Ecological monitoring for potential effects of forestry activity on the intertidal habitats of Whangapoua Harbour

Long-term review 1993 - 2006

Aerial photograph of Whangapoua Harbour (2004). Photograph supplied by Ernslaw One Ltd.

NIWA Client Report: HAM2006-113
November 2006
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Prepared for

Ernslaw One Ltd

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Contents

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Executive Summary

In 1992, NIWA (then the Water Quality Centre, NIWAR) was commissioned by Ernslaw One Ltd to assess the need for a monitoring programme to detect effects of forestry activity on intertidal areas of Whangapoua Harbour. A monitoring programme was subsequently developed for Whangapoua Harbour, focusing on the intertidal sediments of the harbour and their biological communities, and NIWA was commissioned by Ernslaw One Ltd to implement it. Due to the diffuse and widespread nature (in both space and time) of the forestry operations, it was not considered practical to implement a monitoring programme capable of establishing a cause and effect link between forestry activity and any potential changes occurring in the harbour. Rather, the programme was established by Ernslaw One to provide a sound scientific basis against which to assess whether changes occurred in the harbour. Then, if changes did occur, methods of determining the role of harvesting could be investigated. This report summarises the findings from harbour monitoring conducted between 1993 and the present and provides a review of the programme that meets requirements set out by the Environment Court.

In 2001, a number of trends consistent with increased sediment loading to the harbour were documented. The majority of these trends have continued to be observed, and new sediment-related trends have been documented. These changes are not sufficient to drastically alter the macrofaunal communities, although a long-term habitat (and a related community) change from *Zostera* flat to unvegetated firm sand has been recorded at one site, after the March 1995 storm covered the site with mud.

Trapping of sediment is more likely to occur in sheltered habitats such as mangroves and seagrass beds than in the open sandflats, and expansion of these habitats would represent an increased potential for storage of sediment within the harbour. The total area of seagrass beds in the harbour has decreased during the period 1945-2006, and the area occupied by mangroves has increased. It is important to note that much of this change occurred prior to 1993, with the exception of changes related to the storm of March 1995.

Repeated surveys of the harbour bed height demonstrate relatively minor changes, mainly within the 2 cm margin of error. Most of the changes detected were due to small-scale, lateral migration of the channels or beach accretion. Changes observed in the sediment characteristics have been transitory, associated with storms.

Water clarity in the harbour is generally high and the harbour still has high ecological values. Although intertidal seagrass is important for juvenile fish, we do not know if changes in the macrobenthic community and vegetated landscape documented by the monitoring program would have resulted in effects on fish in the harbour. Calculations of shorebird energetic requirements indicate a potential decrease in the food resources the flats provide for shorebirds. But the data

underlying these calculations are limited. For example, we do not have information on the distribution and abundance of shorebirds, or know that they are actually food-limited. A more detailed study would be needed to reach conclusions with any degree of scientific rigor.

Importantly, changes documented in the monitoring programme do indicate the potential for changes in basic ecosystem functions, such as the fluxes of nutrients and oxygen across the sediment-water interface. Our observations also indicate that the effects of sedimentation from the harbour’s catchment may extend on to the open coast.

The monitoring programme cannot directly differentiate between natural ecological variability and ecological changes related to anthropogenic activities, nor between impacts associated with soils sourced from different land-use in each catchment. However, there are a number of lines of evidence that can be used to infer cause-effect relationships. Within the report, research from a number of sources is used to suggest that ecological changes in the harbour are beyond those of natural variability and are likely to be linked to terrestrial sediment input. Further research confirms that it is likely that harvesting increases sediment runoff relative to mature forests. The observed significant statistical correlations of ecological change with harvested area (up to 4 yrs old) demonstrate another link.

It is important to consider what kind of criteria and levels of proof are needed to manage down stream effects of land use. To provide stronger evidence than presented in this report, on the effect of forestry activity on Whangapoua Harbour, would require three things. (1) Direct measurements of the amount of sediment entering the harbour, separated by landuse. This could be done by an extensive network of automatic samplers. A more cost-effective approach will be possible when NIWA’s ‘sediment finger printing techniques’ are fully developed. (2) Modelling of where sediment is deposited once it reaches the harbour, and how much of it remains in the harbour and is resuspended with tide and storm events. (3) More extensive ecological monitoring in the harbour, covering more habitats and including storm-related event sampling. Thus, while it is certainly technically feasible to provide stronger evidence than presented in this report, a cost-benefit analysis for this increased certainty against options for improved catchment management must be considered.

Ernslaw One Ltd initiated this work to provide a baseline of information for the harbour. There is merit in the continuation of monitoring for the on-going management of the harbour and the effects of land-use. It is particularly important that changes in the harbour’s ecology associated with land use should be considered as a catchment-wide issue. While the relevance to Ernslaw One Ltd and the issue of proof of cause and effect need to be resolved before decisions concerning the expansion or contraction of the monitoring programme are appropriate, at the least, we consider monitoring should be continued for State-of-the-Environment purposes.

1. Introduction

1.1 Report outline

This report has been undertaken both to provide Ernslaw One Ltd with a summary of the results of the Whangapoua Harbour Monitoring programme that they have been funding since 1993, and to provide a review of the programme that meets requirements set out by the Environment Court. The minimum requirements of the review are contained in Schedule One of the resource consents (110661 - 110664), Sections 33-34. This states that, as a minimum the report shall:

a) include and summarise all Whangapoua Harbour monitoring data collected by the Consent Holder under previous 961490, 930906 and 101018 and condition 33;

b) critically analyse the data in terms of:

- any trends or changes in biota abundance and diversity, harbour morphology and harbour ecology;
- the potential impacts of any trends or changes on the wider harbour ecosystem, including birds and fish;
- whether any trends or changes observed over the entire 10 year monitoring period fall within what could be expected to be the result of natural variations, or whether they can be partially or wholly attributed to forestry harvesting and associated earthworks operations. This assessment shall take into account the temporal pattern of harvesting over the 10 year monitoring period;

c) identify whether or not it is possible to monitor the effects of forestry operation on harbour morphology and ecology with a degree of certainty sufficient to distinguish the effects of forestry as distinct from other catchment landuses;

d) identify and document the appropriate nature and extent of any ongoing monitoring of the Whangapoua Harbour should the assessment under condition 34 (c) identify that it is possible to monitor the effects of forestry operation on harbour morphology and ecology with a degree of certainty sufficient to distinguish the effects of forestry as distinct from other catchment landuses.

1.2 Aims and design of the monitoring programme

In 1992, NIWA (then the Water Quality Centre, NIWAR) was commissioned by Ernslaw One Ltd to assess the need for a monitoring programme to detect effects of forestry activity on intertidal areas of Whangapoua Harbour. A monitoring programme was subsequently developed for Whangapoua Harbour, and NIWA was commissioned by Ernslaw One Ltd to implement it.

The monitoring programme was designed primarily to detect ecological changes within the harbour. The major threat to the harbour's ecology as a result of forestry activity is increases in the rate of sediment delivery. Thus, the monitoring programme sampled three sites within each arm of the harbour. This design could detect differences in changes to monitored species with distance from the head of each arm, as well as contrasts between arms. This would allow comparisons to be made of the magnitude of any change in monitored species with forestry activity occurring in different sub-catchments of the harbour at different times. At the time of set up, Ernslaw One Ltd was proposing to focus harvesting in the Owera Arm for the first few years, then gradually to increase harvesting in the Opitonui arm, with harvesting in the Mapauriki arm not scheduled to start for 10 yrs.

The monitoring programme also focused on intertidal sandflat habitats. Such habitats are generally species-rich and sensitive to deposition of terrestrial sediment. They also comprise a large portion of the area of Whangapoua Harbour and are generally the area most utilised by people.

While precise cause and effect relationships may be hard to unequivocally define, our approach does enable a gradient of effects to be identified: spatially, because of the site locations and the different timing of harvesting in the different arms, and temporally, because of the collection of data over time. Harbour monitoring programmes generally lack control sites (i.e., sites which are identical to the putative impact sites except they will not be subjected to impact), due to their general unavailability. This is particularly the case in the Coromandel due to localised rainfall patterns. Thus the ability to detect change, determine trends, and link these to possible causes, relies on gathering data over time and our knowledge of the sensitivity of different types of organisms to sediment stress, rather than the direct comparison with similar areas unaffected by forestry.

However, while we can to some extent link changes in catchments of the Opitonui, Owera and Mapauriki arms of the harbour to ecological change at different sites in the harbour, the monitoring programme cannot directly differentiate between ecological changes generated from impacts associated with sediments sourced from different land-use in each catchment. The approach we took from the outset was one that recognised this issue, but also recognised the value of providing quantitative measures of ecological change in the harbour over time.

Thus, the primary focus of the monitoring programme was to obtain precise estimates of the density of specific sediment dwelling animals at each site, augmented by description of sediment particle size to describe how sandy or how muddy the sites were becoming. The density of seagrass cover within monitored sites was also measured. Broader-scale information on the distribution of vegetation types (particularly seagrass and mangroves) was collected based on aerial photographs. Measurement of profiles of the height of the seabed were also made; principally to identify if the harbour channels migrate and, secondarily, to assess major sedimentation events. The important point to note is that the primary focus of the monitoring programme was on documenting ecological change within the harbour. Monitoring ecological variables (e.g., density of animals that live in the sediment) is more sensitive than monitoring physical variables. Although fine terrestrial sediments are most likely to influence the ecology of the harbour, these sediments may be transported away from a particular location by waves and tide, resulting in ecological effects that may not be associated with long-term habitat change. Moreover, by monitoring ecological variables we directly report on ecological effects and trends in the ecological status of the harbour.

The rationale of the monitoring study, the methods used and the results of the first year of the study (1993 – 1994) were presented in the first annual report (Morrisey et al. 1994). Results of the subsequent years of the monitoring programme and any changes to the methods were reported in annual reports for 1995 – 1999 and reviewed in Morrisey et al. (1999). Monitoring was suspended after the March 1999 sampling and reinstated in a reduced form in October 2001. Prior to the resumption of monitoring, the monitoring programme was reviewed by Hewitt (2001) in light of new research on the effects of terrestrial sedimentation on individual estuarine species. Since then key findings of the monitoring programme have been communicated to Ernslaw One Ltd in letter form.

2. Methods

Routine monitoring methods and analyses are given in Appendix 1. The location of the sites, profiles and regions surveyed in the monitoring programme are shown in Figure 1.

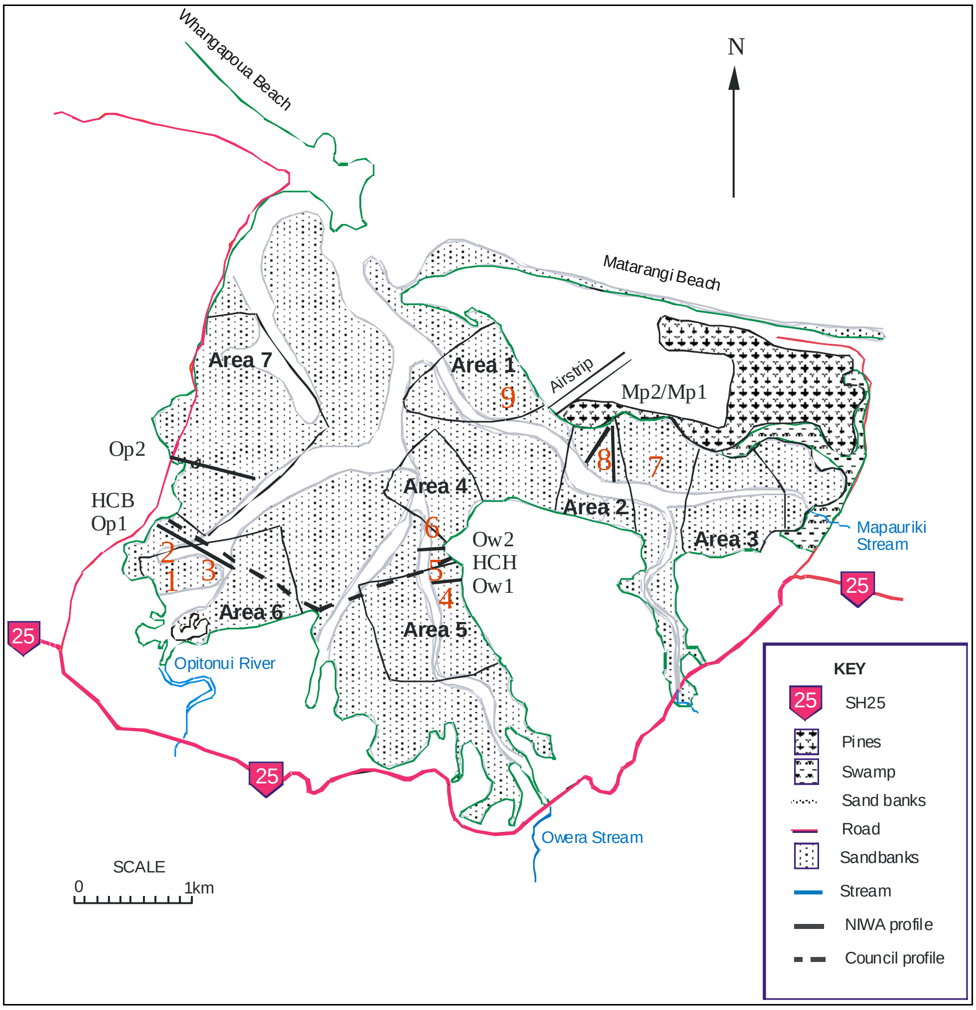

Figure 1: Whangapoua Harbour monitoring sites (1 – 9), sediment profile locations (Op1, Op2, Ow1, Ow2, Mp1 and Mp2) and areas for initial aerial vegetation mapping (Areas 1-7). Location of Environment Waikato profiles (HCA, HCB) are also given.

3. Summary of results of monitoring programme 1993 – 2006

3.1 Whangapoua Catchment 1993 – 2006

Initial harvesting in 1992, focused on the Owera catchment (see Table 1). This catchment was harvested from 1992 through to 1998. Logging then ceased, except for a section cut in 2005. Harvesting in the catchments that feed into the Opitonui arm (Opitonui, Awaroa, Waingaro and Waitekuri) increased from 1993 and between 1999 – 2004 was the major area harvested. Amount of area harvested varied between 29 % to 62 % of each catchment. The maximum amount cleared in any one year was 302 ha (2001), and the maximum amount of land that was covered with trees < 4 yrs old was 1100 ha (2002).

Rainfall in the area is recorded at Whangapoua, Rings Beach and Castle Rock. While patterns of rainfall are localised, correlations between data collected from these sources are in general high (Pearsons R = 0.82 to 0.88). Daily average rainfall is variable, with higher yearly maximums occurring between 1995 and 1997 than at other times (Fig. 2).

Data on stream flows is collected by Environment Waikato only at the Opitonui River near the Awaroa confluence (see Fig. 2).

Table 1: Total harvested area (ha) per catchment per year (1st April to 31st March), using information provided by Ernslaw One Ltd. Note that values for Waitekuri are predictions from 2001.

	Awaroa	**Opitonui**	**Waingaro**	**Waitekuri**	**Owera**
1992	0	4.8			104.7
1993	47.4	77.3	14.5		59.6
1994	60.5	90.9	7.5		66.1
1995	116.4	30.1			81.8
1996	58.2	64.4			74.5
1997	45.3	139.2			11.2
1998	50.4	161.6			16
1999	56	82.7	112.6		
2000	120.2	76.4	13.6	83	
2001	71.8	49.3	46.6	135	
2002	34	1.2	72.1	145	
2003	56.7		12.8	113	
2004			64.4	76	
2005			26.1		141
2006			16.8		
Total	716.9	777.9	387	552	554.9
Catchment area	1159	2280	740	1879	1309
Percent harvested	61.8	34.1	52.2	29.3	42.3

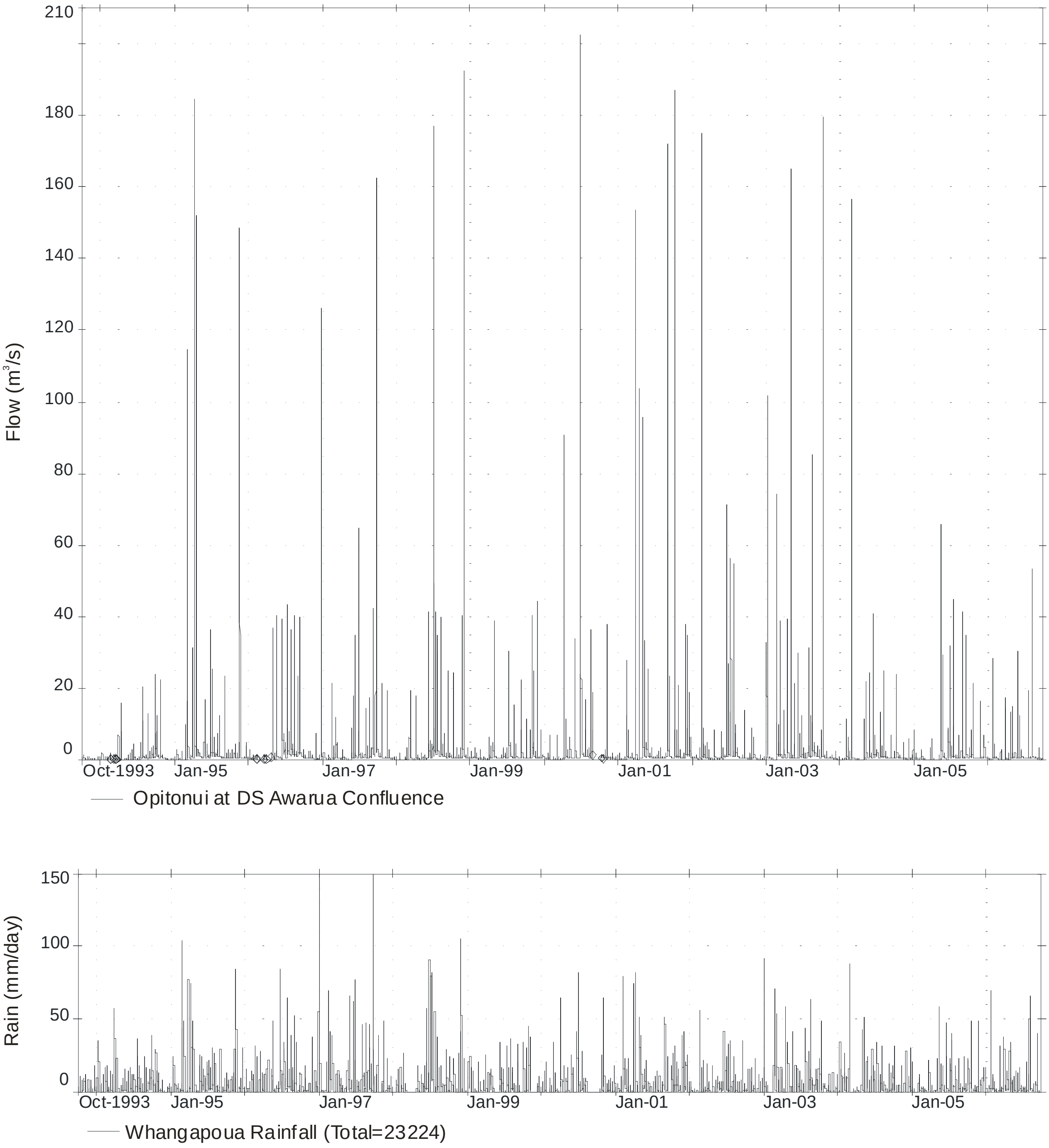

Figure 2: Average daily flow (a) and rainfall (b) recorded over the monitored period at Whangapoua and in the Opitonui River at the Awaroa confluence respectively.

3.2 Changes in the harbour biota abundance and diversity

Ecological effects on sandflat communities of elevated sediment loading can result from both smothering of the sediment surface and increased suspended sediment concentrations. Our research to date has shown that even thin (mm's) layers of terrigenous sediment deposited on the sandflats can significantly affect macrobenthic communities. Although such deposits may be transitory and reworked by waves and tides, such that long-term changes in sediment composition do not occur, effects on macrobenthic communities can ensue. Therefore, this summary concentrates on the changes in abundance of taxa expected to be sensitive to increased sedimentation rates or suspended sediment concentrations. The predicted effect of increased fine sediment loads on the abundance of monitored animals was listed in Hewitt (2001) and an updated summary based on new data is listed in Appendix 2.

Long-term trends in the abundance of several monitored taxa consistent with the effect of increased sediment loading have been detected and are summarised in Table 2a & b for the 6 sites that were monitored post 1999.

Many of the trends in abundance noted at the inner most site on the Owera arm (site 4), since the loss of *Zostera* in 1995, are levelling off as the new community structure stabilises. Site 4 is now a firm, unvegetated sandflat, considerably different from the soft-surfaced *Zostera* flat that it was when the monitoring programme began. The community here differs to its previous state and it is for that reason that the increases in abundance of *Austrovenus* and *Nucula* and the decreases in *Helice* are attributed to sedimentation effects. This change highlights the potential for the Whangapoua catchment to affect the ecology of the harbour over the long-term. The potential for flow-on effects to the rest of the ecosystem is discussed in Section 4.

Table 2a: Taxa for which gradual trends in abundance over the monitored period were detected (n=22). Direction of the change is a decrease unless otherwise indicated by +. Taxa for which the trend is consistent with predicted effects of sediment loading are bolded. P-values and slope estimates for all taxa are given in Appendix 3. The total number of taxa which were abundant enough for trends to be detected and which could have been expected to change in response to sediment addition is given in brackets after the site.

Arm	Site	Taxa	Comments on trend
Opitonui	S1	**Nereids**	
		Scolecolepides	
	S3	***Aonides***	A trend in abundance has been observed since monitoring was reinitiated
		Macomona	A decrease occurred during the unmonitored period or coincident with reinitiation
		Scolecolepides	
Owera	S4	***Arthritica***	
		+ *Austrovenus*	Increase in abundance from 1996 – 2001, probably associated with removal of *Zostera*
		Helice	Probably associated with removal of *Zostera*
		Nereid	Only low abundances since monitoring reinitiated
		+ *Nucula*	Probably associated with removal of *Zostera*
		Paraonids	
	S6	***Austrovenus***	
		Helice	
		+Paraonids	May be a multi-year cycle- resolvable with 2 more years of data
		Nereids	Lower abundances after monitoring reinitiated
Mapauriki	S7	***Aonides***	
		Nereids	
		+ *Nucula*	Increase in last 4 years
		+ ***Torridoharpinia***	Increase in last 3 - 4 years
	S9	***Austrovenus***	May be a multi-year cycle- resolvable with 2 more years of data
		+ Paraonids	Increase in abundance since 1998
		+ *Torridoharpinia*	Increase in last 3 - 4 years- now decreasing, probably cyclic

Table 2b: Summary for each site of the number of taxa abundant enough for trends to be detected (abundant taxa) and the number predicted to show a response to sediment addition (predicted). The number of those for which a change may be related to sediment addition, either as a gradual trend (gradual) or related to the storm of 1995 (storm) is also given.

Arm	Site	Abundant taxa	Predicted	Consistent	Storm
Opitonui	S1	6	6	2	2
	S3	12	11	3	1
Owera	S4	11	11	3	4
	S6	9	9	2	1
Mapouriki	S7	13	12	3	0
	S9	13	12	2	0

In 2001, a number of trends consistent with increased sediment loads to the harbour were documented (Hewitt 2001). The majority of these trends have continued to be observed, and a number of new (probably sediment-related) trends have been documented between 2001 and 2004, in a series of letters to Ernslaw One. With the addition of data from April and October 2005 and April 2006, the following new trends have been observed (see Appendix 3):

- There were two new trends, consistent with predictions of increased sediment loading, detected at Owera site 6 (decreases in Nereidae worms) and Opitonui site 3 (decreases in *Aonides).*

- A significant decrease in the abundance of bivalve *Austrovenus*, consistent with predictions of increased sediment loading, was observed at the outmost Mapauriki Arm (site9). Due to the presence of a multiyear cyclic pattern in abundance, this trend was not detectable last year (2004).

- Some new trends in abundance, probably unrelated to increased sediment loading, have also been observed. At site 6, decreased numbers of *Helice* and increased numbers of Paraonids were observed. The increase in Paraonids may be part of a multi-year cycle, which could be resolved with 2 more years of data. A similar increase in numbers of Paraonids was observed at site 9 and an increase in numbers of *Nucula* was observed at site 7.

In terms of macrofaunal community structure, sites in the Mapauriki arm (7 and 9) continue to exhibit the least variability (Fig. 3). Sites in the Opitonui arm (1 and 3) exhibit increased variability with time.

Based on these data, there continues to be evidence of a decline in the ecological health of Whangapoua harbour. However, these changes are not sufficient to drastically alter the macrofaunal communities found.

3.3 Changes in the distribution and density of mangroves and seagrass

Trapping of sediment is more likely to occur in sheltered habitats such as mangroves and seagrass beds than in the open sandflats, and expansion of these habitats would represent an increased potential for storage of sediment within the harbour. The total area of seagrass beds in the harbour has decreased during the period 1945-2006 (see table cover). The area occupied by mangroves has increased during the same period, particularly in the upper ends of the arms of the harbour (Table 3, Appendix 4).

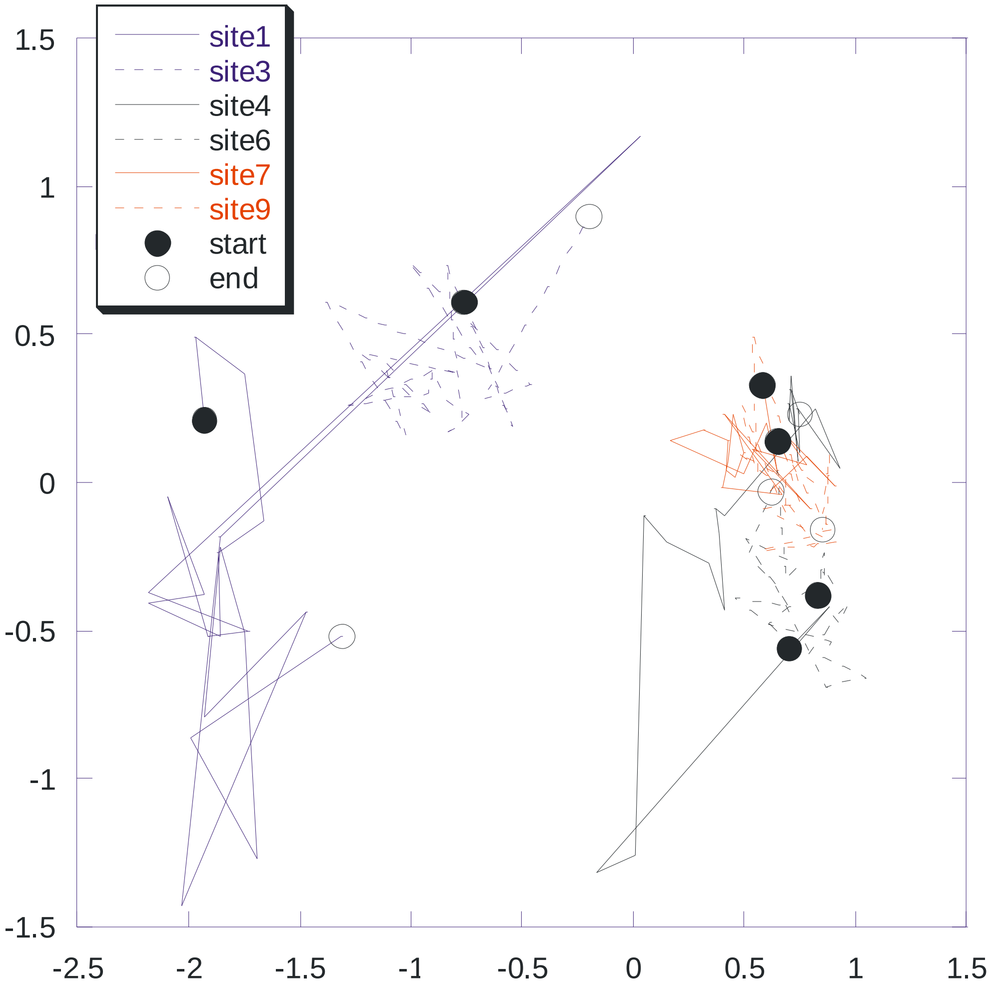

Figure 3: Community changes over time observed at the monitored sites.

The percentage area of the harbour occupied by mangroves from 1945 to 1978 remained relatively static at approximately 12%. Since then the proportion of the harbour occupied by mangroves has increased to about 27.5% (Table 3, Appendix 4). Moreover, since 2000 the area of the harbour occupied by dense mangroves has increased significantly, while the area covered by sparse mangroves has not changed.

Table 3: Vegetation distribution (% of total harbour) in Whangapoua Harbour from aerial photographs. Values in parentheses were derived by methods described in Morrisey et al. (1995). Values not in parentheses were derived by the method described in Craggs et al. (2001).

Vegetation type	1945	1960	1966	1978	1983	1993	1995	2000	2003	2006
1-25% Mangroves	1.38						6.93	6.54	3.61	3.74
25-50% Mangroves	0.66						3.76	3.76	4.67	4.02
50-75% Mangroves	1.08						2.53	1.48	1.97	6.01
75-100% Mangroves	9.07						11.66	14.81	15.33	13.79
Total	12.19						24.88	26.58	25.58	27.58
Mangroves	(11.3)	(13.6)	(12.4)	(11.5)	(18.1)	(24.7)	(22.5)			
Seagrass	32.53						13.60	14.56	14.77	15.24
(%)	(23.7)	(19.5)	(26.3)	(25.0)	(17.7)	(18.1)	(13.7)			

In addition to monitoring changes in the harbour-wide coverage of seagrass, we have also been measuring the density of seagrass leaves within beds (i.e., how much of the surface of the beach within a 0.25-m^2 quadrat was covered with seagrass leaves relative to the amount that was bare sediment). This measurement provides an indication of the ‘health’ of seagrass beds at a more detailed scale than the aerial photographs described above. Dense seagrass beds are presumed to be healthier than sparse ones.

The density of seagrass at the start of the monitoring period was greatest at Sites 6-9. At this time, Site 2 contained small, sparsely-vegetated patches of seagrass; Sites 4-6 lay within a large, dense meadow; half of each of Sites 7 and 9 was covered in dense seagrass and site 8 contained numerous patches (approximately 5 m in diameter) of seagrass. At sites 1 and 3, no seagrass has been observed over the course of the monitoring.

The density of seagrass within beds or patches has changed over the course of the study. The cover at Site 4 and 5 completely or very largely disappeared as a result of the deposition of sediment after the storm in March 1995. While there has been some recovery noted at Site 5 in 1999 report, Site 4 remains completely bare. Seagrass also disappeared at Site 2, but this occurred after April 1996. The seagrass at this site was initially relatively sparse and in small patches, in contrast to Sites 4 and 5, which had been completely covered in a dense meadow of seagrass. At sites 6, 7 and 9, no consistent trends were observed (Figure 4).

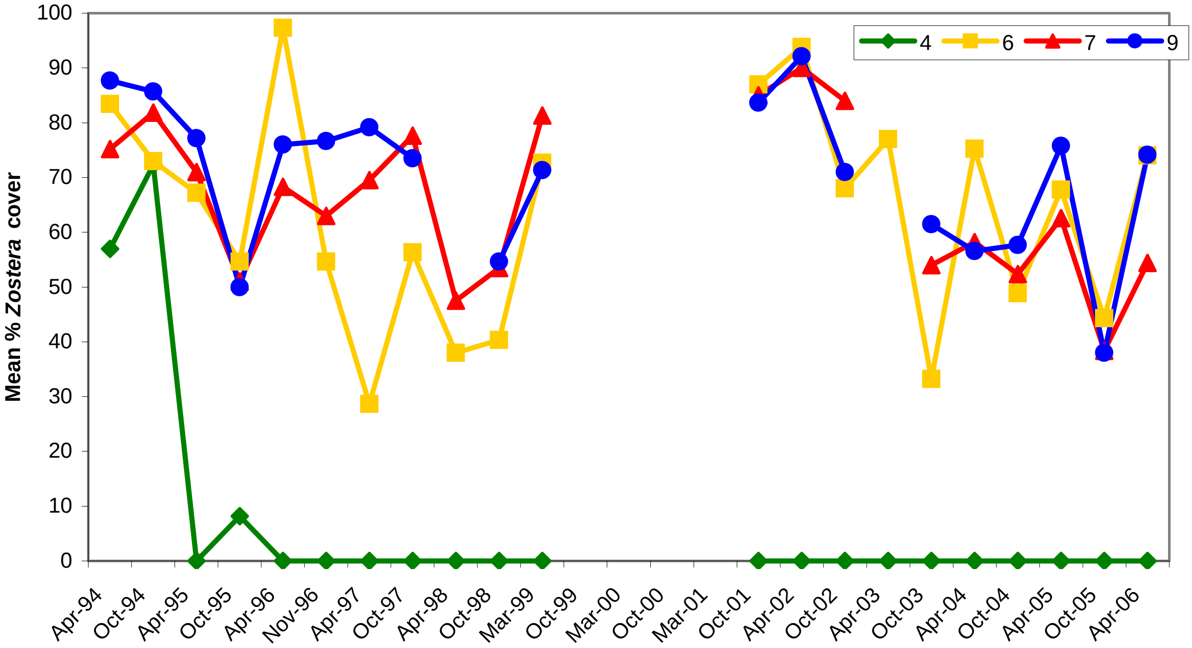

Figure 4: Changes in seagrass cover over time at sites 4, 6, 7 and 9.

3.4 Changes in the height of the bed of the harbour

Appendix 5 gives detailed information on the bed profile surveys taken between 1993 and 2005. In summary, repeated surveys of the harbour bed height along fixed transects (see Fig. 1 for locations) show that changes since 1993 have been relatively minor, and mainly within the 2 cm margin of error caused by small-scale variation in topography, such as sand ripples. Most of the changes detected were due to small-scale, lateral migration of the channels or beach accretion. There is little evidence for consistent harbour infilling from sediment derived from the catchment or elsewhere at the scale of this study. However, the increase in mangrove density and distribution has resulted in localised infilling.

3.5 Changes in the nature of the sediments of the harbour

Changes observed in the sediments characterised as percentages of mud, sand and gravel have been transitory, with no obvious indication of long-term trends (Fig. 5). Changes are been observed associated with three major storms, occurring in March 1995, December 1996 and September 1997 (Appendix 6). The storm of March 1995 was the largest (return period of 20 –50 yrs), with a daily average rainfall of 115 mm, producing a peak flow in the Opitonui River of 9.6 $m^3 s^{-1} km^{-2}$. For comparison, although daily average rainfalls for the other 2 storms were similar (115 – 241 mm), intensity was lower and peak flows in the Opitonui River were 4.4 and 5.6 $m^3 s^{-1} km^{-2}$, respectively. The March 1995 storm affected sediment characteristics at all sites in the harbour (see Morrisey et al. 1995a & b for a description of the changes caused by this storm). The mud content of sediment increased at sites 1-7, but were largest in the Owera arm of the harbour. As discussed by Morrisey et al. (1995a), these sites were blanketed by a layer of orange mud up to 10 cm thick. Within each arm of the harbour, the largest variations in the sediments occurred at the site furthest upstream (Site 1 in the Opitonui arm, Site 4 in the Owera arm and Site 7 in the Mapauriki arm). This suggests that the source of the deposited mud was the catchments rather than other parts of the harbour or adjacent coast. Deposition of fine sediment in the mixing-zone of fresh and salt water is a characteristic of estuaries and in the lower-energy environments upstream, and provides an explanation for the patterns of deposition seen here.

However, even for the March 1995 storm, the amount of mud found at the sites quickly returned to pre-storm levels (Fig 5). Because the sites are intertidal, sediments are constantly reworked by waves that resuspend and remove any deposited mud, thus maintaining the character of the sandflats. We would expect this process to continue if the level of the harbour bed were to rise as a result of infilling with sediments derived from the catchment. Conversely, if changes in the strengths and patterns of water currents in the harbour were to cause a reduction in the height of the bed, we would expect the effects of wave action on these intertidal sediments to decrease and, potentially, the sediments could become muddier. Reduction in height of the bed would need to be of the order of several decimetres or more for this to happen. Changes in the height of the bed of the harbour over the course of the monitoring study, discussed above, did not indicate that either of these changes has occurred at a detectable rate. Given the ability of waves to prevent mud from accumulating in parts of the harbour exposed to their action, any infilling would have to occur either as a result of deposition of sand or gravel or from extreme overloading of the system by fine sediment. No clear changes in the amount of sand or gravel in the sediments were observed at the sampling sites during the course of monitoring and this is in accord with the lack of consistent, observable change in the height of the bed.

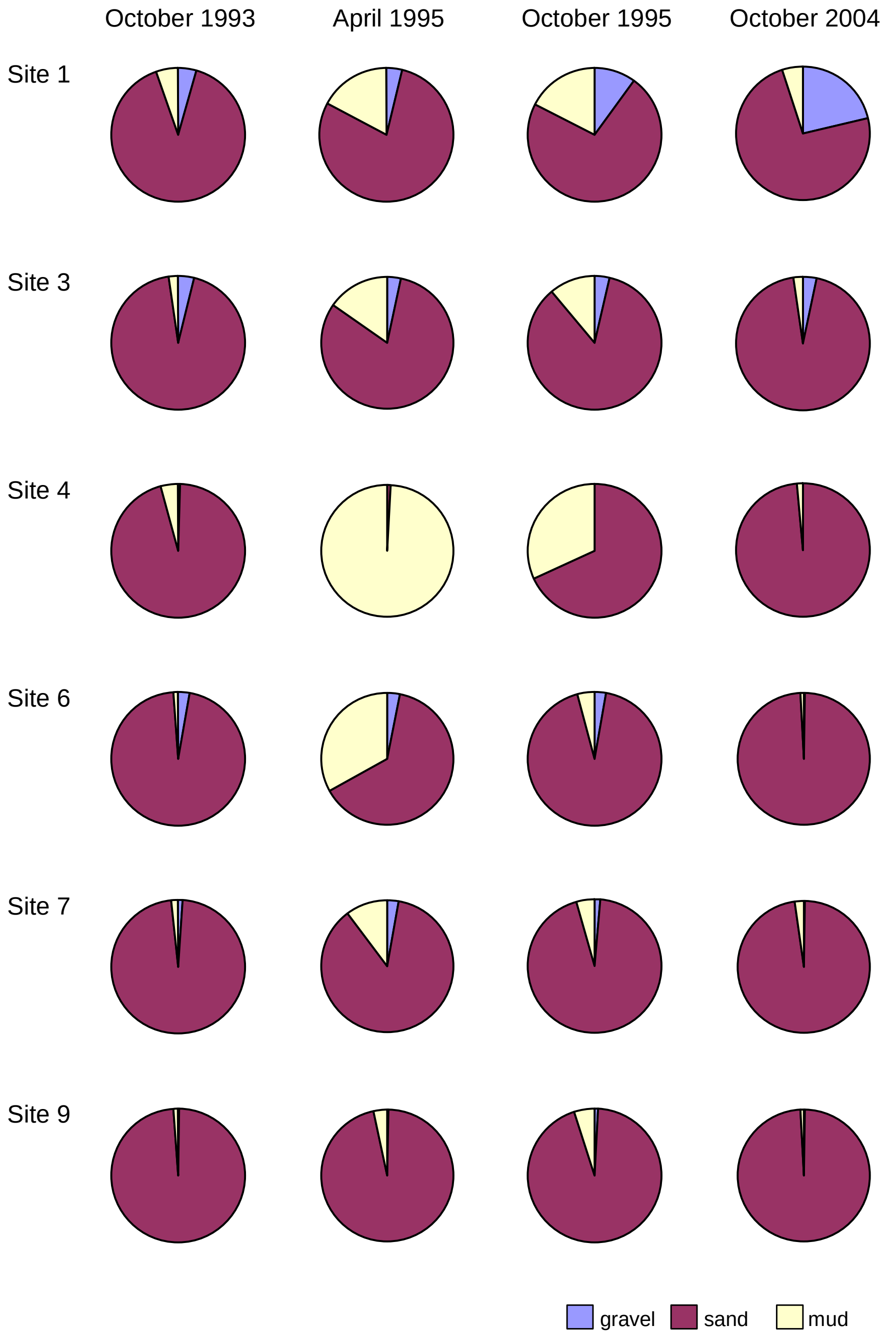

Figure 5: Sediment composition observed at the sites showing little difference between the start and the end of the monitored period and the effects of the March 1995 storm.

4. Impact of changes on wider harbour ecology

Apart from their intrinsic values, species living in the intertidal flats contribute to a number of important ecological processes. Most of the animals living in harbour intertidal sediments provide food for shorebirds. Different bird species feed on different suites of prey, so maintaining species diversity in the sediment dwelling animals is an important factor in supporting the variety of bird species found in the harbour. Sediment-dwelling organisms also provide food for many species of fish. In fact, recent studies in the seagrass beds of Whangapoua indicate these are an important habitat for juvenile snapper (Dr M. Morrison, NIWA Auckland). Plants and animals living in the sediments are also important for nutrient cycling, sediment stability, and water clarity. These fundamental processes are important both for the functioning of the estuary and the broader coastal ecosystem. People also collect natural ecological resources directly from the harbour; pipi and cockle beds are particularly important. There is also one small oyster farm operating in the harbour. Seagrass and suspension-feeding shellfish such as pipis, cockles and oysters are likely to be particularly sensitive to changes in suspended sediment concentrations as these affect light availability (and seagrass growth) and the amount of energy the shellfish use to feed.

It is important to note that, beyond the monitoring programme, there is little information available on the ecology of the harbour and how it has changed. Nevertheless we can infer from aspects of the monitoring programme some potential for change in the fish and shorebirds in the harbour by focusing on the potential for habitat loss for fish and loss of food resources for shore birds.

4.1 Fish

Research conducted by Dr Mark Morrison and colleagues (NIWA-Auckland) has demonstrated that high densities of juvenile fish, particularly snapper, are found in seagrass beds. This observation is based on sampling in Whangapoua along with a number of other harbours/estuaries. Therefore, changes in seagrass distribution could influence the nursery value of Whangapoua harbour for fish. Following the 1995 storm, the seagrass cover within the monitored sites decreased. Broader-scale measurements of the size of seagrass beds from aerial photographs taken between 1993 and 1997 showed that some large changes have occurred, involving complete loss of seagrass from some areas of the harbour, including the area around site 4. However, over a longer time-scale, photographs taken between 1945 and 1995 showed that the percentage of the harbour covered by seagrass has varied between 14 and

26%, with no consistent patterns of increase or decrease. Within this context of historical change, the decline after the 1995 storm was not unprecedented.

It is also important to remember that almost all of the seagrass in Whangapoua is intertidal and is not a suitable juvenile fish habitat when the tide is out. Moreover, there are a lot of as yet unanswered questions concerning habitat quality for juvenile fish, such as the value of different sized patches, the location of patches relative to subtidal channels and the overall spatial structure of the seagrass landscape in terms of providing a balance between predator refugia and access to food resources for juvenile fish. In light of the changes in the macrobenthic community and seagrass documented in the monitoring programme, and the currently available information on how changes in the distribution and abundance of intertidal seagrass will affect juvenile fish, effects on fish seem unlikely.

4.2 Birds

Matarangi (Omara) Spit in Whangapoua Harbour is considered a site of particular importance for indigenous shorebirds (Dowding and Moore 2006) because of its importance as a wintering site for variable oyster catchers, northern New Zealand dotterels, and banded dotterels. The report by Dowding and Moore (2006) considers indigenous shorebirds and thus does not provide information on important migratory shorebirds such as Knots, which may well fly to New Zealand to feed on our harbour flats from Siberia or Alaska, or birds such as black swans, which graze on the seagrass. For the black swans, although there is some fluctuation in the abundance of seagrass, there is not a long-term trend threatening the food resources of this species.

The most likely way that forestry activity could impact on the harbour’s bird populations is via sediment impacts on their food resources. Most of the shore birds feed on the invertebrates living in the sandflats and mudflats, with species-specific dietary preferences dictated by differences in behaviour and bill morphology. A primary assumption is that the birds are food limited, rather than limited by nesting or roosting sites around sand islands and fringes of the harbour.

To properly assess the potential of impacts on shorebirds, we would need detailed information on the distribution and abundance of shorebird species within the harbour. We are unaware of such information. Similarly, the only quantitative long-term data on the harbour we are aware of is that derived from the monitoring programme. However, to provide an assessment, we will compare the food requirements for shorebirds against the change in macrofaunal densities apparent from the monitoring programme, using energetic relationships between birds and their food supply (e.g., see Lundquist et al. 2004). We focus our analysis on 2 common shorebird species, South Island pied oystercatcher (*Haematopus finschii*), and red knot (*Calidris canutus*). These 2 species represent birds of different weights and bill morphologies, which are important parameters for our energetic modelling, but note that we do not have good data on the abundance or distribution of these birds in the harbour.

The best available information on the diets of these species is provided in a study of Fairwell Spit populations (Battley et al. 2005). Oystercatchers tend to feed on near-surface dwelling bivalves and polychaetes with cockles (*Austrovenus stutchburyi*), pipi (*Paphies australis*) and wedge shells (*Macomona liliana*) as important dietary components. These birds are able to eat large shellfish because they can open the shells and extract the soft tissue. Knots are mollusc specialists feeding on smaller sized prey than oystercatchers, including juvenile cockles pipi and wedge shells, as well as nut shells (*Nucula hartvigiana*) and small gastropods; they are also reported to feed on polychaetes and crustaceans.

Our analysis requires the following simplifying assumptions:

- Birds are food limited in Whangapoua. In reality nesting and roosting sites may be a more important issue and for migrants, such as knots, environmental conditions at their nesting sites and along their flyway may be more significant.

- Food requirements to maintain basal metabolic rates are critical. At certain times of the year birds may need to eat more to fuel up prior to migration.

- Birds actually feed in the monitoring sites. This is a conservative assessment as many shore birds can forage over quite large areas.

- Birds do not prey switch. We know they do but we do not have specific details that would enable us to factor this into our analysis.

- Birds show no patch-size or density-dependent foraging behaviour. There is evidence that shorebirds forage in relation to the density and spatial distribution of their prey, meaning that when prey densities are low or only found in small high density patches they are likely to move to more profitable feeding areas (Cummings et al. 1997), but we do not have specific details that would enable us to factor this into our analysis.

We consider only significant trends at the 6 sites currently monitored. We focus on 2 important bivalve prey species for which we estimate that on average about 50% of the individuals are in the right size range to be prey for oystercatchers or knots (note that size of bivalves is not measured by the monitoring programme). Spatial and temporal variation in the density of macrofauna detected by the monitoring programme can be considered as densities at a site scale, and by contrasting densities apparent at the start and end of the time series.

The analysis of Lundquist et al. (2004) revealed that a typical South Island pied oystercatcher weighing 0.583 kg, or a knot weighing 0.13 kg will consume about 33, or 11 g ash free dry weight of bivalve per day. If both bird species feed only on medium sized *Macomona liliana* or *Austrovenus stutchburyi*, (i.e., individuals that have an ash free dry weight of about 0.045g), then each oystercatcher consumes about 733, and each knot about 244, bivalves. In other words, these simplistic calculations indicate that one individual of each species will collectively consume about 1000 medium sized shellfish a day.

We can extrapolate from significant changes in the average number of individuals per core of *Macomona* or *Austrovenus* to changes in density at the site scale of 9000 m^2 (Table 4).

Table 4: Summary of changes in *Macomona* and *Austrovenus* observed at the monitored sites scaled to the size of the site.

Site	Change
Site 1	No change
Site 3	*Macomona* decrease over the site by about 2M individuals (1.2M remain)
Site 4	*Austrovenus* increase over the site by about 6.8M individuals (resulting in about 10M at the site at the end of the time series, note this increase is associated with the loss of seagrass)
Site 6	*Austrovenus* decrease over the site by about 4M individuals (2.7M remain);
Site 7	No change
Site 9	*Austrovenus* decrease over the site by about 6.8M individuals (5.4M remain)

These calculations indicate that across the 6 sites currently monitored there has been a net loss of about 6.8M *Macomona* and *Austrovenus*. This is a total number of individuals and will include many small and a few large shellfish that are outside the size preference range for oystercatchers and knots. If, on average, 50% of the shellfish populations are in the appropriate size range for the birds, and 1000 shellfish are required for one oystercatcher and one knot per day, this would indicate that the ability of the monitoring sites to support these birds has decreased to the extent of supporting 9 less oystercatchers and 9 less knots at the end of the monitored period compared to the start.

Given all our simplifying assumptions, these calculations nevertheless indicate a decrease in the productivity of the intertidal flats. They indicate a potential for changes in the food resources of the flats for higher trophic levels, but our calculations are very simplistic and far more detailed study would be needed to reach conclusions with any degree of scientific rigor.

4.3 Ecosystem functions

Species living in the intertidal flats contribute to a number of important ecological processes that can affect the wide harbour ecosystem. For instance, in marine soft-sediments, large organisms are potentially important in affecting their chemical environment, all of which influence the contribution of benthos to ecosystem function through processes such as nutrient flux and primary production. Recent experiments conducted on the sandflats in the Auckland region that contain similar species to those monitored in Whangapoua have demonstrated that the removal of large bivalves and polychaete worms can influence nutrient regeneration, microphyte standing stock (Thrush et al. in press). Our results demonstrated that the removal of large suspension (e.g., *Austrovenus*) or deposit feeders (e.g., *Macomona*) influenced the flux of nitrogen and oxygen, surficial sediment characteristics and community composition. In the deposit feeder community, interactions between nutrient regeneration and grazing highlight important feedbacks between large macrofauna and biogeochemical processes and production by microphytes, indicating that the loss of large infauna driven by increased rates of anthropogenic disturbance (such as sediment deposition) may lead to shifts in ecosystem performance. While this research identifies the potential broader ramifications of the trends in the abundance of species, it does not indicate how changes of the magnitude observed at the monitoring sites are likely to lead to changes in nutrient fluxes or primary productivity at the scale of the monitoring sites or more broadly throughout the harbour.

4.4 Far field effects

The geomorphology and local hydrodynamic conditions at Whangapoua help to maintain the harbours high water quality, by eroding and transporting recently deposited sediments so that these sediments become either locked up in the fringing saltmarsh and mangrove habitats or are transported out of the harbour on to the adjacent open coast. Effects on the open coast ecology of sediment transiting Whangapoua can also be considered within the context of broader scale effects. In fact one of the earliest reports in the scientific literature of the impacts of terrestrial sediment deposition on benthic communities is derived from samples collected offshore from Whangapoua (McKnight 1969). We have observed horse mussels (*Atrina zelandica)* growing on the seaward side of the entrance to Whangapoua to be surviving but practically buried in fine sediment, indicating that sediments transported out of the harbour are likely to affect the adjacent coastal benthic communities.

5. Linking measured harbour trends to forestry activity

5.1 Linking measured trends to increased sediment loading

Trend detection is complicated by natural variability in population density. Such variability varies from seasonal cycles driven by recruitment, to multiyear cycles related to long-term environmental factors (ENSO events) or biotic interactions. Thus, measured variability is always a function of both natural and anthropogenic factors, and trends detected over a short time period may merely be part of long-term multiyear cycles. Recent FRST-funded work on long-term data collected on benthic macrofauna in Manukau Harbour (18 yrs) highlights cycles that occur from 2 – 13 yrs in response to large-scale environmental factors such as the Southern Oscillation pressure difference and long-term temperature and rainfall variability. The time period covered by the Whangapoua Harbour monitoring programme, particularly considering the unsampled period, is thus short enough that detected trends could be part of long-term cycles.

It is difficult to establish cause and effect when the effect is not a single point source but many, and is variable in time. However, there are a number of lines of evidence that can be used to infer cause-effect relationships such as the trends of individual or suites of species in relation to our knowledge of how species respond to different types of stressors. These approaches have been employed in the ongoing analysis of monitoring results since 2001. The use of these approaches makes it unlikely that the observed trends are merely natural variability, unless the factors producing the variability are also affecting sediment loading.

Moreover, in the Manukau, the incidence of negative trends noted at six sites varies between 40 – 50 %. In Whangapoua, incidence of negative trends over the six sites varies from 33 – 100%. When the sites in Mapauriki arm (i.e., sites furtherest away from harvesting activity) are removed from this analysis, the incidence of negative trends increases, to vary between 71 – 100%.

5.2 Linking measured trends to forestry activity

The primary focus of the monitoring programme was to document ecological change within the harbour, likely to be associated with increased sediment loading. The monitoring programme has done this, but cannot directly differentiate between ecological changes generated from impacts associated with sediments sourced from different land-use in each catchment.

Completing the link between ecological change in the harbour and forestry activity in the catchment is complicated by the likelihood of time lags occurring between the ‘cause’ and the ‘effect’. These arise, for example, from changes in the sediment risk profile from different forestry activities (e.g., the time between harvesting exposing bare soil to rainfall, revegetation and pine forest canopy closure following replanting) and the transport of sediment through the catchment into the harbour. Once in the harbour, deposited sediments may be transported away from a particular location by waves and tides, resulting in ecological affects that may not be associated with long-term habitat change.

Furthermore, even data on the effect of forestry activity on sediment load entering the harbour is scarce. Monitoring of sediment load in the streams has been limited to (1) water clarity measurements upstream of the freshwater monitoring sites, mainly collected from the forestry area (Quinn and Wright-Stow 2004), and (2) suspended sediment concentrations in the Opitonui River. Unfortunately, auto sampling of the Opitonui River was only begun after harvesting had already altered a portion of the catchment.

We have attempted to link the ecological changes observed to forestry activities by two methods:

1. Statistical correlations between ecological change and harvesting.

2. Weight-of-evidence linking harvesting to changes in sediment load entering the harbour.

5.2.1 Correlations between ecological change and harvesting.

Information on harvesting in the Whangapoua catchment was provided by Ernslaw One Ltd on a yearly basis. The potential for effects on yearly changes in species abundances at a site was measured using regression with cleared area as an explanatory factor. There is no general consensus of the time over which an area that has been harvested continues to be at risk of producing higher sediment runoff. For example, Phillips et al. (2005) conclude that highest risk occurs in the third year after harvesting, although O’Loughlin (2005) states that 2 – 8 yrs is the most crucial time. We used accumulated areas for 1, 2, 3 and 4 years post harvesting.

Quinn and Wright-Stow (2004) document effects on communities in response to combined effects of logging and severe storms. To account for this, we included yearly maximum and average rainfall, recorded at Whangapoua, as another explanatory variable and included a multiplicative term between the rainfall and the harvested area. As distance from source is also likely to be a factor, this was also included, with the source point being the entry of the Owera and Opitonui Rivers respectively.

Not only were the changes at individual sites examined, changes on the harbour as a whole were also investigated. In order to do this analysis, the taxon had to occur at all sites, limiting this analysis to two taxa (Nereids and *Scolecolepides)*. Details of the statistical techniques are given in Appendix 7.

The majority of the taxa, for which gradual trends over the monitored period, consistent with those predicted for increased sediment loading, were observed (see Table 2), exhibited statistically significant relationships with harvesting activity (Table 5). Only 4 populations and the % cover of *Zostera* at sites 7 & 9 did not exhibit such trends (although those at site 4 responding to the change in habitat were not tested (*Austrovenus*, *Nucula* and *Helice*)). Of the taxa not exhibiting statistically significant relationships with harvested area, one (*Scolecolepides* at site 3) did exhibit a weak negative relationship.

For most taxa, the relationships were strongest with harvested area accumulated over a 4 year period, and few interactions with rainfall were observed. This is not surprising, as time lags between the rainfall that initiates the sediment runoff, the rainfall which flushes the sediment down to the harbour and the resuspension of the sediment within the harbour were expected to confound such relationships.

Abundances of taxa at sites in the Opitonui arm were related to harvesting area adjusted by distance to input, whereas abundances of taxa at sites in Owera and Mapauriki were more closely related to the harvested area in Owera catchment, or the total harvested area in the Whangapoua catchment respectively. This suggests that sites in Owera are predominantly exposed to sediment from Owera, Opitonui sites get sediments from both (although more from Opitonui), and sites in Mapauriki get sediment from both the other arms of the harbour.

Similar to the results of Hewitt (2002), a relationship between the change in abundance of Nereids and *Scolecolepides* from the initiation of the monitoring to the end and harvested area was also found.

This analysis presents good evidence that sediment from forestry activities is affecting the ecology of the harbour.

5.2.2 Weight-of-evidence linking harvesting to changes in sediment load entering the harbour.

There is some evidence supporting the fact that harvesting has had an effect on the sediment load entering the harbour. Most of this is to be found in the report by Wild and Hicks (2005). They found:

- the average peak flow for Opitonui increased after logging and there was a large increase in low flows from 1992 – 2002;
- some evidence of a correlation between catchment area harvested and conditional sediment concentration at a given flow rate;
- a hint that extreme events may cause an overall increase in sediment loading that may take on the order of a decade to decline.

For the latter point, it is certainly true that events that reach the harbour may have long-term effects both on the fauna and flora, but also on the medium-term turbidity of the harbour as storms resuspend deposited sediment. However, it is important to note that new practices to minimise erosion risk have been adopted, by Ernslaw One Ltd, post the 1995 storm.

Also, they report the finding by Marden and Rowan (1995) that sediment production from cutover was 4 times that generated from mature forest, and sediment production increased with increasing time from clear felling.

Table 5: Taxa for which gradual trends over the monitored period, consistent with those predicted for increased sediment loading, were detected. Any statistically significant relationship with forestry activity is given, see Appendix 7 for details of results.

Taxa	**Comments on trend**
Nereids across all sites *Scolecolepides* across all sites	Harvested area accumulated over the monitored period, adjusted by distance of the site to the catchments
S1 Nereids S1 *Scolecolepides* S3 *Macomona*	Harvested area accumulated over 4 yrs adjusted by distance
S6 *Zostera* % cover	Interaction between harvested area (accumulated over 2 years) and rainfall
S7 *Torridoharpinia*	Interaction between harvested area (not accumulated) and rainfall
S4 Paraonids S7 *Aonides* *S7* Nereids *S9 Austrovenus*	Harvested area accumulated over 4 yrs
S4 *Arthritica*	Harvested area in Owera catchment accumulated over 2 yrs
S4 Nereids S4 *Paraonids* S6 *Austrovenus*	Harvested area in Owera catchment accumulated over 4 yrs
S3 *Aonides* S3 *Scolecolepides* S6 Nereids S9 Torridoharpinia S7 & 9 *Zostera*	No relationship detected

6. Monitoring design to link forestry operation on harbour morphology and ecology

Determining cause - effect relationships is difficult when dealing with diffuse source impacts that occur in the environment (see previous section) and generally rests on the accumulation of different lines of evidence to link cause and effect. Where decisions need to be made concerning the use of multiple lines of evidence and inference, e.g., where there are no feasible control site(s), a number of ways of strengthening causal interpretation are recognised in the ecological, environmental impact, and epidemiological literatures (e.g., Hewitt et al. 2001). For example, strength of effect, consistency among studies, specificity, temporality (i.e., does the cause precede the effect), gradient of effects, plausibility, and analogy (with similar causes leading to similar effects). These issues are readily apparent in many of the human and environmental health debates of the last 50 years (e.g., smoking causes cancer, climate is changing with contributions from human activity, fishing can result in ecosystem level changes). For these reasons, good practice in considering effects in a situation like this should employ the precautionary principle.

There are always competing hypotheses that could explain patterns and trends; some hypotheses may be readily refuted while others will require testing and thus access to additional data. Inevitably, in the application of any monitoring programme, this requires cost-benefit decisions. To improve the link between sediment impacts on the harbour and forestry activity, information on forestry activity and resulting sediment loads in streams and rivers would be needed. Because sediment impacts can arise from other land-use within the catchment, this type of information would be needed to be gathered from the whole catchment, not just the plantation forestry areas. Given the highly patchy nature of rainfall in the Whangapoua catchment, and the importance of extreme rainfall events in driving extreme sediment loads into the streams and rivers that run into the harbour, this data would need to be gathered at a high frequency (Wild and Hicks 2005) These factors may well mean that data would need to be collected for some time to identify such patterns and link it to changes in the harbour ecology. While implementing such a monitoring programme is technically feasible, even with extensive use of automated sampling it would be expensive. Moreover, if the argument is that this level of investment is necessary in the monitoring, then the benefits of increased spatial coverage and temporal resolution in monitoring the ecological response variables in the harbour (and adjacent coast) also need to be considered. In particular, event monitoring would be necessary, as would monitoring of channel areas and areas further up the harbour in sediment deposition zones.

Sampling would therefore need to include:

- High intensity automatic sampling of suspended sediment concentrations upstream and downstream of forestry activity, and also where streams enter the harbour. This would also need to be done on streams not containing forestry activity in order to determine control levels, and overall levels in case threshold effects are affecting the harbour (this could happen if harvesting activity on top of other catchment activities results in suspended sediment concentrations crossing a threshold that affects the ecology).

- Automatic sampling of suspended sediment concentrations at, at least, the 6 fully monitored sites.

- Increased spatial coverage of sampling of macrofauna and *Zostera* density within the harbour, including the sampling of specific shellfish beds, channel areas, subtidal seagrass, and areas in depositional zones further up the harbour.

- Event-driven sampling of selected sites, triggered by suspended sediment concentrations entering the harbour.

- Some sampling of sites outside the harbour to determine whether effects are occurring.

- Modelling of the harbour to enable tracking of sediment entering the harbour.

Another approach to define cause - effect relationships is the application of forensic “sediment fingerprinting” techniques that are currently being developed by NIWA. The approach involves collecting samples of surface sediments from different regions in the harbour and soils from the catchment and subjecting these samples to compound specific isotope analysis to identify trace level compounds that indicate what proportion of a specific sample of the harbour’s sediment was contributed from different sources (pasture, pine or native forest soils). As part of the development of this technique it has been trialed in Whangapoua Harbour in a study commissioned by Environment Waikato (Gibbs 2006). This study, based on 22 samples from the harbour and its catchment (8 samples from within the harbour), found that in samples from all three arms of the harbour a substantial contribution of soil from recent pine forest logging was apparent (54-74%).

While these results are highly promising in their ability to link sediment source to effects at specific locations, the techniques are still under development. In particular Gibbs (2006) highlights the importance of understanding the sediment transport processes within the harbour, the timing of events and potential for transformation and degradation of sediment fingerprints (see further assumptions on P11 of Gibbs 2006). Nevertheless, with some further development, this would be a cost effective way of linking catchment-derived sediment impacts to ecological changes at the monitoring sites with a high potential of deriving certainty in cause-effect relationships. After initial development, sediment fingerprint sampling could augment both the routine monitoring of streams and harbour sediments, with some chasing of specific events to add further certainty to the application and interpretation of this technique.

It would be of particular importance, if monitoring of sediment loads and increased monitoring of harbour ecology were to be undertaken, to determine what level of proof would be acceptable in a court of law.

7. Future recommendations

We have highlighted the value of information on determining the magnitude of change in the harbour’s ecology and how this is currently related to forestry activity. We have identified how, in the near future, it is likely that new methods will be able to definitively link sediment sources to specific impacts within the estuary. However, it is important to consider what kind of criteria and levels of proof are needed to manage down stream effects of land use. We note the commissioner requested that we ‘identify that it is possible to monitor the effects of forestry with a degree of certainty sufficient to distinguish the effects of forestry as distinct from other catchment landuses’. Thus, the key issue is the definition of “degree of certainty”. This is an important issue and needs careful and thoughtful consideration. Certainly it is technically feasible to provide stronger evidence, but a cost-benefit analysis for this increased certainty against options for improved catchment management must be considered. This analysis should consider the current trends in the harbour’s ecology, the history of sediment impacts and the current ecological value of the harbour, but also the type of proof that would be accepted in a court of law.

We consider the monitoring programme in Whangapoua has provided important information on a valuable ecological resource. The monitoring programme in its current form was never designed to show direct cause-effect relations with specific forestry activity. Nevertheless Ernslaw One Ltd initiated this work to provide a baseline of information on the harbour. There is merit in the continuation of monitoring for the on-going management of the harbour and the effects of land-use, particularly considering the precautionary principle that underpins the RMA. The relevance to Ernslaw One Ltd and the issue of proof of cause and effect need to be resolved before decisions concerning the expansion or contraction of the monitoring programme are appropriate. But, at the least, we consider monitoring should be continued for State-of-the-Environment purposes, although it is not for us to comment on how continued monitoring is supported. However this point is resolved, it is important that changes in the harbour’s ecology associated with land use should be considered as a catchment-wide issue.

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9. Appendices

9.1 Appendix 1: Monitoring methods (1993 – 2006)

The primary focus of the monitoring programme is on the ecology of the intertidal sand flat communities. Nine monitoring sites were established in 1993, three in each arm of the harbour (Figure 1 in main text). These 9 sites were sampled twice yearly (generally in April and October) from October 1993 to March 1999. No sampling occurred from March 1999 to April 2002, and from April 2002, monitoring of two sites per arm of the harbour (the inner and outer most arms) has been performed. Intertidal harbour bed elevations were surveyed annually from 1993 to 1996; the surveys have been conducted approximately every three years since (1998, 2001, 2003, 2005). Seagrass and mangrove distributions have been analysed from aerial photographs taken in 1945, 1960, 1966, 1978, 1983, 1993, 1995, 2000, 2003 and 2006.

At each of the monitoring sites, 12 replicate sediment cores (13 cm diameter x 15cm deep) were collected. To provide an adequate spread of cores over the site, a site was ‘divided’ into 12 equal sections and one core sample was taken from a random location within each section. To reduce the influence of previous sampling activity and spatial autocorrelation, samples were not placed within a 5 m radius of each other or of any samples collected in the previous 12 months. Core samples were sieved through a 500 µm mesh and the residues stained with rose bengal and preserved in 70 % isopropyl alcohol in seawater. Samples were then sorted and stored in 50 % isopropyl alcohol. The 20 selected species (see Table below) were counted and stored in 50 % isopropyl alcohol.

Table: Monitored macrofaunal taxa. Note that some taxonomic name changes have occurred over the monitored period; new names are given in brackets.

Order	Family	Taxa
Amphipoda (sand hoppers)	Lysianassidae	*Parawaldeckia* aff. *karaka*
	Phoxocephalidae	*Torridoharpinia hurleyi*
	Phoxocephalidae	*Wildus (Waipirophoxus) waipiro*
Bivalvia (shellfish)	Erycinidae	*Arthritica bifurca*
	Veneridae	*Austrovenus stutchburyi*
	Tellinidae	*Macomona liliana*
	Nuculidae	*Nucula hartvigiana*
	Mesodesmatidae	*Paphies australis*
Cumacea	Diastylidae	*Colurostylis lemurum*
Decapoda (crabs)	Hymenosomatidae	*Halicarcinus whitei*
	Grapsidae	*Helice crassa*
Polychaeta (marine worms)	Spionidae	*Aonides oxycephala*
	Spionidae	*Aquilaspio (Prionospio) aucklandica*
	Lumbrineridae	*Lumbrineris brevicirra*
	Maldanidae	*Macroclymenella stewartensis*
	Nereidae	Nereidae
	Paraonidae	Paraonid spp.
	Spionidae	*Scolelepis* sp.
	Orbiniidae	*Scoloplos cylindrifer*
	Spionidae	*Scolecolepides benhami*

At the monitoring sites with seagrass (*Zostera muelleri*), six replicate quadrats (0.25 m^2) were placed on the sandflat and photographed to assess the density of the seagrass cover. At 50 random locations on these photos, the presence or not of seagrass blades was assessed. From these counts, the percentage cover of seagrass was calculated. In the initial sampling regime, this % visual cover was correlated to above-ground biomass dry weight.

Changes in communities over time were assessed for all sites simultaneously to see if all sites were behaving similarly, using non-metric multidimensional scaling. This technique is particularly effective at producing 2-dimensional plots of community variability (in this case showing differences between sites and times). All community analyses were done using square root transformed data, thus down weighting the effect that a few very abundant taxa could have on the analyses.

Trends over time in abundances were conducted for each taxa at each time. Plots of abundance versus time were used to determine whether trends were step (particularly those related to the March 1995 storm), logarithmic or linear and the appropriate test was conducted within a generalised linear model framework. This allowed error structures other than normal errors to be used in the calculation of the regressions.

Large-scale changes in the distribution and density of seagrass and mangroves were assessed from 1:5000 aerial photographs. Initially, the percentage cover of seagrass and mangroves was determined for 7 areas within the harbour (Morrisey et al. 1995). Latter, as GIS technology improved, the percentage cover was assessed and compared for the whole harbour (Craggs et al. 2001). The distribution of mangroves and seagrass within the harbour was also assessed from historic aerial photographs dating back to 1946.

Sediment characteristics (i.e., grain size, percentage mud content) were also assessed at each site on each sampling occasion. At the 12 core locations within the site, small sediment surface scrapes were collected to determine grain size. The 12 sediment surface scrapes were pooled, and kept frozen prior to being analysed. In the lab, the samples were homogenised and a subsample of approximately 5 g of sediment taken, and digested in ~ 9% hydrogen peroxide until frothing ceased. The sediment sample was then wet sieved through mesh sieves sized 2000 μm (gravel), 500 μm (coarse sand), 250 μm (medium sand) and 63 μm (fine sand). Pipette analysis was used to separate the <63 μm fraction (mud) into >3.9 μm (silt) and <3.9 μm (clay). All fractions were then dried at 60^{o}C until a constant weight was achieved (fractions are weighed at ~ 40 h and then again at 48 h).

Changes in the erosion (scour) and accretion (build-up) of the bed of the intertidal flats was monitored by surveying the bed profiles at selected sites in each of the 3 main arms of the harbour (Figure 1 in main text). The 6 profile sites were chosen to cover a range of environments and types of sediment and to be near the biological sampling sites. The profiles ranged in length from 188 to 843 m. Permanent bench marks (BMs) were established at the origin of these 6 lines. Along each survey line, pegs marked the places where the bed level changed in elevation. The surveying was done with a

Geodimeter 464, which given position to a few cm, level to +/- 1 cm. In practice, it is difficult to measure changes in mean bed level to this degree of accuracy because the bed has ≤2 cm micro-relief features (e.g., sand ripples, mounds of sand in seagrass patches) which change over short time periods. These features produce a "noise" in the measurement of bed level, such that changes in mean bed level must be greater than this to be considered as significant.

9.2 Appendix 2: Macrofauna responses to sediment.

Results from a number of research projects, funded by the Foundation for Research, Science and Technology, MFish and ARC is summarised in Gibbs and Hewitt 2004. An abbreviated version for the monitored taxa is given here. S – will react negatively to increased fine sediment, M - will react positively to increased fine sediment, I – will initially react positively to increased fine sediment, and then negatively as input continues.

Preference	Faunal group	Information taxa	Monitored taxa if different
S	Bivalve	*Paphies australis* adults	
S	Cumacean	*Colurostylis lemurum*	
S	Polychaete	*Aonides oxycephala*	
S	Polychaete	*Scoloplos cylindrifera*	
S	Bivalve	*Macomona liliana*	
S	Amphipod	*Waipirophoxus waipiro*	
S	Polychaete	*Prionospio aucklandica*	
I	Bivalve	*Austrovenus stutchburyi*	
I	Bivalve	*Arthritica bifurca*	
I	Bivalve	*Nucula hartvigiana*	
I	Polychaete	*Scolecolepides benhami*	
I	Polychaete	*Lumbrineris* sp. (*Aeotearia*)	*Lumbrineris*
I	Polychaete	*Macroclymenella stewartensis*	
I	Polychaete	*Aricidea* sp.	Paraonids
I	Polychaete	*Nicon aestuariensis*	Nereidae
M	Decapod	*Helice crassa*	

9.3 Appendix 3: Macrofaunal trends in abundance observed over the monitored period at sites 1, 3, 4, 6, 7 and 9.

Results of trend analyses carried out on all taxa, with mean abundances ≥ 2 individuals per core at a site, are given as slope, associated p-value and for significant trends, the magnitude of the change. Information on type of change is given in the column headed type, where trend = gradual change over monitored period, storm = storm-related step trend, cycle = a long-term cycle.

Site1	**slope estimate**	**p-value**	**type**	**change**
Aonides oxycephala				
Aquilaspio aucklandica				
Arthritica bifurca	-0.259	0.0123	storm	-7.7
Austrovenus stutchburyi				
Colurostylis lemurum				
Halicarcinus whitei				
Helice crassa		0.8080		
Lumbrineris brevicirra				
Macomona liliana				
Macroclymenella stewartensis				
Nereid spp.	-0.809	0.0043	trend	-21.0
Nucula hartvigiana				
Paphies australis	0.033	0.6869		
Paraonid				
Parawaldeckia aff. *Karaka*				
Scolecolepides benhami	-1.026	<0.0001	trend	-26.7
Scolelepis sp.		0.4594		
Scoloplos cylindrifer	-0.101	0.0250	storm	-2.6
Torridoharpinia hurleyi				
Wildus waipiro				

Site 3	**slope estimate**	**p-value**	**type**	**change**
Aonides oxycephala	-0.097	0.0287	trend	-2.5
Aquilaspio aucklandica		0.2470		
Arthritica bifurca	-0.199	0.0378	storm	-5.2
Austrovenus stutchburyi		0.2906		
Colurostylis lemurum		0.3130		
Halicarcinus whitei				
Helice crassa				
Lumbrineris brevicirra				
Macomona liliana	-0.084	<0.0001	trend	-2.2
Macroclymenella stewartensis				
Nereid spp.		0.1306		
Nucula hartvigiana		0.5411		

Paphies australis		0.7041		
Paraonid				
Parawaldeckia aff. *karaka*				
Scolecolepides benhami	-0.296	0.0049	trend	-7.7
Scolelepis sp.		0.8875		
Scoloplos cylindrifer		0.2729		
Torridoharpinia hurleyi				
Wildus waipiro				

Site 4	**slope estimate**	**p-value**	**type**	**change**
Aonides oxycephala				
Aquilaspio aucklandica		0.3891		
Arthritica bifurca	-0.057	0.0110	trend	-1.5
Austrovenus stutchburyi	0.767	<0.0001	trend	19.9
Colurostylis lemurum	0.163	0.0235	cycle	4.3
Halicarcinus whitei				
Helice crassa	-0.046	0.0067	trend	-1.2
Lumbrineris brevicirra				
Macomona liliana		0.1271		
Macroclymenella stewartensis				
Nereid spp.	-0.234	0.0059	trend	-6.1
Nucula hartvigiana	1.448	<0.0001	trend	37.7
Paphies australis				
Paraonid	-4.016	0.0061	trend	-104.4
Parawaldeckia aff. *karaka*				
Scolecolepides benhami				
Scolelepis sp.				
Scoloplos cylindrifer				
Torridoharpinia hurleyi		0.5021		
Wildus waipiro	-0.218	0.0418	storm	-5.7

Site 6	**slope estimate**	**p-value**	**type**	**change**
Aonides oxycephala				
Aquilaspio aucklandica		0.7387		
Arthritica bifurca				
Austrovenus stutchburyi	-0.257	0.0246	trend	-6.7
Colurostylis lemurum				
Halicarcinus whitei				
Helice crassa	-0.044	0.0001	trend	-1.2
Lumbrineris brevicirra				

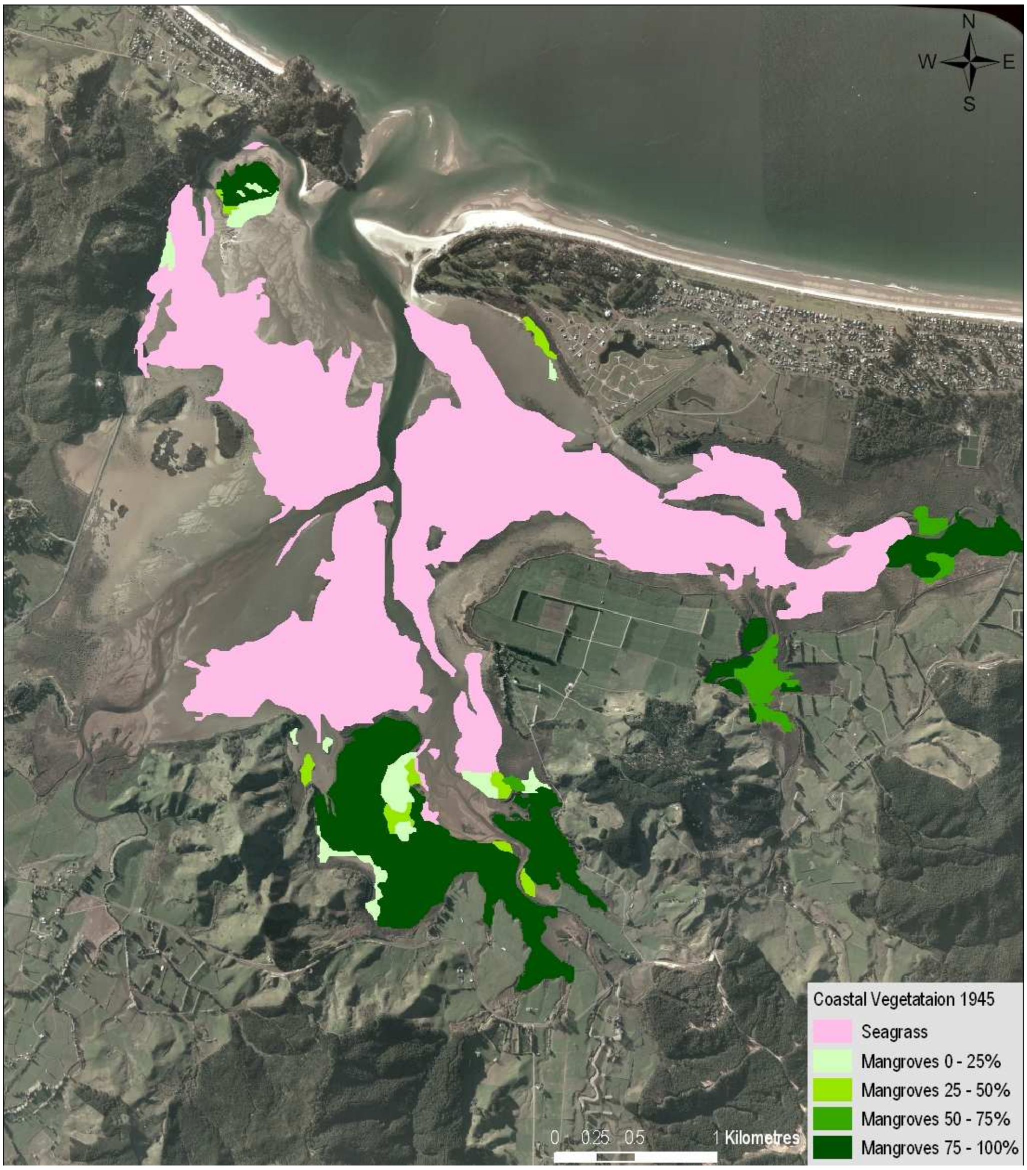
Macomona liliana		0.1242		
Macroclymenella stewartensis				
Nereid spp.		0.0607		
Nucula hartvigiana		0.4663		
Paphies australis				
Paraonid	2.146	0.0462	trend	55.8
Parawaldeckia aff. *Karaka*				
Scolecolepides benhami				
Scolelepis sp.				
Scoloplos cylindrifer				
Torridoharpinia hurleyi		0.0572		
Wildus waipiro		0.0260	storm	-9.5

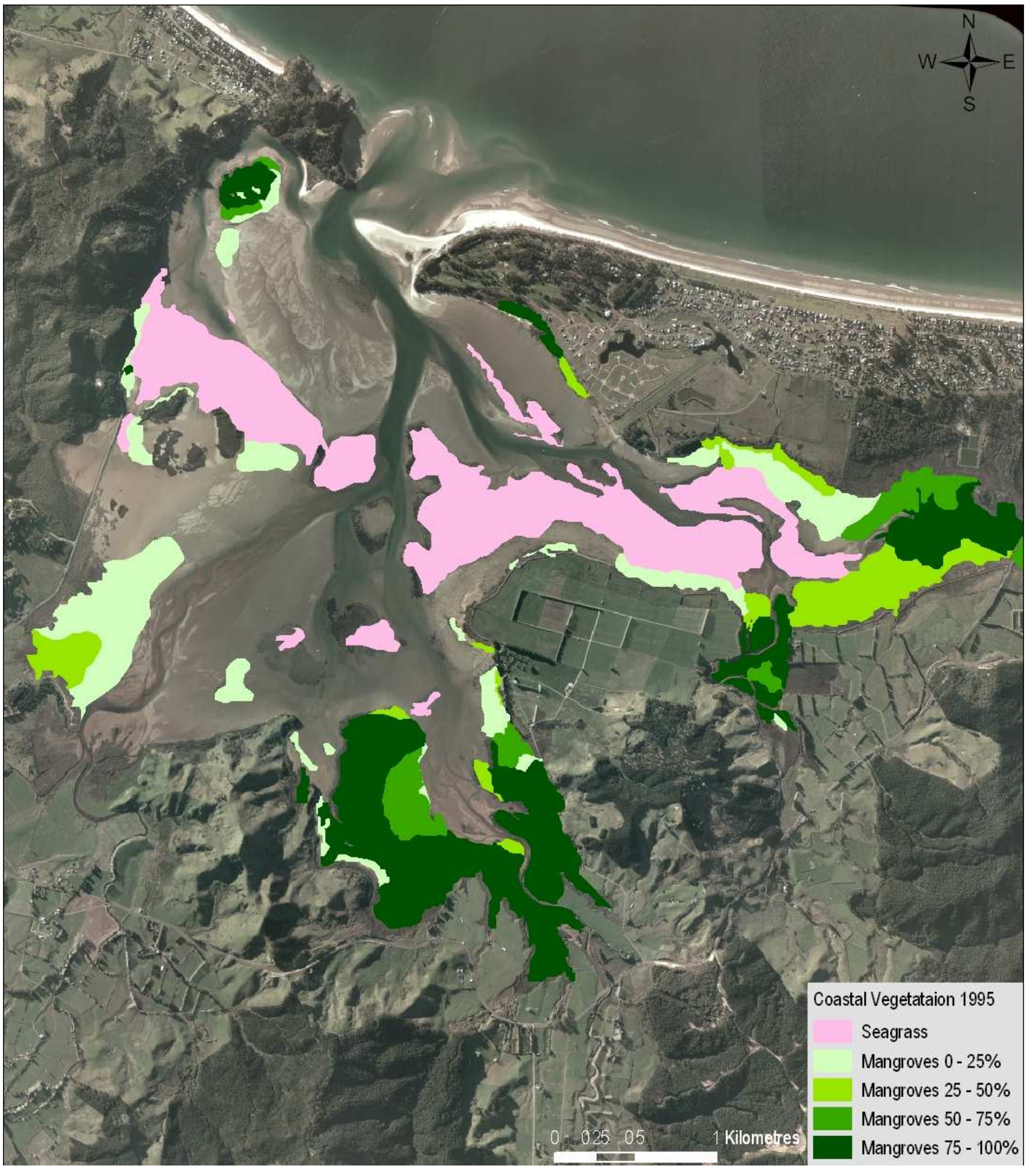
Site 7	**slope estimate**	**p-value**	**type**	**change**
Aonides oxycephala	-0.238	0.0001	trend	-6.2
Aquilaspio aucklandica		0.4547		
Arthritica bifurca	-0.026	0.0485	cycle	-0.7
Austrovenus stutchburyi		0.2418		
Colurostylis lemurum		0.1461		
Halicarcinus whitei		0.5600		
Helice crassa				
Lumbrineris brevicirra				
Macomona liliana		0.3478		
Macroclymenella stewartensis				
Nereid spp.	-0.406	0.0036	trend	-10.6
Nucula hartvigiana	0.334	<0.0001	trend	8.7
Paphies australis				
Paraonid	0.636	0.0049	cycle	16.6
Parawaldeckia aff. *karaka*		0.3714		
Scolecolepides benhami				
Scolelepis sp.				
Scoloplos cylindrifer				
Torridoharpinia hurleyi	0.206	0.0054	trend	5.4
Wildus waipiro		0.4223		

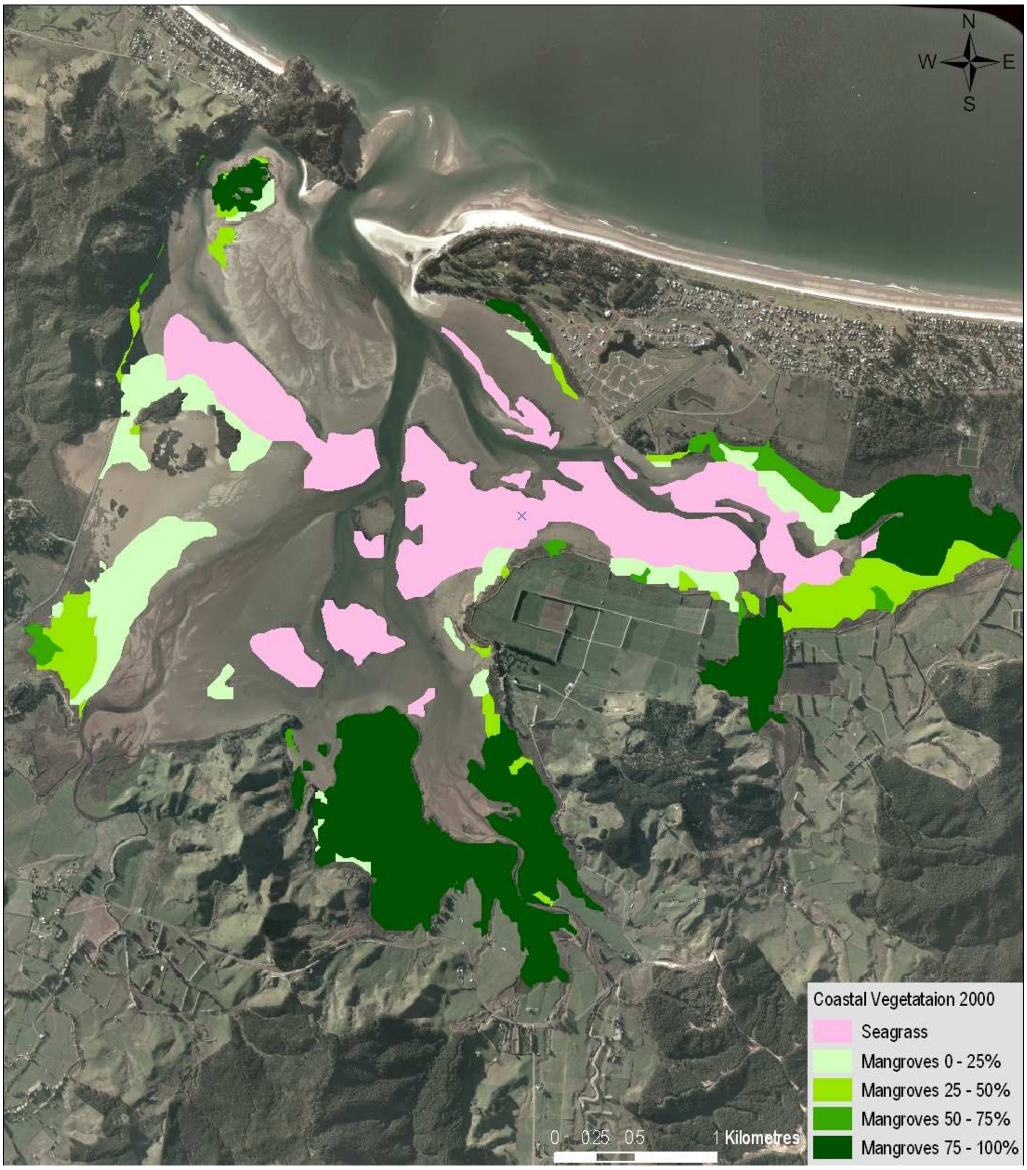
Site 9	**slope estimate**	**p-value**	**type**	**change**
Aonides oxycephala				
Aquilaspio aucklandica		0.7213		
Arthritica bifurca				
Austrovenus stutchburyi	+0.234	0.0167	trend	-6.1

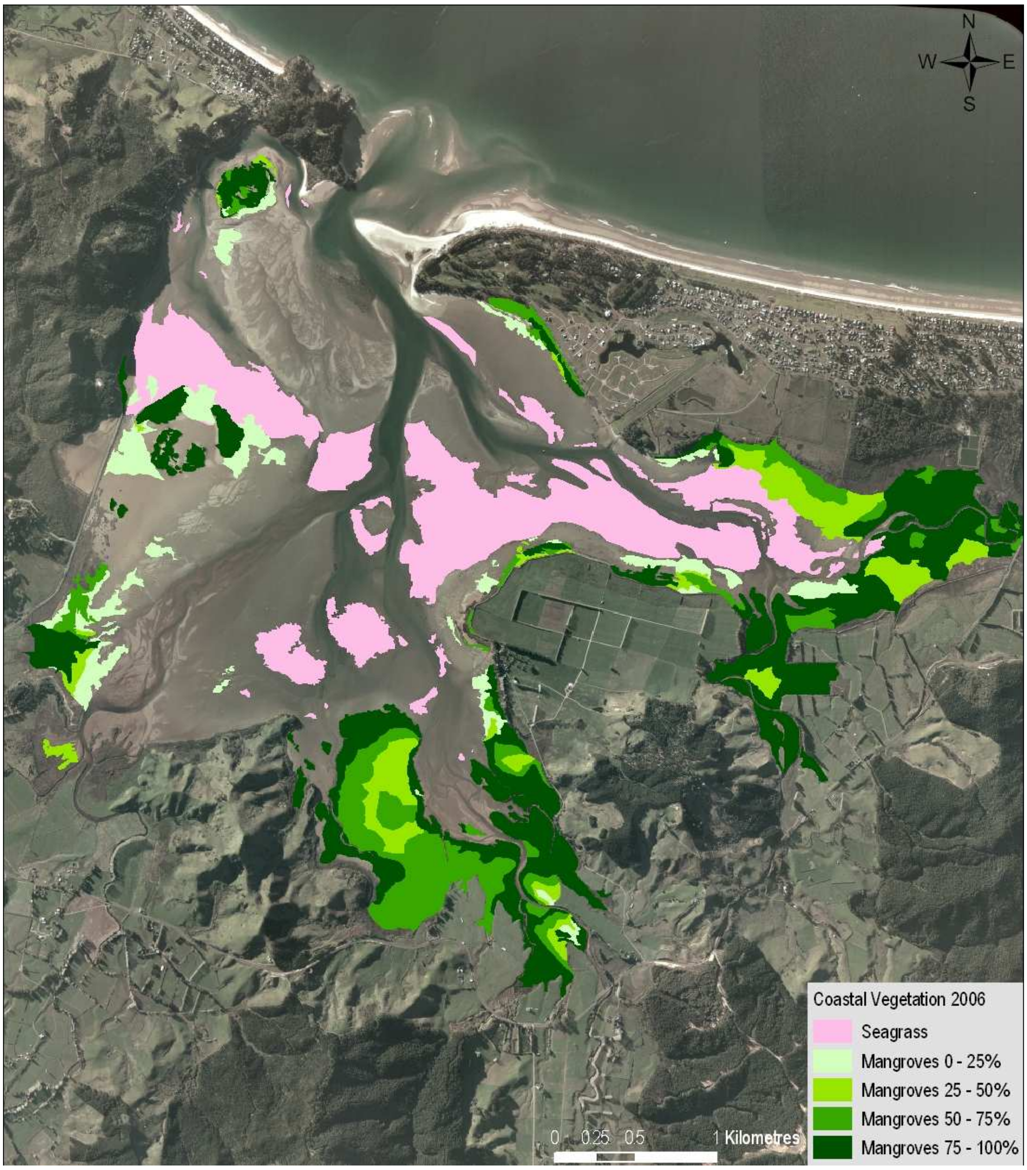
Colurostylis lemurum		0.0567		
Halicarcinus whitei		0.0695		
Helice crassa		0.1201		
Lumbrineris brevicirra				
Macomona liliana		0.1058		
Macroclymenella stewartensis		0.1728		
Nereid spp.		0.1118		
Nucula hartvigiana	-0.131	0.0275	cycle	-3.4
Paphies australis				
Paraonid	0.464	0.0001	trend	12.1
Parawaldeckia aff. *karaka*		0.6277		
Scolecolepides benhami				
Scolelepis sp.				
Scoloplos cylindrifer				
Torridoharpinia hurleyi	0.364	0.0108	trend	9.5
Wildus waipiro		0.0869		

9.4 Appendix 4: Changes in mangrove and seagrass cover over time.




N
W
E
S
Coastal Vegetataion 1995
Seagrass
Mangroves 0 - 25%
Mangroves 25 - 50%
Mangroves 50 - 75%
Mangroves 75 - 100%
0
0.25
0.5
1 Kilometres


N
W
E
S
Coastal Vegetataion 2000
Seagrass
Mangroves 0 - 25%
Mangroves 25 - 50%
Mangroves 50 - 75%
Mangroves 75 - 100%
0 0.25 0.5 1 Kilometres


N
W
E
S
Coastal Vegetation 2006
Seagrass
Mangroves 0 - 25%
Mangroves 25 - 50%
Mangroves 50 - 75%
Mangroves 75 - 100%
0 0.25 0.5 1 Kilometres

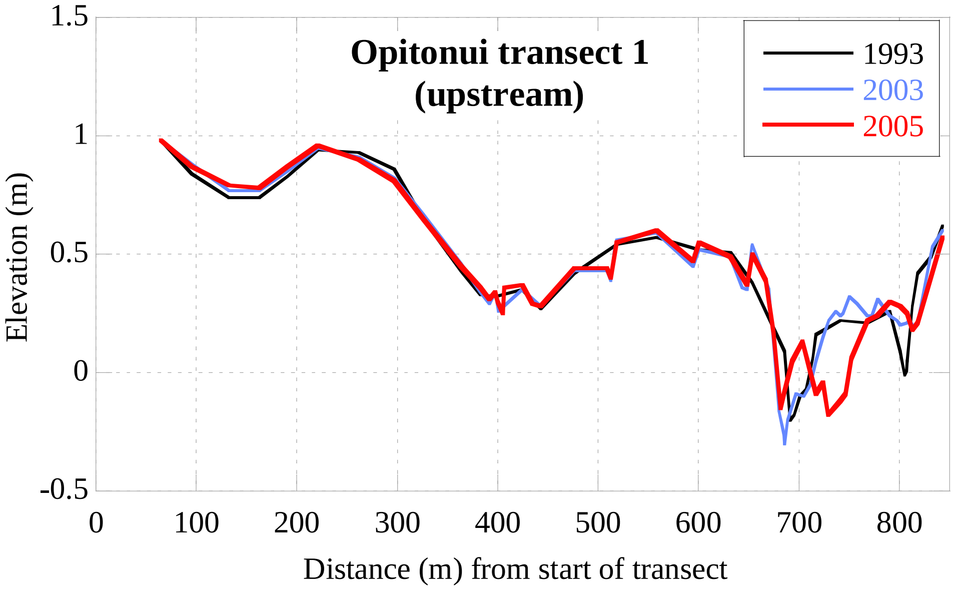
9.5 Appendix 5: Summary of changes in bed-profiles

Transect 1 in the Opitonui arm of the harbour showed the greatest changes, with differences +/- 38 cm from the original (October 1993) survey (Fig. A5.1). These large changes in sandflat height are due to migration of the channel in the lower part of the transect. Channel migration is a natural process that occurs as sediment deposits during low flow periods and is redistributed during high flow events. Over the more stable upper part of the transect, mangrove density increased (Ovenden pers com.), with some evidence of sediment entrapment behind these mangroves in the upper part of the profile. Transect 2 in the same arm showed no significant change over the monitoring period (Fig. A5.2).

The intertidal flats along transect 1 in the Owera arm showed erosion at the top of the beach (up to 7 cm over the course of the study) but ~ 10 cm of deposition just downshore of this (Fig. A5.3). Other deposits (< 10 cm) have formed in the upper 50 m, probably associated with the increased density and size of mangroves over the monitoring period (Ovenden pers com.). Sediment deposited over the lower part of the transect between 1994 and 1995, associated with the March 1995 storm, has been removed. Transect 2 also showed erosion, especially at the top of the shore (up to 30 cm since 1993; Fig. A5.4).

Transect 1 in the Mapauriki arm has experienced deposition at the top of the shore (up to 25 cm since 1993) and on the sandflats fringing the channel (Fig. A5.5). Transect 2 in the Mapauriki arm also experienced beach accretion (up to 25 cm) and sediment deposition (up to 15 cm) on the sandflats fringing the channel (Fig. A5.6). The density and height of mangroves has been increasing at the top of each of these profiles (Ovenden pers com.). Entrapment of sediment by mangroves could explain the consistent beach accretion at these transects.

A.



B.

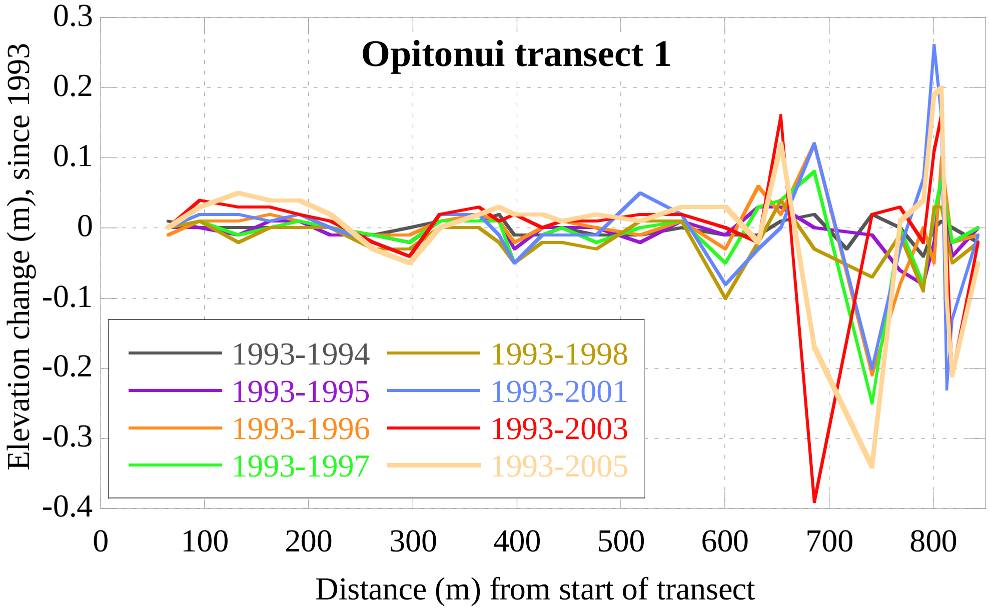
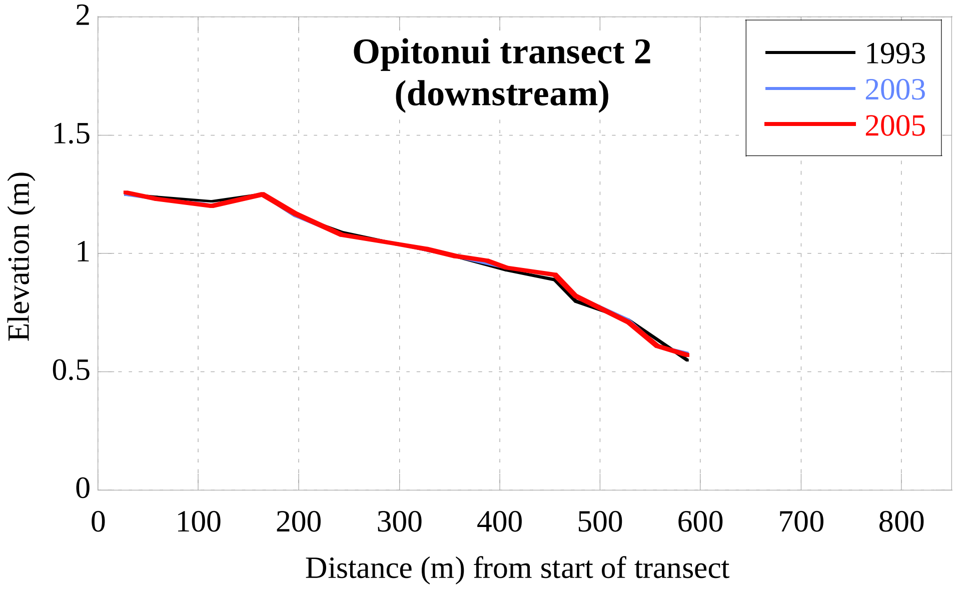


Figure A5.1: (A) Elevation so the bed of Whangapoua Harbour along Opitonui transect 1 for selected surveys (1993, 2003 & 2005), and (B) changes in bed height along transect 1 between 1993 and subsequent surveys.

A.



B.

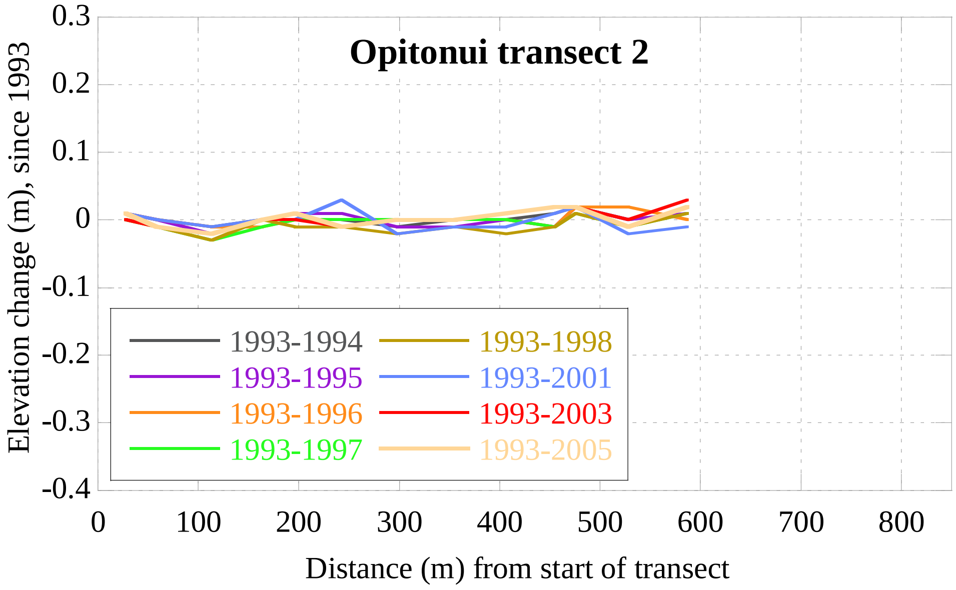
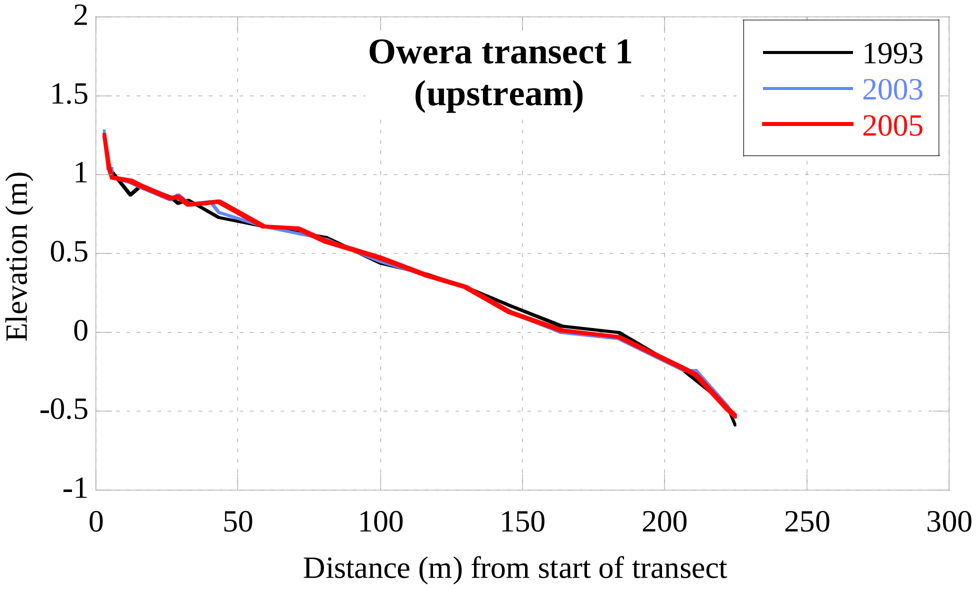


Figure A5.2: (A) Elevation so the bed of Whangapoua Harbour along Opitonui transect 2 for selected surveys (1993, 2003 & 2005), and (B) changes in bed height along transect 2 between 1993 and subsequent surveys.

A.



B.

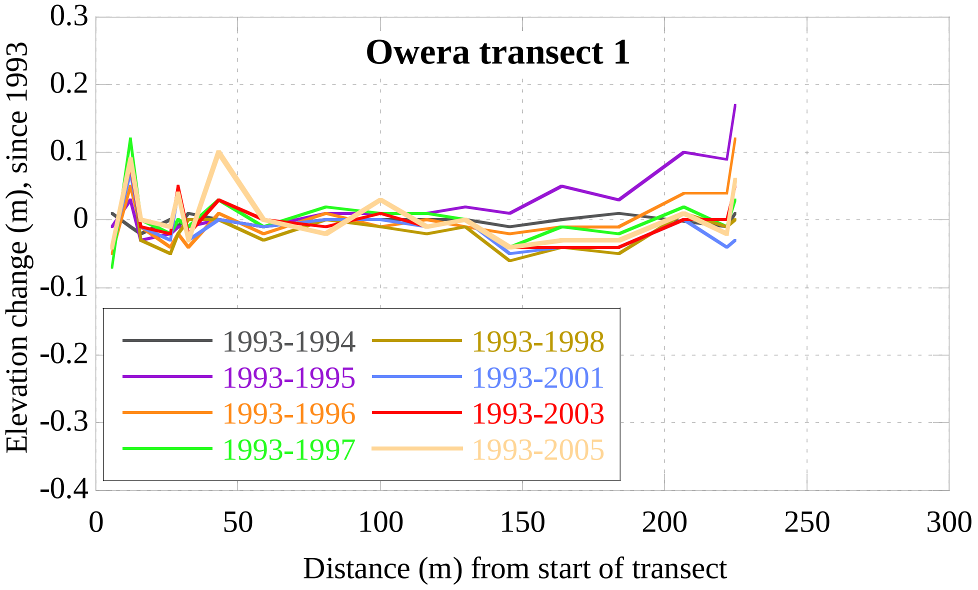
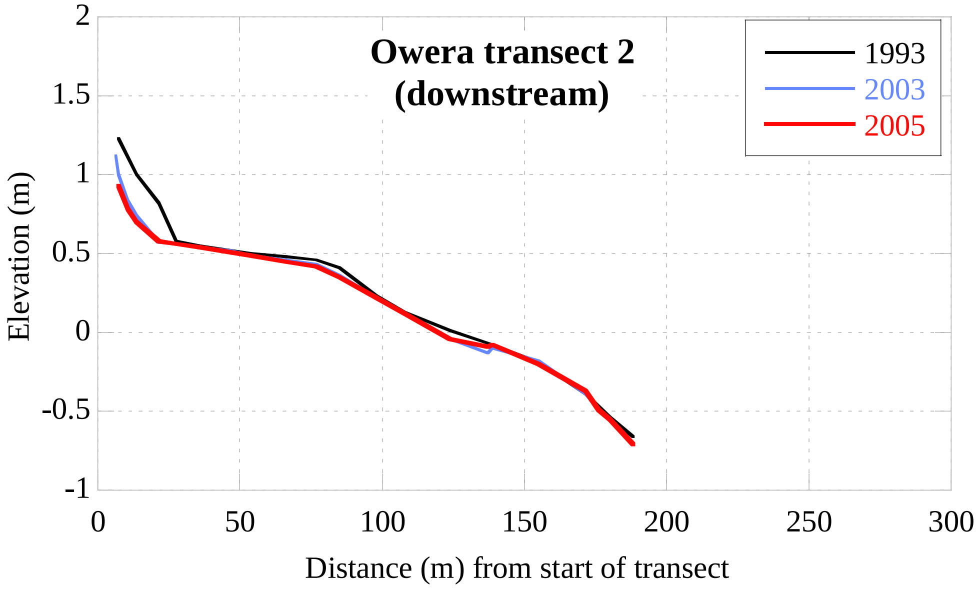


Figure A5.3: (A) Elevation so the bed of Whangapoua Harbour along Owera transect 1 for selected surveys (1993, 2003 & 2005), and (B) changes in bed height along transect 1 between 1993 and subsequent surveys.

A.



B.

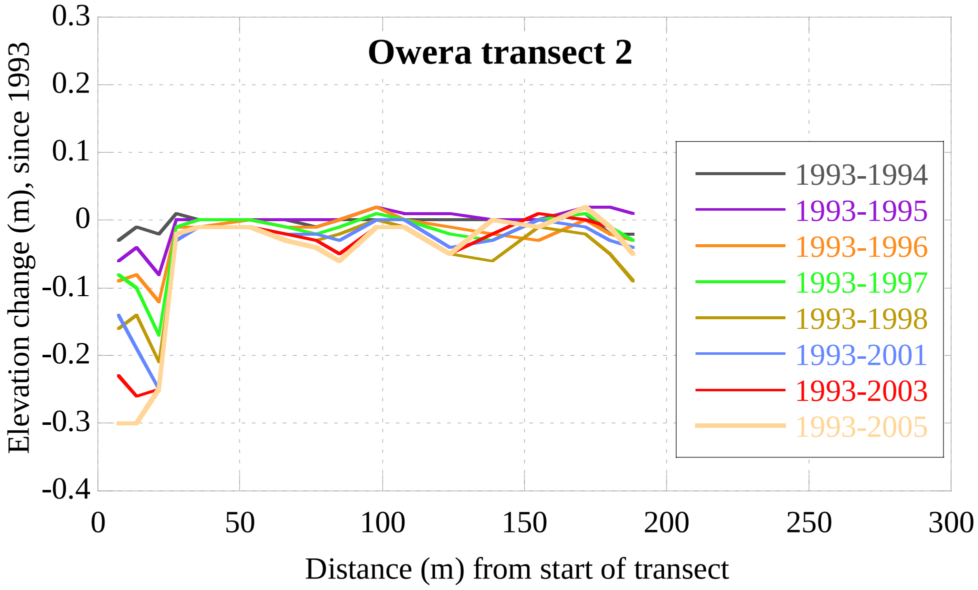
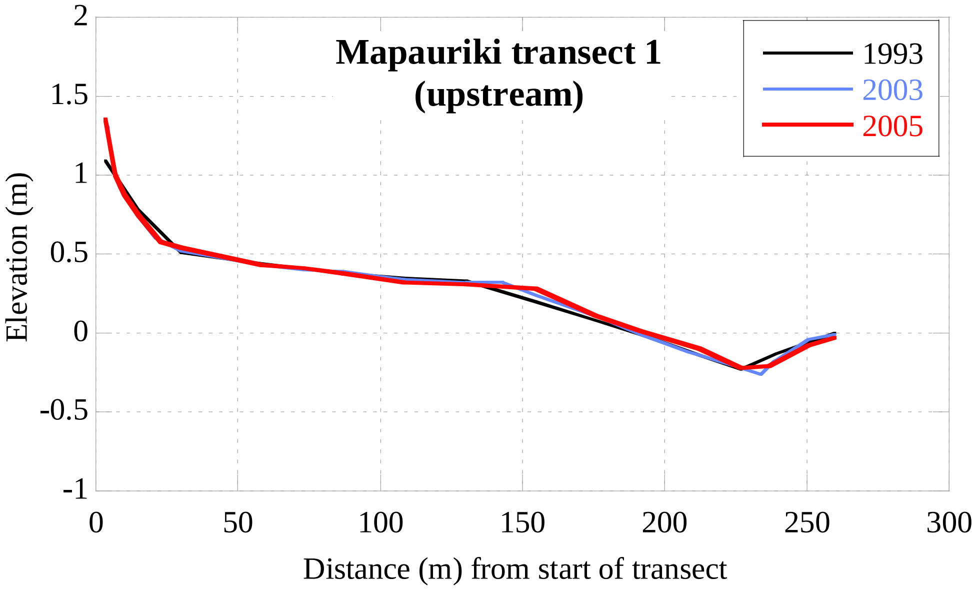


Figure A5.4: (A) Elevation so the bed of Whangapoua Harbour along Owera transect 2 for selected surveys (1993, 2003 & 2005), and (B) changes in bed height along transect 2 between 1993 and subsequent surveys.

A.



B.

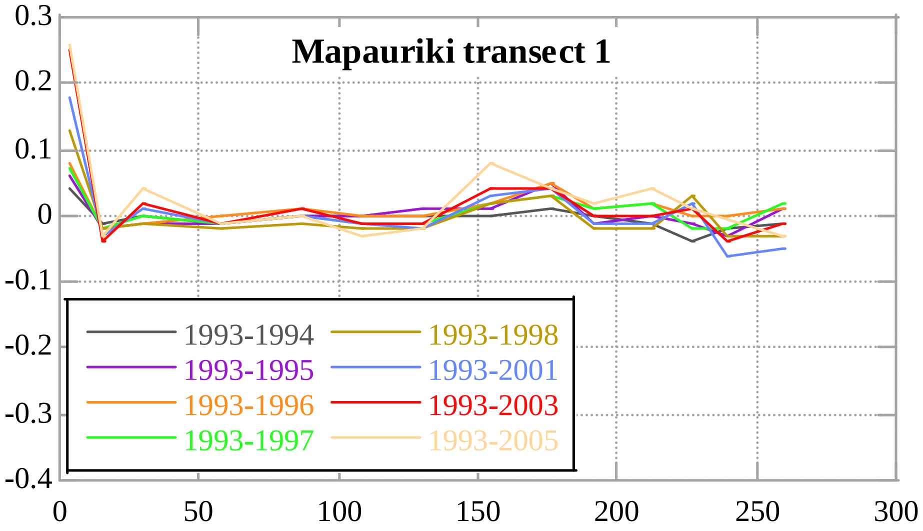
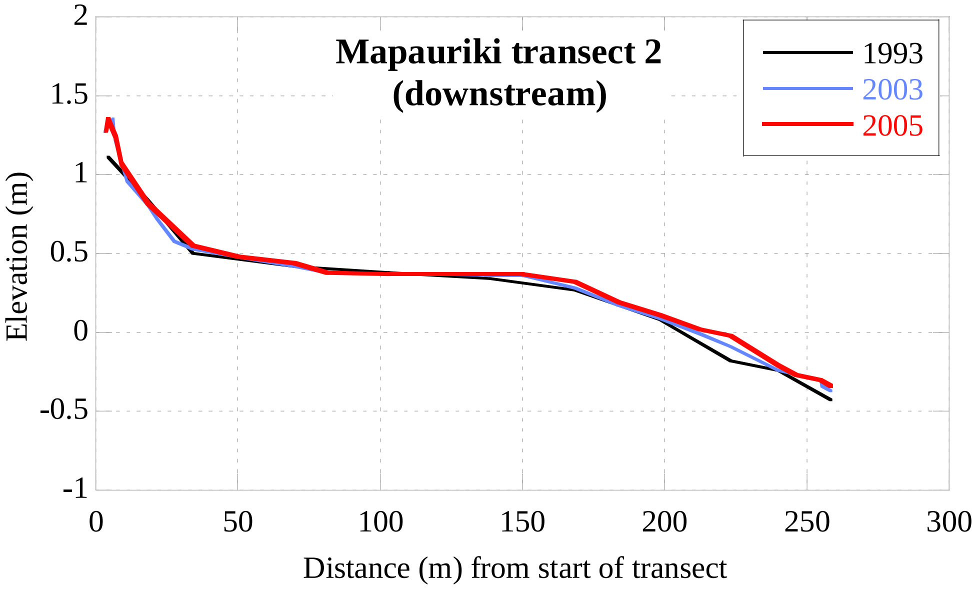


Figure A5.5: (A) Elevation so the bed of Whangapoua Harbour along Mapauriki transect 1 for selected surveys (1993, 2003 & 2005), and (B) changes in bed height along transect 1 between 1993 and subsequent surveys.

A.



B.

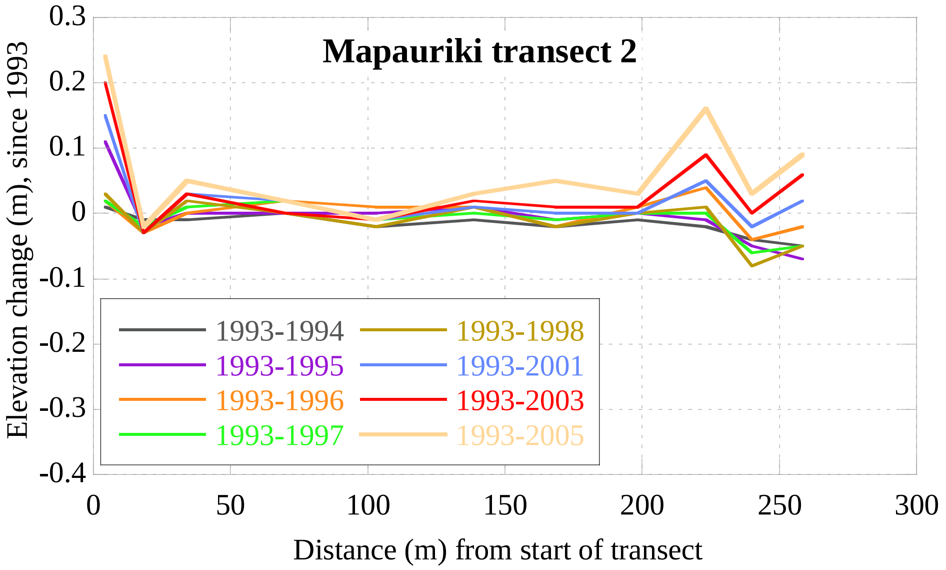
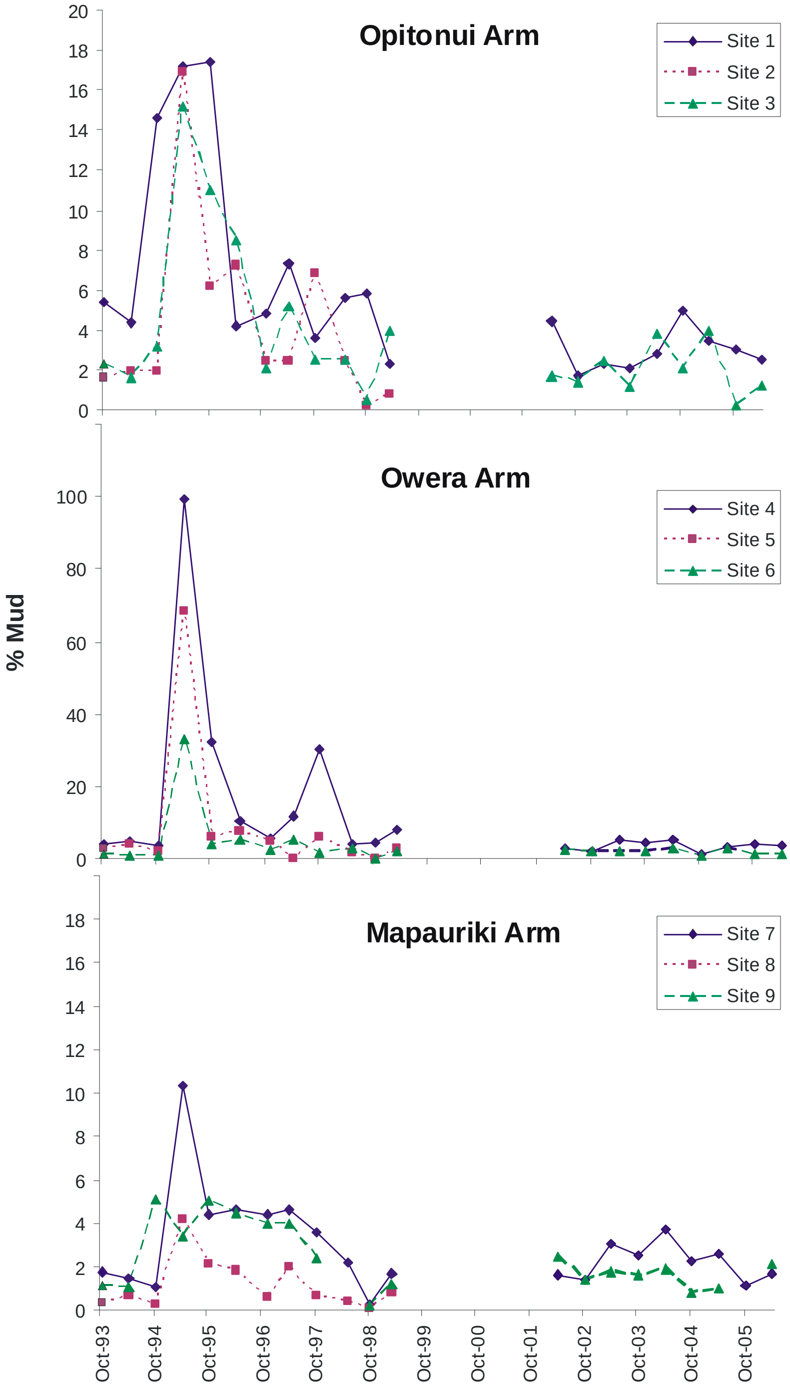


Figure A5.6: (A) Elevation so the bed of Whangapoua Harbour along Mapauriki transect 2 for selected surveys (1993, 2003 & 2005), and (B) changes in bed height along transect 2 between 1993 and subsequent surveys.

9.6 Appendix 6: Changes in %sediment mud content over the monitored period

Changes in the percentage mud content of sediments at the nine sampling sites over the monitoring period. Note: no sampling was conducted between March 1999 and October 2001. Also note the different y-axis scales.



9.7 Appendix 7: Linking ecological changes to forestry activity- methods and results

Using data on harvesting activity, stream discharges and rainfall in the area, we have attempted to synthesise changes at all sites with respect to forestry activity. Explanatory variables used in a generalised linear model were: harvested area in each catchment; distance of site to nearest input of sediment (= distance within arm to stream entry point) and second nearest input of sediment (= distance to stream entry point in next arm); and variations in measured rainfall at Whangapoua and discharge of the Opitonui River (maximums and averages over the period prior to each sampling). As there is no general consensus of the time over which an area that has been harvested continues to be at risk of producing higher sediment runoff, we used accumulated areas for 1, 2, 3 and 4 years post harvesting. To account for combined effects of logging and severe storms we included a multiplicative term between the rainfall and the harvested area.

Modelling was done for taxa for which an effect consistent with increased sediment loading had been observed, with the exception of those taxa responding to the change in habitat at Site 4. These taxa were not investigated by regression as their responses were more of a step trend. Modelling was also done for % Zostera cover at sites 6, 7 and 9, as well as changes in the abundance from the start to then end of the monitoring programme at all sites for Nereids and *Scolecolepides*.

In all cases, whether areas used in the regression were those accumulated for 1, 2, 3 and 4 years post harvesting was determined by correlation in advance of the model. The taxon abundances, % cover and changes were done on yearly averages to coincide with the harvested area information. For Nereids and *Scolecolepides*, the end period was calculated over the final two years of the monitoring programme; unfortunately the Storm in March 1995 prevented this being done at the start. Note that this is a change; a negative effect of harvested area is found if a larger change is associated with larger harvested areas.

Plots were used to determine whether transformations from linearity were needed. Finally, backwards selection that removed variables with p-values > 0.15 was used to obtain a parsimonious model.

Table: Results of generalised linear modelling for taxa abundances, % cover, or change over the monitored period. % explained = R2, or, for models using poisson errors, model MS / total MS. Areaj = harvested area accumulated over J years. Rain = average daily rainfall for a year. Area_dis = harvested area for each catchment divided by distance to site. Oweraarea = harvested area in Owera catchment only. Area*Rain = multiplicative interaction between harvested area and rainfall.

Site	Taxa	type	% Explained	P-value	Variables	Estimate
6	*Zostera*	% cover	0.55	0.0817	Area2 Rain Area2*Rain	-0.359 -48.35 0.091
7	*Zostera*	% cover		>0.10		
9	*Zostera*	% cover		>0.10		
All	*Scolecolepides*	change	0.97	<0.0001	Area_dis	0.108
All	Nereids	change	0.85	0.0084	Area_dis	0.113
1	Nereids	Abundance	0.47	0.0142	Area4_dis	-0.025
1	*Scolecolepides*	Abundance	0.41	0.0009	Area4_dis	-0.0036
3	*Macomona*	Abundance	0.28	0.0632	Area4_dis	-0.0015
3	*Aonides*	Abundance		>0.10		
3	*Scolecolepides*	Abundance	0.21	0.11	Area4_dis	
4	*Arthritica*	Abundance	0.30	0.0540	Oweraarea3	0.005
4	Nereids	Abundance	0.91	<0.0001	Oweraarea4	1.22
4	Paraonids	Abundance	0.67	0.0117	Area4	-0.205
6	*Austrovenus*	Abundance	0.59	0.0021	Oweraarea4	0.024
6	Nereids	Abundance		>0.10		
7	*Aonides*	Abundance	0.33	0.0400	Area4	-0.007
7	*Torridoharpinia*	Abundance	0.35	0.0113	Rain -Rain*Area1	0.556 -0.002
7	Nereids (log)	Abundance	0.55	0.0038	Area4	-0.0025
9	*Austrovenus*	Abundance	0.48	0.0084	Area4	-0.026
9	*Torridoharpinia*	Abundance		>0.10		