19 | 0.4382 | 0.55 | 0.7232 | 0.01 | 0.8510 | 1.75 | 0.0222 | 0.08 | 0.4351 | -0.32 | 0.3863 | 0.00 | . |
| 5 | 0.13 | 0.3967 | 0.24 | 0.8234 | 6.34 | 0.0089 | 0.08 | 0.2441 | -0.05 | 0.2470 | -1.23 | 0.2455 | 0.43 | 0.3474 |
| 6 | 0.35 | 0.7957 | 5.99 | 0.1145 | 0.04 | 0.1139 | 4.10 | 0.0937 | 2.37 | 0.1431 | 0.29 | 0.5042 | 0.42 | 0.3805 |
| 7 | -0.48 | 0.0884 | -0.50 | 0.5384 | 4.30 | 0.0113 | 1.38 | 0.0337 | 0.71 | 0.5857 | -0.01 | 0.8415 | 0.58 | 0.1032 |
| 8 | -0.05 | 0.3242 | 0.05 | 0.7994 | 1.74 | 0.0868 | 0.00 | . | 0.00 | . | 0.00 | . | -0.48 | 0.1426 |
| 9 | 0.00 | . | 0.12 | 0.7270 | 1.91 | 0.0669 | 0.00 | . | 0.00 | . | 0.00 | . | 0.79 | 0.5180 |
| 10 | 0.00 | . | -0.05 | 0.3242 | -0.11 | 0.1215 | 0.00 | . | -0.01 | 0.6849 | 0.00 | . | 0.21 | 0.2580 |
| *Aonides* | | | | | | | | | | | | | | |
| 1 | 0.05 | 0.8437 | -5.50 | 0.0057 | 0.07 | 0.4033 | -0.15 | 0.1139 | -1.20 | 0.5061 | -0.38 | 0.0702 | -0.16 | 0.1963 |
| 2 | 4.51 | 0.3249 | -0.08 | 0.1675 | 0.69 | 0.6056 | -0.08 | 0.1139 | 0.19 | 0.8464 | -0.68 | 0.4402 | 0.04 | 0.1139 |
| 3 | 1.22 | 0.4665 | 0.05 | 0.6353 | -5.74 | 0.0588 | -0.04 | 0.1139 | -1.55 | 0.1275 | -0.07 | 0.2528 | -0.15 | 0.1139 |
| 4 | -0.26 | 0.1037 | 0.24 | 0.8530 | 0.00 | . | -0.39 | 0.1160 | 0.07 | 0.5850 | -0.19 | 0.1961 | 0.00 | . |
| 5 | 0.02 | 0.7445 | -0.16 | 0.5522 | 0.09 | 0.9030 | 0.00 | . | -0.03 | 0.3044 | -0.30 | 0.0176 | 0.25 | 0.1459 |
| 6 | 0.04 | 0.9325 | -1.77 | 0.0003 | -0.06 | 0.2847 | -0.14 | 0.2298 | -0.04 | 0.4858 | 2.58 | 0.0419 | -0.07 | 0.2026 |
| 7 | -0.13 | 0.2063 | -0.30 | 0.7246 | 0.01 | 0.9294 | 0.14 | 0.1269 | -0.10 | 0.2254 | -9.08 | 0.4439 | -0.27 | 0.3326 |
| 8 | 0.01 | 0.8110 | -0.06 | 0.8122 | -0.12 | 0.0603 | -0.16 | 0.1215 | 0.04 | 0.4676 | -0.06 | 0.5669 | -0.11 | 0.4151 |
| 9 | -0.03 | 0.6882 | -0.04 | 0.3324 | -0.42 | 0.2944 | 0.00 | . | -0.03 | 0.3044 | -0.04 | 0.4858 | -2.53 | 0.0006 |
| 10 | -0.07 | 0.0228 | 0.00 | . | -0.02 | 0.6305 | -0.15 | 0.0306 | -0.03 | 0.2063 | 0.02 | 0.7539 | 0.09 | 0.0855 |

| | Mangemangeroa | | Okura | | Orewa | | Puhoi | | Turanga | | Waikopua | | Waiwera | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| site | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value |
| *Austrovenus* | | | | | | | | | | | | | | |
| 1 | -4.04 | 0.2007 | -18.39 | 0.0002 | -1.58 | 0.6222 | -3.09 | 0.0063 | -0.36 | 0.7233 | 0.71 | 0.2811 | -3.16 | 0.0924 |
| 2 | 1.80 | 0.6201 | -1.01 | 0.5002 | 2.36 | 0.7411 | 0.99 | 0.4959 | 0.02 | 0.9418 | -3.08 | 0.1675 | -0.59 | 0.7772 |
| 3 | -3.62 | 0.6743 | 1.99 | 0.6856 | -8.48 | 0.1991 | -0.72 | 0.7842 | 0.26 | 0.5469 | -3.10 | 0.1092 | -0.21 | 0.8128 |
| 4 | -1.85 | 0.3022 | -0.48 | 0.8726 | 8.73 | 0.0214 | 33.81 | 0.0513 | 1.08 | 0.3037 | -0.90 | 0.4417 | -0.15 | 0.7809 |
| 5 | 1.20 | 0.4617 | 6.53 | 0.0973 | -0.51 | 0.8856 | 0.13 | 0.5718 | 0.42 | 0.4810 | -3.55 | 0.0723 | 1.04 | 0.9315 |
| 6 | 1.42 | 0.7551 | 2.54 | 0.4090 | 0.98 | 0.2513 | 10.04 | 0.0794 | -0.16 | 0.9585 | -0.35 | 0.7187 | 18.96 | 0.0485 |
| 7 | -1.42 | 0.0607 | 2.04 | 0.3730 | 6.48 | 0.5424 | 9.13 | 0.0044 | -3.02 | 0.1181 | 0.70 | 0.6799 | -5.04 | 0.5277 |
| 8 | -1.01 | 0.0590 | 0.10 | 0.9633 | 3.12 | 0.1293 | 0.33 | 0.8190 | 0.07 | 0.5793 | -0.80 | 0.1294 | 1.86 | 0.2803 |
| 9 | -0.67 | 0.0967 | -3.74 | 0.0787 | 1.66 | 0.3066 | 0.05 | 0.9397 | -0.02 | 0.6849 | -0.94 | 0.2701 | 7.81 | 0.1815 |
| 10 | 0.48 | 0.3056 | 0.21 | 0.5923 | -0.50 | 0.3366 | 0.82 | 0.6292 | -0.01 | 0.9049 | -0.10 | 0.7004 | 0.12 | 0.9850 |
| *Colurostylis* | | | | | | | | | | | | | | |
| 1 | 0.10 | 0.8510 | 3.73 | 0.0520 | -2.24 | 0.4714 | -5.22 | 0.4845 | 0.30 | 0.7197 | -0.65 | 0.4712 | -0.09 | 0.0925 |
| 2 | 0.51 | 0.4373 | 0.17 | 0.5457 | -1.73 | 0.1216 | -0.37 | 0.4563 | 0.37 | 0.7401 | -0.70 | 0.5073 | -0.13 | 0.4201 |
| 3 | -0.24 | 0.7934 | -0.10 | 0.9775 | -6.72 | 0.0870 | -0.30 | 0.2475 | 0.08 | 0.7344 | -0.23 | 0.6733 | -9.78 | 0.0066 |
| 4 | 0.15 | 0.4511 | -7.33 | 0.0672 | 0.79 | 0.6165 | 4.14 | 0.4750 | 0.28 | 0.0767 | 0.03 | 0.9140 | -0.18 | 0.7518 |
| 5 | 0.01 | 0.9356 | 0.35 | 0.8686 | -0.66 | 0.6690 | 0.55 | 0.5033 | 0.06 | 0.6583 | -0.34 | 0.5982 | -1.01 | 0.4464 |
| 6 | 0.27 | 0.7385 | -1.51 | 0.6533 | -0.27 | 0.1595 | 0.22 | 0.9126 | 0.41 | 0.4019 | 0.16 | 0.7424 | -2.13 | 0.5943 |
| 7 | 0.13 | 0.7657 | -0.71 | 0.7569 | -0.67 | 0.8871 | -2.94 | 0.2346 | 0.08 | 0.8868 | 0.70 | 0.6645 | -1.42 | 0.6192 |
| 8 | 0.14 | 0.0685 | -0.63 | 0.5543 | -0.43 | 0.7828 | -0.24 | 0.7590 | -0.09 | 0.0193 | 0.01 | 0.6849 | -8.06 | 0.2361 |
| 9 | -0.11 | 0.1586 | -1.41 | 0.0461 | 0.22 | 0.5433 | 0.00 | 0.9853 | 0.00 | . | 0.00 | 0.8928 | -6.16 | 0.0126 |
| 10 | -0.05 | 0.7585 | -0.68 | 0.0015 | -0.03 | 0.9186 | -4.05 | 0.0222 | 0.00 | . | 0.04 | 0.2441 | 0.27 | 0.6554 |

| | Mangemangeroa | | Okura | | Orewa | | Puhoi | | Turanga | | Waikopua | | Waiwera | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| site | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value |
| *Macomona* | | | | | | | | | | | | | | |
| 1 | -1.89 | 0.1416 | -0.22 | 0.8802 | -2.99 | 0.2532 | -0.70 | 0.2260 | -2.03 | 0.0292 | 0.03 | 0.9045 | -2.78 | 0.0837 |
| 2 | -0.91 | 0.0277 | -4.54 | 0.2962 | -2.33 | 0.6732 | -0.30 | 0.3955 | -1.14 | 0.0460 | -4.34 | 0.0296 | -0.13 | 0.5658 |
| 3 | -0.62 | 0.0143 | 1.68 | 0.0708 | -3.67 | 0.2868 | -0.98 | 0.0010 | -1.51 | 0.0318 | -1.30 | 0.2059 | -0.35 | 0.6575 |
| 4 | -0.50 | 0.2349 | 4.61 | 0.0168 | -0.25 | 0.4790 | 0.46 | 0.8281 | -0.17 | 0.5289 | -0.47 | 0.5481 | -0.01 | 0.9857 |
| 5 | -0.33 | 0.3325 | 3.12 | 0.2634 | 0.25 | 0.8790 | -1.10 | 0.4169 | -0.05 | 0.4895 | -3.33 | 0.0013 | -1.36 | 0.4520 |
| 6 | -0.76 | 0.3608 | 2.07 | 0.2177 | -1.37 | 0.2716 | 4.01 | 0.0620 | -0.05 | 0.9356 | -0.90 | 0.0901 | -1.08 | 0.5220 |
| 7 | 0.32 | 0.3558 | 1.14 | 0.3085 | 2.36 | 0.3541 | 5.21 | 0.0049 | -1.22 | 0.0771 | -1.19 | 0.0198 | -1.24 | 0.1718 |
| 8 | -0.34 | 0.0615 | 0.02 | 0.9922 | -0.83 | 0.4967 | -0.42 | 0.4150 | -0.25 | 0.2738 | -0.71 | 0.0042 | -1.02 | 0.1126 |
| 9 | -0.12 | 0.3802 | -7.96 | 0.4332 | -4.64 | 0.4170 | -0.78 | 0.1562 | 0.00 | . | -0.14 | 0.3455 | 0.67 | 0.4509 |
| 10 | 0.08 | 0.6821 | -2.20 | 0.6313 | -0.96 | 0.5644 | -0.52 | 0.7999 | -0.02 | 0.4954 | -0.88 | 0.4161 | 1.24 | 0.2489 |
| *Paphies* | | | | | | | | | | | | | | |
| 1 | -0.24 | 0.3552 | -7.00 | 0.1119 | 20.53 | 0.4382 | -1.35 | 0.9381 | 0.38 | 0.4249 | -0.11 | 0.0844 | -0.41 | 0.0555 |
| 2 | -0.06 | 0.1196 | -0.12 | 0.1304 | -0.95 | 0.1733 | -0.40 | 0.1781 | 2.91 | 0.4395 | -0.15 | 0.3094 | -0.07 | 0.6962 |
| 3 | -0.91 | 0.2074 | 2.23 | 0.0089 | 4.95 | 0.7653 | -0.23 | 0.0254 | -2.82 | 0.1819 | -0.10 | 0.4608 | -26.50 | 0.1120 |
| 4 | -0.01 | 0.9406 | -0.23 | 0.0804 | -11.64 | 0.0014 | -8.93 | 0.1508 | 0.08 | 0.5504 | -0.11 | 0.1377 | -1.27 | 0.1538 |
| 5 | -0.07 | 0.3339 | -0.36 | 0.5452 | 0.00 | 1.0000 | -0.24 | 0.0941 | -0.05 | 0.3339 | -0.13 | 0.2295 | -1.29 | 0.0823 |
| 6 | -0.02 | 0.3339 | -0.13 | 0.1853 | -0.09 | 0.4749 | -0.06 | 0.6822 | -0.18 | 0.0627 | 0.00 | 1.0000 | -2.71 | 0.5813 |
| 7 | -0.01 | 0.6882 | 0.77 | 0.5086 | -0.72 | 0.2082 | -0.40 | 0.0883 | -0.07 | 0.3709 | -0.07 | 0.2889 | -3.51 | 0.0397 |
| 8 | -0.06 | 0.4161 | -0.03 | 0.7896 | -0.10 | 0.3313 | 0.15 | 0.2191 | -0.24 | 0.1982 | -0.07 | 0.1674 | -16.00 | 0.1909 |
| 9 | -0.07 | 0.3339 | -0.05 | 0.7514 | -0.08 | 0.4577 | -0.52 | 0.2168 | 0.00 | . | -0.03 | 0.2063 | -1.84 | 0.0168 |
| 10 | -0.24 | 0.1596 | -0.02 | 0.8228 | -0.27 | 0.1305 | -2.42 | 0.3297 | -0.04 | 0.6848 | 0.00 | . | -0.16 | 0.1469 |

| | Mangemangeroa | | Okura | | Orewa | | Puhoi | | Turanga | | Waikopua | | Waiwera | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| site | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value |
| *Waitangi* | | | | | | | | | | | | | | |
| 1 | -0.06 | 0.4639 | 0.36 | 0.6989 | -5.06 | 0.4132 | -12.48 | 0.0251 | 0.04 | 0.1139 | -0.18 | 0.1258 | -0.02 | 0.6336 |
| 2 | 0.02 | 0.3339 | -0.06 | 0.3273 | -0.37 | 0.0974 | -0.09 | 0.3879 | -0.03 | 0.6954 | -0.11 | 0.3336 | 0.04 | 0.6327 |
| 3 | 0.00 | . | 0.17 | 0.6504 | -0.71 | 0.8632 | -0.05 | 0.6298 | 0.00 | . | -0.39 | 0.1085 | -12.48 | 0.1049 |
| 4 | -0.08 | 0.2441 | -1.79 | 0.0665 | -13.52 | 0.0003 | -6.42 | 0.3315 | 0.00 | . | -0.05 | 0.6094 | -0.36 | 0.2923 |
| 5 | 0.00 | . | -0.22 | 0.2977 | 0.10 | 0.6079 | -0.02 | 0.8110 | 0.04 | 0.1139 | 0.00 | . | 0.08 | 0.1263 |
| 6 | 0.00 | . | -0.84 | 0.0131 | -0.04 | 0.7664 | 0.01 | 0.8830 | 0.00 | . | -0.06 | 0.0467 | -7.13 | 0.2262 |
| 7 | 0.00 | . | -0.14 | 0.1715 | -0.50 | 0.0482 | -0.16 | 0.0439 | -0.08 | 0.1263 | 0.00 | . | -0.45 | 0.3000 |
| 8 | 0.00 | . | -0.08 | 0.1139 | 0.00 | 0.8928 | -0.01 | 0.8735 | 0.00 | 1.0000 | -0.02 | 0.4954 | -7.39 | 0.4657 |
| 9 | 0.00 | . | -0.06 | 0.1196 | 0.02 | 0.6305 | 0.00 | . | 0.00 | . | 0.00 | . | -0.19 | 0.1193 |
| 10 | 0.00 | . | 0.02 | 0.7729 | -0.09 | 0.2421 | -0.06 | 0.2087 | 0.00 | . | 0.00 | . | -0.02 | 0.8735 |
| Corophidae | | | | | | | | | | | | | | |
| 1 | -0.02 | 0.6305 | 0.19 | 0.0349 | 0.03 | 0.9780 | -0.05 | 0.8802 | 0.02 | 0.7843 | -0.08 | 0.6294 | 0.70 | 0.8796 |
| 2 | -0.01 | 0.8415 | -0.02 | 0.9289 | -0.76 | 0.5200 | -27.17 | 0.1526 | 0.08 | 0.4858 | 0.22 | 0.2616 | -4.32 | 0.0651 |
| 3 | -0.15 | 0.0406 | 0.26 | 0.9383 | -0.11 | 0.6310 | -5.77 | 0.4165 | -0.04 | 0.3324 | 0.42 | 0.1534 | -0.06 | 0.5378 |
| 4 | -0.21 | 0.8795 | 0.01 | 0.8928 | 1.68 | 0.7990 | -0.21 | 0.1476 | 0.01 | 0.8608 | -0.01 | 0.9759 | -2.67 | 0.2758 |
| 5 | 0.47 | 0.6444 | -21.64 | 0.0360 | 0.26 | 0.5970 | -1.87 | 0.0347 | -0.65 | 0.0382 | -0.02 | 0.7729 | -4.83 | 0.2205 |
| 6 | 0.20 | 0.2528 | -0.32 | 0.7070 | -0.28 | 0.0902 | -0.47 | 0.0998 | -1.10 | 0.0731 | 0.07 | 0.4965 | 0.02 | 0.7306 |
| 7 | -0.12 | 0.3140 | -4.28 | 0.0330 | -0.10 | 0.5414 | -0.31 | 0.2736 | 0.80 | 0.3795 | 0.05 | 0.8205 | -0.64 | 0.5883 |
| 8 | -0.34 | 0.2441 | -2.69 | 0.1600 | -9.35 | 0.1799 | -6.24 | 0.1676 | -1.23 | 0.3666 | -0.21 | 0.6771 | 0.05 | 0.8682 |
| 9 | -0.52 | 0.8448 | -0.38 | 0.1590 | -4.06 | 0.2395 | -27.27 | 0.0302 | -0.49 | 0.9604 | 2.20 | 0.4535 | -0.12 | 0.8084 |
| 10 | -0.97 | 0.1241 | -4.85 | 0.1994 | -67.89 | 0.1350 | -29.15 | 0.1114 | 4.14 | 0.8684 | 3.45 | 0.2754 | -5.07 | 0.4900 |

| | Mangemangeroa | | Okura | | Orewa | | Puhoi | | Turanga | | Waikopua | | Waiwera | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| site | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value | Slope | p-value |
| Crabs | | | | | | | | | | | | | | |
| 1 | -0.65 | 0.3259 | 0.00 | 0.9315 | 0.02 | 0.6598 | 0.06 | 0.6053 | -0.01 | 0.9137 | -0.23 | 0.2955 | 0.98 | 0.4097 |
| 2 | -0.20 | 0.5554 | -0.32 | 0.6436 | 1.31 | 0.0275 | 0.39 | 0.4766 | 0.01 | 0.9645 | -0.89 | 0.2919 | -0.23 | 0.3093 |
| 3 | -0.20 | 0.6969 | -0.70 | 0.3009 | 0.62 | 0.3054 | 0.31 | 0.5348 | -0.44 | 0.3107 | -1.13 | 0.0607 | 0.02 | 0.8125 |
| 4 | -0.95 | 0.4070 | 0.02 | 0.8785 | 0.92 | 0.0096 | -0.43 | 0.0529 | -0.53 | 0.5744 | -0.35 | 0.5850 | -1.19 | 0.2883 |
| 5 | -0.33 | 0.7022 | -0.84 | 0.2539 | 0.52 | 0.1173 | -0.92 | 0.0084 | 0.49 | 0.6473 | -1.02 | 0.3499 | 0.25 | 0.6529 |
| 6 | -0.09 | 0.9206 | -0.34 | 0.5799 | -0.17 | 0.8021 | -0.44 | 0.2200 | -0.95 | 0.2166 | -0.20 | 0.7853 | -0.03 | 0.7245 |
| 7 | -0.36 | 0.5570 | -0.92 | 0.0568 | 0.48 | 0.2356 | -0.04 | 0.8243 | -0.07 | 0.9490 | -0.09 | 0.9096 | 0.31 | 0.5705 |
| 8 | -0.72 | 0.2652 | 0.03 | 0.9394 | 0.46 | 0.6789 | -1.09 | 0.0393 | -1.06 | 0.3702 | -0.10 | 0.9368 | -0.13 | 0.2063 |
| 9 | 0.00 | 0.9969 | -0.03 | 0.9464 | 1.68 | 0.1767 | -0.47 | 0.4069 | -0.53 | 0.7372 | 1.12 | 0.2717 | -0.13 | 0.2530 |
| 10 | -0.54 | 0.6345 | 0.55 | 0.2193 | 1.13 | 0.2258 | 0.14 | 0.8652 | -1.06 | 0.5122 | -0.03 | 0.9786 | -0.45 | 0.5646 |
| Nereididae | | | | | | | | | | | | | | |
| 1 | -0.21 | 0.5098 | 0.21 | 0.0477 | 0.02 | 0.6657 | -0.05 | 0.7720 | 0.30 | 0.4753 | 0.11 | 0.8426 | -1.48 | 0.5023 |
| 2 | 0.51 | 0.2509 | 2.42 | 0.1211 | 0.23 | 0.2964 | -0.89 | 0.1174 | 0.33 | 0.2449 | -7.86 | 0.0165 | 0.06 | 0.7393 |
| 3 | -0.27 | 0.4404 | 0.17 | 0.2470 | -0.24 | 0.2525 | -0.91 | 0.2188 | -0.04 | 0.8346 | -1.92 | 0.1262 | 0.14 | 0.4890 |
| 4 | -0.72 | 0.4826 | 0.58 | 0.0475 | 0.09 | 0.1638 | 0.37 | 0.3019 | 0.49 | 0.5023 | -0.37 | 0.8285 | -0.16 | 0.2984 |
| 5 | -1.17 | 0.1452 | 0.95 | 0.0795 | 0.38 | 0.3192 | 6.48 | 0.6050 | -0.22 | 0.6261 | -2.71 | 0.1879 | 0.12 | 0.8450 |
| 6 | -0.86 | 0.4556 | 0.29 | 0.1497 | 0.60 | 0.4303 | 0.34 | 0.5409 | 0.69 | 0.3562 | 0.07 | 0.9439 | 1.46 | 0.0571 |
| 7 | -1.05 | 0.2026 | 0.38 | 0.0573 | 1.53 | 0.1951 | 5.11 | 0.2437 | 0.06 | 0.9359 | -0.69 | 0.2274 | -0.02 | 0.9556 |
| 8 | -1.62 | 0.0599 | 0.60 | 0.7395 | -0.04 | 0.9495 | -1.40 | 0.3055 | -1.41 | 0.0851 | 0.49 | 0.5490 | 0.88 | 0.1634 |
| 9 | -0.23 | 0.7473 | 0.91 | 0.4704 | -0.95 | 0.6231 | 1.16 | 0.7739 | -0.10 | 0.6406 | -0.19 | 0.6109 | 5.68 | 0.2945 |
| 10 | -0.24 | 0.5783 | 0.27 | 0.9244 | -3.64 | 0.6039 | -1.35 | 0.5199 | -0.39 | 0.2158 | 0.55 | 0.2604 | 0.75 | 0.1480 |

## 10.5 Appendix 5: Full isotopic signature results

Full results of % contribution of likely source sediments to the sediment found at each site in September 2009. Delta = samples taken in the uppermost portion of the estuary, well above monitored sites. Coast = marine sediment from nearby coast. S# = site number.

| | | s9 | stdev | s4 | stdev | s1 | stdev |
|---|---|---|---|---|---|---|---|
| Puhoi | delta1 | 2.25 | 1.6 | 0.16 | 0.9 | 0.32 | 1 |
| Puhoi | delta2 | 59.05 | 1.6 | 0.22 | 1.7 | 0.32 | 1.4 |
| Puhoi | s9 | | | 6.78 | 4.1 | 15.07 | 2 |
| Puhoi | s4 | 23.21 | 0 | | | 2.47 | 2.9 |
| Puhoi | s1 | | | 33.01 | 6.4 | | |
| Puhoi | Coast | 15.49 | 0 | 59.83 | 2 | 81.83 | 1.6 |

| | | s8 | stdev | s6 | stdev | s2 | stdev |
|---|---|---|---|---|---|---|---|
| Waiwera | delta1 | 0.00 | 0 | 0.07 | 1.1 | 7.96 | 0.6 |
| Waiwera | delta2 | 0.00 | 0.2 | 0.19 | 1.1 | 0.27 | 0.6 |
| Waiwera | s8 | | | 0.18 | 4 | 25.86 | 1.2 |
| Waiwera | s6 | 0.69 | 4.3 | | | | |
| Waiwera | s2 | 96.52 | 3.8 | 91.29 | 5.5 | | |
| Waiwera | Coast | 2.79 | 0.6 | 8.28 | 1.3 | 65.91 | 0.6 |

| | | s8 | stdev | s4 | stdev | s1 | stdev |
|---|---|---|---|---|---|---|---|
| Orewa | delta1 | 0.03 | 1.4 | 0.50 | 9.3 | 0.00 | 0 |
| Orewa | delta2 | 0.02 | 1.2 | 0.81 | 8.7 | 0.14 | 0.7 |
| Orewa | delta3 | | | | | | |
| Orewa | delta4 | 0.02 | 2.1 | | | | |
| Orewa | delta5 | 0.03 | 2.1 | | | | |
| Orewa | s8 | | | 11.05 | 5.1 | 0.63 | 0.7 |
| Orewa | s4 | 0.22 | 2.6 | | | 27.74 | 1.4 |
| Orewa | s1 | 99.69 | 2 | 87.16 | 4.9 | | |
| Orewa | Coast | | | 0.48 | 0.8 | 71.49 | 0 |

| | | s9 | stdev | s6 | stdev | s3 | stdev |
|---|---|---|---|---|---|---|---|
| Okura | delta1 | 0.18 | 0.8 | 0.25 | 1.2 | | |
| Okura | delta5 | 3.72 | 0.7 | 0.02 | 0.4 | | |
| Okura | s9 | | | 40.29 | 6.3 | 15.42 | 2.5 |
| Okura | s6 | 68.56 | 4.8 | | | 8.64 | 4.3 |
| Okura | s3 | 23.61 | 4.8 | 43.71 | 11.4 | | |
| Okura | Coast | 3.93 | 1.5 | 15.73 | 5.7 | 75.93 | 1.8 |

| | | s9 | stdev | s6 | stdev | s3 | stdev |
|---|---|---|---|---|---|---|---|
| Mangemangeroa | delta1 | 3.81 | 1.2 | 0.08 | 0.6 | 0.02 | 0.4 |
| Mangemangeroa | s9 | | | 41.00 | 2.7 | 10.36 | 15.7 |
| Mangemangeroa | s6 | 77.02 | 4.9 | | | 20.78 | 18.5 |
| Mangemangeroa | s3 | 19.17 | 3.8 | 17.86 | 4.4 | | |
| Mangemangeroa | Coast | 0.00 | 0 | 41.06 | 2.3 | 68.84 | 2.9 |

| | | s7 | stdev | s4 | stdev | s3 | stdev |
|---|---|---|---|---|---|---|---|
| Turanga | delta1 | 3.22 | 1 | 0.17 | 1 | | |
| Turanga | s7 | | | 53.12 | 2 | 3.26 | 4.9 |
| Turanga | s4 | 90.86 | 2.2 | | | 2.92 | 5.8 |
| Turanga | s3 | 3.17 | 1 | 19.68 | 5 | | |
| Turanga | Coast | 2.75 | 1 | 27.03 | 4.2 | 93.82 | 0.9 |

| | | s8 | stdev | s6 | stdev | s3 | stdev |
|---|---|---|---|---|---|---|---|
| Waikapoa | delta1 | 0.00 | 0.3 | 0.32 | 1.6 | 0.47 | 1 |
| Waikapoa | s8 | | | **64.04** | **7.3** | 54.21 | 6.8 |
| Waikapoa | s6 | 25.79 | 7.3 | | | 1.49 | 2.3 |
| Waikapoa | s3 | 69.45 | 4.9 | 8.50 | 5.9 | | |
| Waikapoa | Coast | 4.76 | 1.2 | 27.14 | 7.1 | 43.83 | 5.2 |