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Effects of sedimentation on macrofaunal communities: a synthesis of research studies for ARC

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Effects of sedimentation on macrofaunal communities: a synthesis of research studies for ARC

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1 Executive Summary

Previous to 1999, there were few studies and little information on the effects of terrigenous sediment1 on soft sediment systems, even internationally. Over the last five years a considerable amount of research by NIWA, both FRST- and ARC-funded, has been undertaken on the effects of sedimentation on macrofaunal communities. While this is all available in various reports, this report provides a synthesis of the different strands of the research and documents our current understanding of the effects of sedimentation on macrofaunal communities

The research covers catastrophic, sublethal and cumulative impacts and is based on field and laboratory experiments and surveys of macrofauna and sedimentation history. Catastrophic and thin, sublethal depositions, together with increased suspended sediment concentrations, can result in long-term changes in habitat. In estuaries, multiple habitat types, such as saltmarsh, seagrass and unvegetated intertidal flats promote diversity by enhancing recruitment and maintaining species with requirements for multiple resources. The modification of available habitats due to elevated sedimentation has been shown to reduce the overall ecological heterogeneity. The general exclusion of slow-growing, large species frequently results in lower diversity and reduced ecological functioning of ecosystems.

Three approaches have been used in the investigations. (1) A combination of modeling, surveying and experimentation. Experiments on effects of terrestrial sediment deposits on macrobenthic communities in different habitats are combined with models of sediment runoff from the catchment and particle dispersal models within the estuary, to assess the relative ecological risk to different estuarine habitats under different development scenarios. These risk assessments allow managers to contrast the threats posed by various scenarios of land development and thus improve decision-making. (2) Statistical models that relate ecological variables to environmental factors enabling forecasts of species responses to increased muddiness or changes in the relative proportion of habitats to be made. Such models reveal species sensitivities to habitat change. (3) Changes in abundance, growth or health of species that are sensitive to increased sedimentation. The sensitivity of species, the relative changes observed in different species and the number of species exhibiting changes are all ways of building a picture of the potential cause and its magnitude.

The work that has been done on the effects of increased sedimentation rates, suspended sediment concentrations and mud content has been summarized to produce a list of sensitive species. Table 5 presents a list of species that have provided consistent responses across a range of studies, together with their likely value to the functioning of the ecosystem. Generally, most species provided consistent responses across studies.

[1] Terrigenous sediment in this report is defined as “clay” newly arrived from land recently eroded. This is distinct from resuspended sediments which are recycled from the sea floor within the estuarine system.

An important role for ecologists in environmental management is the provision of guidelines, based on thresholds of response or percentages of ecological response. Four guidelines have been produced from the sedimentation work:

- In general, the thicker the layer of mud, the more animals will be killed and the longer recovery will take. This will affect both the number of species and the number of animals within each species, however some species are more sensitive than others.
- If mud that has been washed down a stream to one of the tributary estuaries or the embayment results in a mud layer greater than 2 cm thick, remaining for longer than five days, then all the resident animals in that area (with the exception of mobile crabs and shrimp) will be killed due to lack of oxygen.
- A mud thickness of around ½ cm, persisting for longer than 10 days, will reduce the number of animals and the number of species, thereby changing the structure of the animal community.
- Frequent deposition of mud, less than ½ cm, may still have long-term impacts that can change the animal communities.

It is important that the limitations of knowledge, either in terms of information gaps, underlying assumptions of studies and models and the effect of simplification of results, are understood. Four points are of general importance for this work. (1) The large spatial and temporal scales of community responses in an estuary or coastal area are extrapolated from the spatial and temporal scale of a manipulative or one-off-survey. The underlying assumption is that the processes defined in the small scale experiments in one part of the system can be applied to the whole system. (2) There has been little work on sub-lethal effects such as organism health, growth or reproductive output. All of these are, however, likely to be important when making long-term forecasts of population and community changes. (3) Interactions between the stress caused by increased sediment inputs and other factors, whether natural (e.g., predation) or anthropogenic (e.g., contaminants) are likely to be multiplicative. (4) Little knowledge has yet been generated on the effect of duration and frequency of events over long-time scales, or on large-spatial changes, to the distribution of estuarine and coastal habitats.

2 Introduction

Previous to 1999, there were few studies and little information on the effects of terrigenous sediment on soft sediment systems, even internationally. It was expected that animals in those areas would be able to cope. Over the last five years a considerable amount of research by NIWA, both FRST- and ARC-funded, has been undertaken on the effects of sedimentation on macrofaunal communities. The research covers catastrophic, sublethal and cumulative impacts and is based on field and laboratory experiments and surveys of macrofauna and sedimentation history. Work has been carried out in a number of Auckland estuaries on a number of different species and communities in both intertidal and subtidal areas.

This report provides a synthesis of the different strands of that research and documents our current understanding of the effects of sedimentation on macrofaunal communities and includes a summary of risks to the value and function of estuarine ecosystems.

We summarise the studies conducted by NIWA Hamilton on the effects of elevated sediment in terms of the:

- effects of increases in suspended sediment;
- effects of catastrophic and chronic sedimentation, and
- effects of long-term changes in habitats.

We provide a list of reports and papers available, and outline the tools and guidelines produced, together with caveats and limitations of each. We also present a list of species sensitive to sedimentation effects that would be useful for monitoring, together with their ecological function, value and what is known of risks.

2.1 Background

Throughout the Pacific Rim, terrigenous sediment is increasingly recognized as a disturbance agent in coastal marine communities. However, while sediment run-off is a natural processes, human activity in the catchment can dramatically increase the rate at which this occurs. In run-off events, terrigenous sediment can muddy the waters for fish and cause loss of oxygen which impacts all levels of the community. Elevated suspended solids directly impact suspension feeders, interfering with their ability to feed or diluting the food quality with inorganic particles and, in extreme events, smothering them and other benthic infauna on the sea floor.

We have shown that benthic communities on intertidal sand and mudflats are highly vulnerable to deposition of terrigenous sediment from coastal catchments. These communities comprise a diverse range of benthic organisms, which have adapted to cope with the stress associated with tidal immersion and emersion (e.g., potentially large fluctuations in temperature, salinity, and porewater ammonium concentrations) and have developed interdependence between functional groups. While catastrophic events may defaunate the intertidal zone, even small terrigenous sediment deposits could alter interdependences and cause shifts in the structure of benthic communities. The change in sediment structure due to accumulation of small deposits of terrigenous sediment over time may favour one species over another and is a factor in the progradation of fringe vegetation into estuaries.

The full spectrum of possible impacts range from lethal catastrophic events that smother the benthic communities, to sublethal deposition events and increases in suspended sediment concentrations that pervasively alter the functional stability of the benthic community through subtle changes to food supply and physical structure of the sediments that comprise the habitat of that community. However, while the magnitude of the event is an important factor in determining the impact, the frequency of event may be more important in determining the risk to the benthic community. Catastrophic events are rare but sublethal events may occur with every rainfall (Fig. 1; Photo set 1). In this case the impact could depend on the ability of the benthic community to recover between events and may involve a long-term change in the habitat with resultant changes to the benthic community.

There are likely to be threshold levels in thickness of the terrigenous sediment deposit between catastrophic and sublethal events where complete defaunation does not occur immediately and some species are adversely affected while others thrive. Modelling has shown a relationship between the magnitude of the sediment erosion event and the thickness of terrigenous sediment depositing on the intertidal zone (e.g., Fig. 1).

The recovery of a benthic community from sublethal deposition events may depend on many factors, including depth of deposition, the previous history of that community and the sediment structure of the habitat before the event. For example, terrigenous sediment depositing on a diverse sandflat community is likely to have a far greater impact on that benthic community than the same deposition on a mudflat community where diversity is lower and the benthic community has already adapted to a silt/clay environment. Recovery from lethal catastrophic events may be driven by physical (e.g., wave action) and biological (e.g., bioturbation) parameters and considerable time can elapse before the original benthic community returns, if it ever does. Recovery of defaunated sediment may depend on the availability of appropriate macrofauna to recolonise the sediment.

Figure 1:

Modelled sediment load derived from the catchment of Okura Estuary under present land-use. "A" is the critical load needed to produce a 2 cm deep depositional event. "B" is the critical load needed to produce a 2-3 mm deep depositional event. See Stroud et al. (1999).

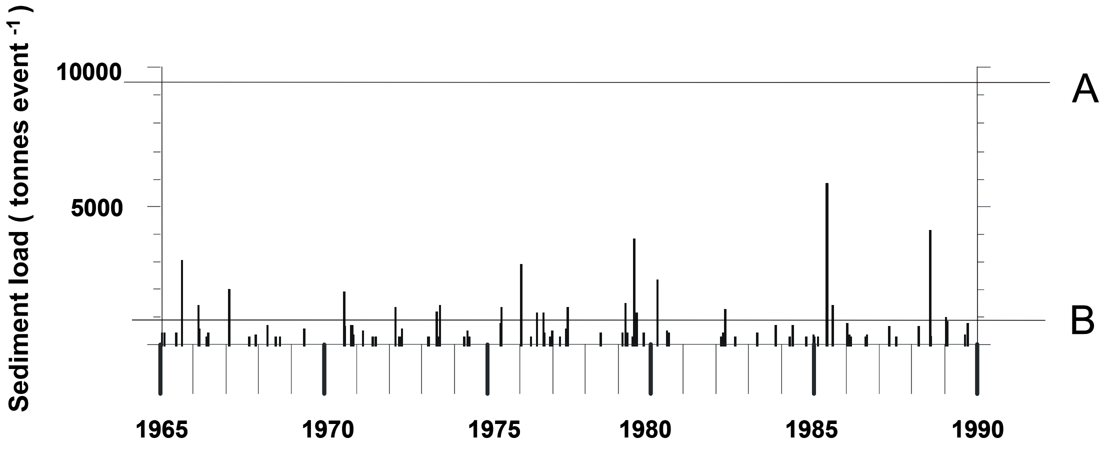
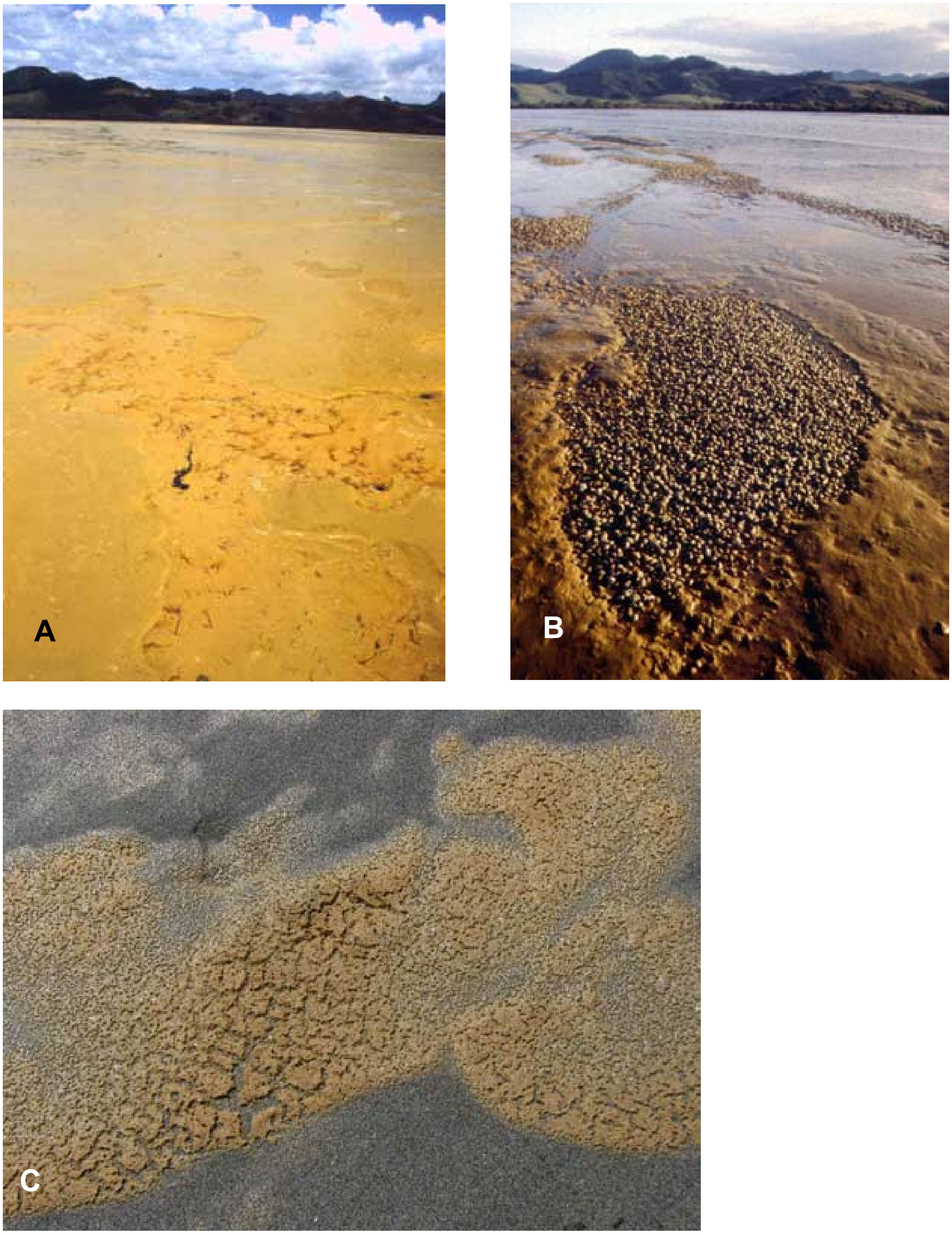


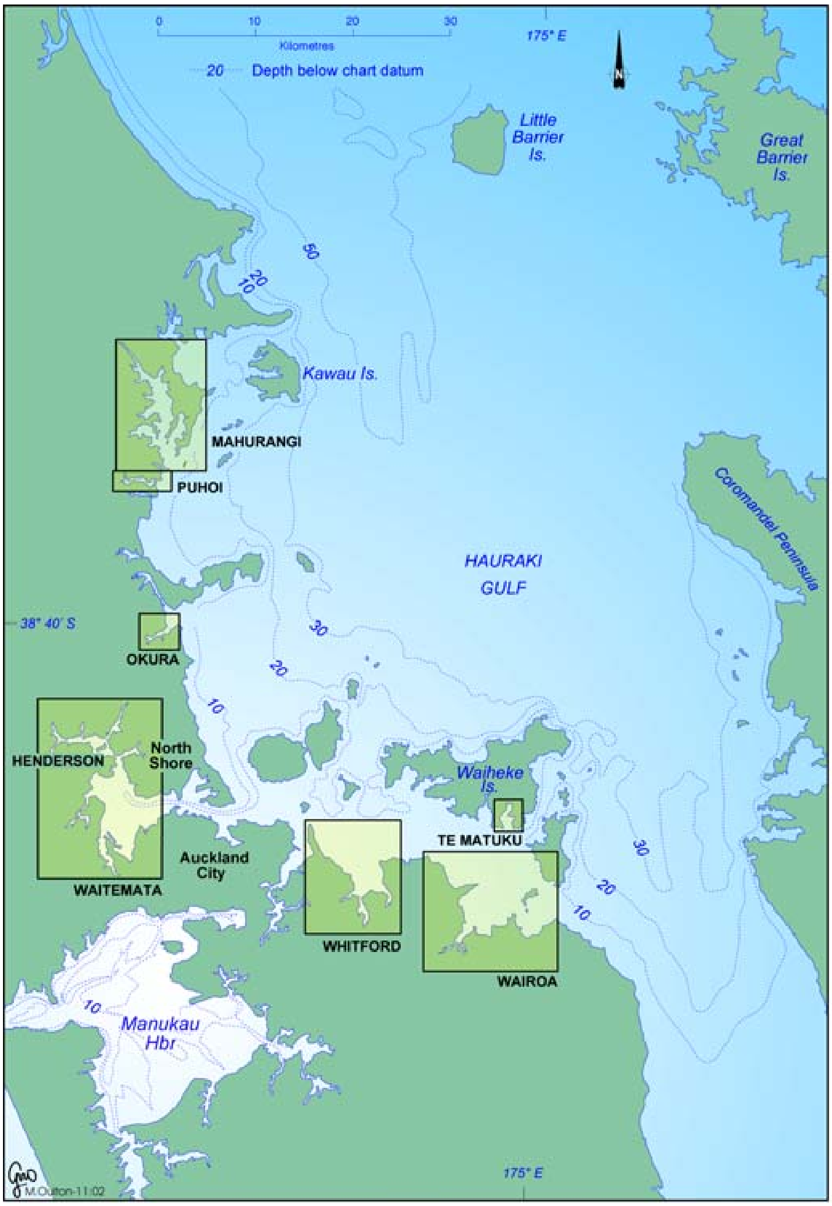
Photo set 1:

Rare catastrophic deposition of terrigenous sediment on A) a seagrass bed and B) a cockle bed after a storm. C) More common sublethal terrigenous sediment deposition on sandflats after light rain in a disturbed catchment.



The effects of terrigenous sedimentation on benthic macrofaunal communities and the recovery from sublethal to catastrophic events has been the subject of much research, both FRST funded and commissioned by the Auckland Regional Council. In particular, the Auckland Regional Council has commissioned a series of studies to determine the risk that the urban development process poses to the receiving environment of the Whitford Embayment and other estuaries in the Auckland region (Fig. 2).

Figure 2:
Auckland estuaries selected for the regional sedimentation study.



Specifically for Whitford, the studies used a multifaceted approach:

- Catchment modelling was used to determine the potential for sediment entry into the three estuaries entering the embayment.
- Hydrodynamic modelling was used to investigate dispersal within and through the system, concentrating on potential areas for increases in sediment deposition and suspended sediment concentrations.
- Studies of mangrove and salt marsh communities of the estuaries and fringing environment of the larger embayment determined their sensitivity to increased deposition and the effect they have on depositional patterns.
- Laboratory and field experiments determined macrofaunal species, communities and habitats sensitive to sediment deposition.
- Laboratory and field experiments also determined the potential for sublethal effects of increased suspended sediment concentrations on the macrofauna.

2.2 What is terrigenous sediment?

In many of the recent studies, terrigenous sediment manipulation experiments have been performed *in situ* on intertidal and subtidal zones while others have been laboratory based studies. In the reports produced for the Auckland Regional Council, the term "terrigenous sediment" has been used synonymously with "clay". There is a technical difference but this does not detract from the studies conducted. In all cases the intention is to describe or report the impact of locally sourced terrigenous sediment on the marine environment.

Terrigenous sediment is derived from the land through erosion and, in the Auckland region and elsewhere, appears as yellow-orange soil sometimes referred to as "clay". True clay is defined as the size fraction 0-3.9 m and has specific chemical and weathering properties (Text Box).

In practice, the Auckland "clay" is somewhat coarser material with the majority falling in the silt and very fine sand range (Table 1). It is often very much finer sediment than the ambient sediments from sandy and shelly intertidal zones. However, it has less clay content than the mudflat sediments. These distinctions become important when assessing the impact of terrigenous sediment on the various habitats studied.

Another important consideration is the change in chemistry associated with newly deposited terrigenous sediment in the marine environment. Clay can cause a lowering of pH in seawater due to the ion exchange properties (Text Box) — consequently, the impacted zone may become acidic until neutralised by the seawater. This introduces the possibility that part of the impact by terrigenous sediment may be toxicity rather than just a physical effect.

Text Box: Clay weathering and ion exchange

Clay minerals are crystalline solids, typically less than 1 µm in diameter and are generally produced by terrestrial weathering of igneous rocks (such as basalt or granite). Clays are composed of layered sheets of aluminium silicate, in which oxygen atoms surround a central silicon atom. The four most abundant clay types (illite, kaolinite, montmorrillonite and chlorite) differ in the number and layering of these sheets. The exterior surfaces of these aluminium silicate sheets possess a small negative charge, due to the electronegativity of the peripheral oxygen atoms. The overall effect is a negative surface charge of the clay mineral, which causes it to attract and adsorb cations, primarily hydrogen, alkali, and earth alkali metal ions. The degree to which a specific clay mineral can bind or exchange cations with its surroundings depends on the relative ion concentrations, the ability of a particular ion to compete for an adsorption site and the cation exchange capacity (CEC) of the clay mineral. For example, montmorillonite and illite have very high CECs, whereas kaolinite and glauconite have lower ones. New Zealand brown soils, which are also found around the Whitford/Howick area, commonly contain substantial percentages of illite (mica) and montmorillonite (vermiculite), although kaolinitic components often predominate. (Hewitt 1998; Rijkse and Hewitt 1995; Soil Bureau 1968).

During chemical weathering, hydrogen and hydroxide ions in interstitial water react with the rocks' crystalline lattice, resulting in breakage of some cation-oxygen bonds. This hydrolysis reaction is greatly accelerated in the presence of acids (such as present in rainwater) and can lead to a significant adsorption of hydrogen ions by the clay matrix. When the clay comes into contact with river water (whose cation content is higher than that of rainwater), incorporation of cations (K+, Ca2+, and trace metal ions) and exchange with hydrogen ions (H+) can occur.

Upon delivery to the estuary, clay minerals react with seawater. Most cation exchange occurs in estuaries, due to the large difference in cation concentrations between river and seawater. As river borne clay materials enter seawater, adsorbed potassium and calcium are displaced by sodium and magnesium, because the Na+/K+ and Mg2+/Ca2+ ratios are higher in seawater than in river water. If the clay reacts directly with seawater, Na+ and Ca2+ can directly replace H+. Release of hydrogen ions, if remaining unbuffered, can exert toxic effects on organisms living in it.

Table 1:

Physical and biogeochemical characteristics of four sediment types compared with terrigenous sediment (TS) at Whitford. Particle size distribution of sediments is given as mean % volumetric composition (± 1 S.E.).

Habitat / Sediment type	Cockle bed	Shell bed	Sandflat	Mudflat	TS
Clay (0-3.9 µm)	2.8 (1.0)	2.2 (0.8)	1.5 (0.7)	23.0 (1.6)	12.1
Silt (3.9-63 µm)	0.1 (0.0)	0.3 (0.1)	0.1 (0.1)	0.8 (0.2)	66.0
Fine sand (63-250 µm)	95.6 (1.2)	86.7 (1.0)	98.2 (0.8)	75.9 (1.6)	19.9
Medium sand (250-500 µm)	0.3 (0.1)	7.8 (0.8)	0.0 (0.0)	0.2 (0.1)	2.0
Coarse sand (500-2000 µm)	0.4 (0.1)	0.7 (0.1)	0.0 (0.0)	0.0 (0.0)	0.0
Gravel (>2000 µm)	0.8 (0.1)	2.2 (0.7)	0.0 (0.0)	0.0 (0.0)	0.0

3 Effects of sedimentation

3.1 Suspended sediments

Terrigenous sediment normally enters the coastal waters as a suspension via estuaries following erosion of a disturbed catchment during rain. Consequently, the first impact on the benthic communities is an increase in turbidity or suspended sediment concentrations. Typically, increased turbidity reduces light penetration into the water column impacting primary production of pelagic phytoplankton and benthic microphytes (algae that live in or on the sediments) and thus reducing a key food component to suspension feeders, herbivorous benthic grazers and deposit feeders.

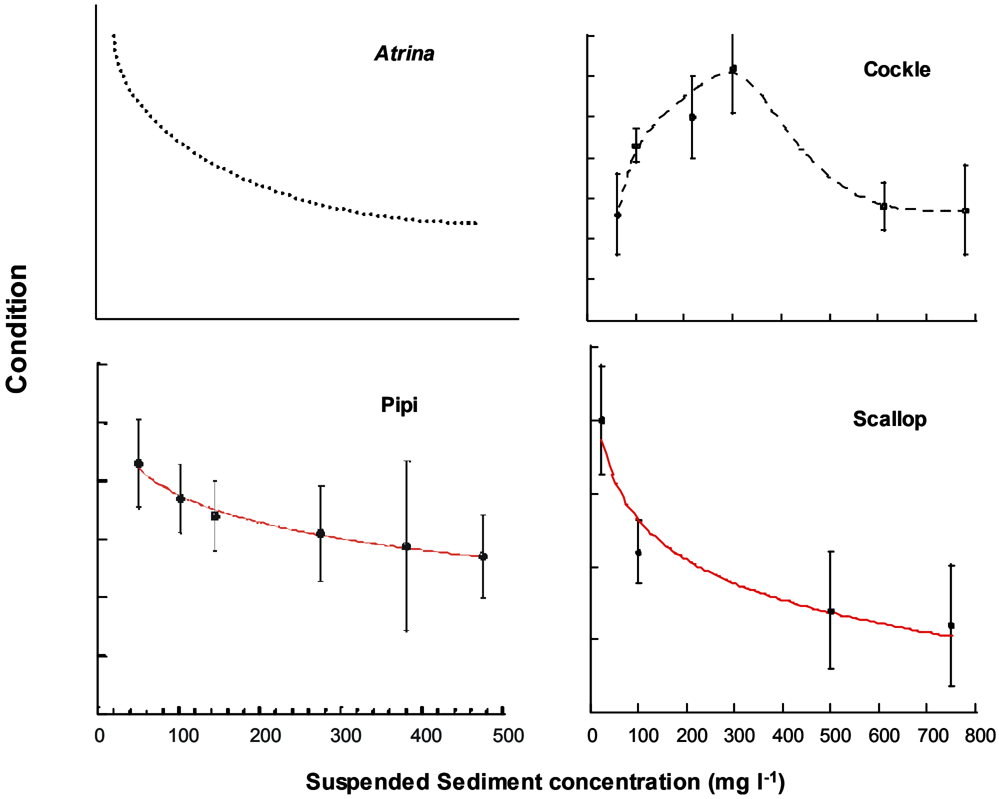
Suspended sediment work includes:

- Horse mussel (*Atrina zelandica*) condition (Mahurangi).
- *Atrina* feeding (Mahurangi, Kawau and Tauranga).
- Cockle (*Austrovenus stutchburyi*) feeding and condition (Whitford, Okura).
- Pipi (*Paphies australis*) feeding and condition (Whitford, Tauranga).
- Scallop (*Pecten novaezelandiae*) feeding and condition (Kawau).
- Non-suspension feeders (*Macomona*, *Echinocardium*, *Zeacumantus*, *Boccardia*).
- Sediment, nutrient and oxygen fluxes (Mahurangi and Kawau Bay).

NIWA studies have investigated the effects of increased suspended solids on suspension feeders *in situ* and using laboratory studies (Hewitt et al. 2001; 2003; Hewitt & Pilditch 2004). Early studies in Mahurangi Harbour indicated that populations of the large epibenthic pinnid bivalve, *Atrina zelandica*, were declining and suggested that their habitat was limited by turbidity (Ellis et al. 2002). Hewitt and Pilditch (2004) found that *Atrina* were sensitive to suspended sediments and exhibited high rejection of filtered particles (mostly 75 – 100 %) but high organic absorption efficiencies (0.9 – 1) at all suspended sediment levels. Although the studies showed variable site-specific feeding responses of *Atrina* to suspended sediment concentrations, the results consistently indicate that *Atrina* experience increasing stress to increasing suspended sediment concentrations. This would be translated into a reduction in suitable habitat as suspended sediment concentrations increase in Mahurangi Harbour.

Adult cockles, pipis, and scallops all exhibited the ability to continue feeding in high levels of suspended sediment over the short-term (< 1 week) but their condition was adversely affected by high suspended sediment concentrations occurring for long time periods. Cockles had difficulties coping with suspended sediment concentrations higher than 400 mg l^{-1} over long periods. For scallops, variation in clearance rates suggested that suspended sediment concentrations higher than 100 mg l^{-1} affected their ability to process the particles (Nicholls et al. 2003) (Fig. 3). The type of suspended sediment was also important, for example, suspended terrigenous sediment affected cockles more than resuspended marine sediment.

Figure 3:
Change in the condition of four suspension feeding bivalves relative to increasing concentrations of terrigenous suspended sediment.



Growth rates of juvenile cockles and adult reproductive status of cockles and pipis in the field (8 sites in the Whitford Embayment) were adversely affected by high suspended sediment concentrations.

Some non-suspension feeders were also adversely affected by increasing levels of terrigenous suspended sediments while others were not. The herbivorous gastropod, *Zeacumantus lutulentus*, that can be found in high densities in the surface layers of intertidal sand and mud flats throughout the Auckland region, showed no direct effects to increasing suspended solids. However, if the reduction in light associated with increased suspended solids reduced primary production by benthic microphytes, this should reduce the available food supply to *Zeacumantus*.

The heart urchin, *Echinocardium australe,* a large burrowing deposit feeder common in the subtidal zone in both sandy and muddy subtidal habitats, was adversely affected after 3 days at suspended solids concentrations above 80 mg l^{-1}. Burial times and death rates in *Echinocardium* increased with increasing exposure to suspended sediment. While it is unlikely that deaths occurred directly from the suspended sediments, sub-lethally stressed animals remaining on the sediment surface are more vulnerable to predators (Lohrer et al. 2003).

The deposit-feeding polychaete, *Boccardia syrtis*, which lives in tubes that protrude from the sediment surface in intertidal and subtidal habitats, was also adversely affected at suspended solids concentrations above 80 mg l^{-1} but after 9 days. Feeding rates for *Boccardia* decreased over time, with the largest decreases occurring in treatments with the highest suspended sediment concentrations (750 mg l^{-1}). Nicholls et al. (2000) found that *Boccardia* were also highly sensitive to terrigenous sediment deposition.

The wedge shell, *Macomona liliana*, a common inhabitant of soft sediments, and often a numerically- dominant species in sandy to muddy-sand areas, was adversely affected at suspended sediments concentrations above 300 mg l^{-1} after 9 days. After 14 days of exposure to the highest suspended sediment concentrations, most of the *Macomona* had died or were lying exposed on the surface of the sediment.

Increasing concentrations of terrigenous suspended sediment influences the sediment-water flux rates of sediment, nutrients and oxygen. Suspended sediments consume oxygen from the water column due to biochemical oxygen demand and microbial processes in the water column. As suspended sediment concentrations increase, sedimentation increases and this has a smothering impact on the sea floor altering the biogeochemistry. This process can be enhanced by suspension feeders which produce bio deposits (including pseudofaeces) and increase nutrient supply through excretion of ammoniacal nitrogen (NH_4-N). The fine material reduces the exchange of water across the sediment water interface so that oxygen depletion occurs in the sediment below the terrigenous deposit. This causes a change in the diffusion of nutrients out of the sediments and allows higher concentrations of ammoniacal nitrogen (NH_4-N) to accumulate in the near-surface sediments. The reduction of nutrient supply directly influences pelagic and benthic primary production.

3.2 Sedimentation

Terrigenous sediment carried by the freshwater inflow through an estuary is initially held in the less dense freshwater layer until the freshwater mixes and disperses into the coastal waters. There are a number of geochemical changes that occur during this process including flocculation and aggregation of the fine particles which induces sedimentation. When this occurs on a ebbing tide, the terrigenous sediment is carried rapidly out of the estuary to become a subtidal deposit (Gibbs et al. (2001) where it is not seen. However, on a flooding tide, the deposition is most likely to occur on the sand and mudflats intertidal zone where it is highly visible. The thickness of the deposited layer and the period it remains on the intertidal sediments determines the impact on the benthic community.

NIWA studies to date include:

- Thin depositions (3-7 mm) in Mahurangi and Kawau Bay on macrofauna, nitrogen and oxygen fluxes: subtidal.
- Catastrophic depositions (>3 cm) in Okura and Whangapoua on macrofauna: intertidal.
- Thinner depositions (1.5 - 2 cm) in Whitianga on macrofauna: intertidal.

- Thin depositions (1 – 7 mm) in Whitford on macrofauna, mangroves, and salt marsh, and nutrient and oxygen fluxes: intertidal.
- Laboratory studies on individual taxa from Okura, Whitford, Mahurangi and Kawau Bay.
- Monitoring of Okura during a period of motorway development.

3.2.1 Subtidal

Terrigenous sediment can impact the benthic community by settling on the sea floor and forming a blanketing layer that alters the sediment structure (Lohrer et al. 2003). Underwater, the sediment does not form a hard layer but produces an amorphous ooze through which the benthic macrofauna must burrow to survive. Benthic microphytes trapped beneath the terrigenous sediment die.

The experiment at a coastal and a harbour site at Mahurangi (Lohrer et al. 2003) used a range of animals to determine the immediate and longer-term impacts of subtidal sediment deposition. Infaunal and epifaunal responses were measured. In particular, three highly visible sedentary epifauna were studied. The horse mussel, *Atrina zelandica*, had already been shown to be sensitive to increased suspended sediment levels at the seabed which may interrupt feeding and respiration by clogging gill structures. Two other filter feeders were also used; golf ball sponges (*Aaptos spp.*), and the solitary ascidian *Styela plicata*. While bivalves can close their shells and isolate their tissues from environmental challenges, other phyla may be more susceptible to the effects of sediment deposition

Immediately after the deposition of sediment, *Atrina* and *Styela* were siphoning 'normally'. Some large mobile organisms escaped from the plots, while others could not. The tracks from hermit crabs and sea stars were not well defined; small bow waves preceded these animals as they moved and the slurry was too fluid to stay in place after displacement. A sizeable shrimp was observed at the surface of one plot, outside its burrow, mired in the deposit. A juvenile scallop (*Pecten novaezelandiae*) and another small free-swimming bivalve (*Limidae?)* were also observed at the surface of coastal plots. Burrow cleaning was evident, the burrows probably occupied by fan worms, crabs, shrimps, and/or infaunal bivalves.

The adverse effects of the terrigenous sediment deposition began to appear over time. *Atrina* and *Styela* were able to shed the initial deposit of clay, but *Aaptos* could not. The feeding rates of both *Atrina* and *Aaptos* were significantly affected by the sediment deposition, and the condition of these three animals deteriorated. The condition of sponges was difficult to assess visually, but all sponges (transplanted and naturally occurring) survived the initial deposition event and until collection 21 days later. The decrease in condition of sediment-treated animals (over three weeks) was apparently related to their feeding capabilities. Both *Atrina* and *Aaptos*, when placed in clean seawater (no sediments added), were unable to feed efficiently.

The ability of polychaete worms and shrimps to move up through the terrigenous sediment decreased with increasing terrigenous sediment deposit thickness, with a threshold level of about 3 mm. Substantial numbers of heart urchins were found dead on the sediment surface. Heart urchins are slow moving and respire through small ventilation shafts created in the sediment column. It is likely that the terrigenous deposit interfered with the construction of these shafts and drove them to the surface for oxygen, where they fell prey to opportunistic predators such as sea stars and snappers. Carnivorous gastropods were observed scavenging the tissues of dead heart urchins and the occasional bivalve.

There was a difference between the responses at the coastal and harbour sites with the harbour site animals apparently less sensitive to the terrigenous sediment. It is postulated that this may reflect an established tolerance to chronic terrigenous sedimentation in Mahurangi Harbour but not in the clean seawater outside the harbour. It is also possible that chronic terrigenous material loading and pulsed depositional events associated with land use change around Mahurangi Harbour may have reduced or eliminated the most sensitive taxa in the harbour prior to the experimental work, making the present day communities seem more tolerant of such disturbances. This can be a natural process and does not necessarily invoke any arguments of human degradation.

3.2.2 Intertidal sedimentation

3.2.2.1 Catastrophic depositions

Catastrophic deposition events are rare and cause sudden changes. The results of the NIWA catastrophic sedimentation studies showed that:

- In the Okura experiment, within 10 days, nearly all the macrofauna in the clay/silt treatments had died. Based on laboratory and field experiment results we can define the critical burial depth as 2-3 cm.
- Okura monitoring showed that deposition of terrestrial sediment 1-2cm thick lasting > 7 days can adversely affect macrofauna.
- At Whangapoua, all macrofauna under the deposits were dead after 8 days. Terrestrial sediments have consistently lower levels of NH_4-N and chlorophyll, and higher levels of organics, fine particles and shear strength.
- There was consistently slow recovery of plots from catastrophic deposition lasting up to 2 years in estuaries, although a single storm event could bury the terrigenous sediment in a coastal situation.
- Laboratory experiments found high mortality of the polychaetes, Glycerids, Nereids, Spionids, Orbinids and the mud snail *Amphibola crenata*. Adult bivalves such as pipis, *Macomona liliana*, *Nucula hartvigiana* and cockles showed stress after 24, 72, and 144 hrs, but the mud crab *Helice crassa* and the snapping shrimp *Alpheus* were unaffected.
- Thick deposits of terrigenous sediment also adversely affected mangroves by covering their pneumatophores and blocking oxygenation of their roots.

These studies show that long-lasting thick layers of terrigenous sediment defaunate the intertidal zones and the recovery process is slow. Unlike the subtidal deposition where the terrigenous sediment remains partially fluid for some time after deposition, thick layers of terrigenous sediment on the intertidal zone become dewatered during the emersion phase of the tide. In hot weather the sediment becomes hard and impervious to small macrofauna. Large crabs can burrow through terrigenous sediment layers up to 9 cm thick and are the first to colonise a new deposit. This burrowing action helps breakdown the terrigenous sediment deposit by mixing it with the natural sediments from below. Wave action, especially as the deposit becomes immersed on each tidal cycle erodes the terrigenous sediment and continues the breakdown and burial process.

3.2.2.2 Non-catastrophic deposition

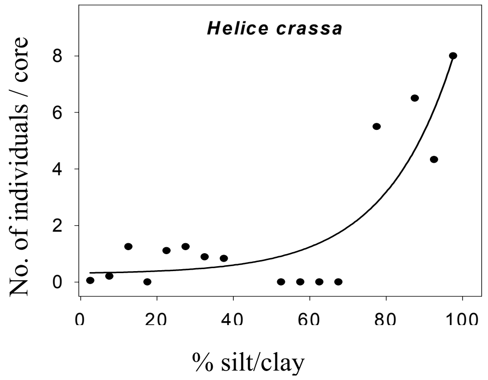
Non-catastrophic events are more common and may cause minimal changes. The results of the NIWA non-catastrophic sedimentation studies showed that:

- At Whitianga, differences in the sediment properties lasted about 50 days, and effects varied between sites. Deposition of ~2 cm of sediment had an immediate negative effect on macrofauna, recovery of which lagged behind the recovery of the sediment properties. Recovery of sediment properties occurred after 50 days, while effects were still observed for some species after 210 days.
- At Whitford, thin deposits (3–7 mm) had a negative impact on communities and affected microphytes. Response of communities and sediment properties varied with habitat. Repeated additions of 3 mm over a 6-month period had a cumulative effect.
- At Whitford, thin layers of sediment are likely to aide the spread of mangroves but did not appear to affect the salt marsh meadows.
- Laboratory studies on *Amphibola, Aonides, Nucula, Atrina, Aaptos* and *Styela* showed stress caused by thin layers, while cockles, Fellaster (sand dollar), Oligochaetes and Orbinids were unaffected.

Sub-lethal, non-catastrophic events are the most likely occurrence of terrigenous sedimentation on the intertidal zones. However, while the sediments are unlikely to be defaunated, they can undergo subtle changes which may be cumulative and ultimately alter the structure of the benthic communities impacted. The results obtained at Whitford indicate that mat-forming benthic microphytes are likely to die beneath even a very thin terrigenous sediment deposit in the finer sediments while the terrigenous sediment may stabilise coarser sands against movement by wave action allowing other benthic microphyte species to thrive.

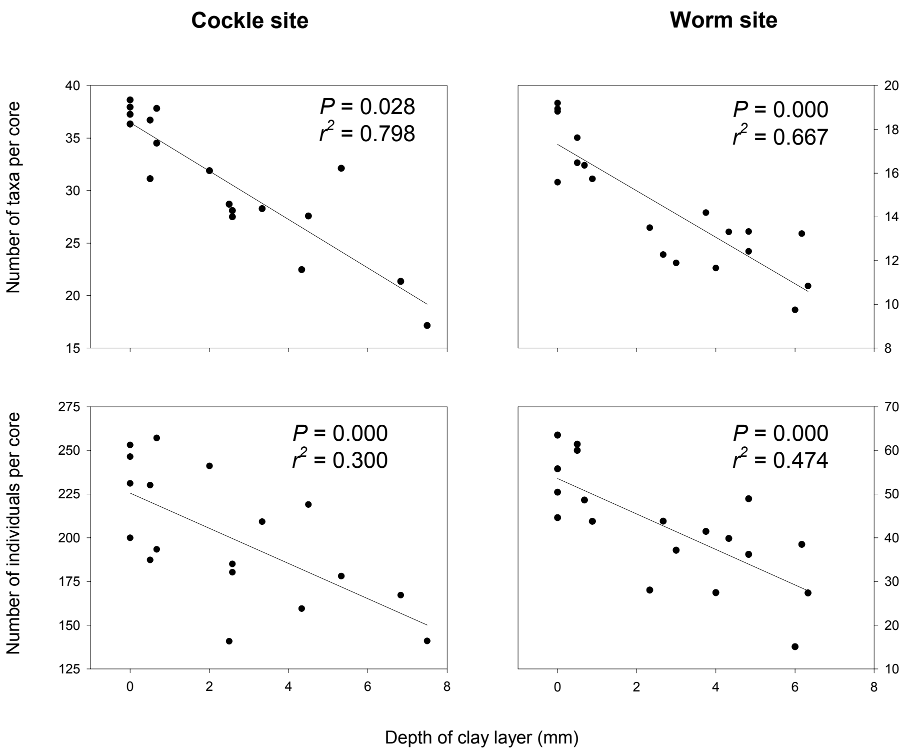
In contrast, macrofauna generally survive unaffected although the thin deposit experiments demonstrated negative impacts on most taxa with terrigenous sediment deposits of >3 mm. The exception was *Helice* which is highly tolerant to silt/clay environments (Fig. 4). Although cockles could selectively reject organic detritus to feed on pelagic phytoplankton, they were unable to reject the fine terrigenous sediment particles in the same size range as the phytoplankton and thus lost condition.

Figure 4:
Examples of strong positive effect on populations of the mud crab, *Helice crassa,* to increasing silt/clay content of the sediment.



While thick layers of terrigenous sediment blocked oxygen and nutrient transfer through the sediment deposit, thin terrigenous sediment layers were more permeable to water and gaseous exchange allowing the benthic macrofauna to remain in their sediment habitats during the recovery process albeit at lower numbers (Figs. 5, 6).

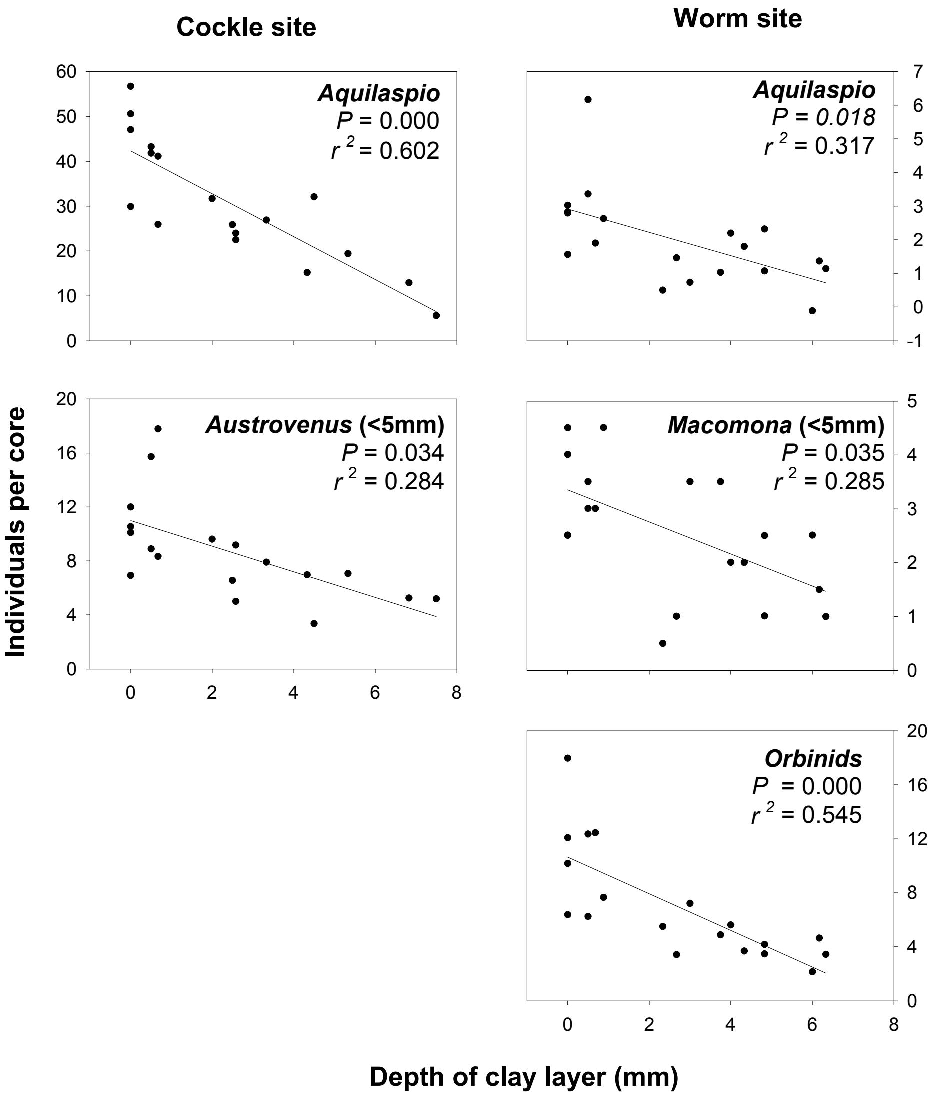
Figure 5:
Relationship between the number of taxa and individuals and clay depth (mm) at the Cockle and Worm sites at the end of the experiment. Note the different scales (on the y-axis) used at each site.



Whereas benthic communities may quickly recover from a single deposition event, a succession of deposition events at shorter intervals than the recovery time can result in cumulative effects that can cause the habitat and the benthic community to change.

Figure 6:

Relationship between individual common taxa and clay depth (mm) at the Cockle and Worm sites at the end of the experiment. Note the different scales (on the y-axis) used at each site.



4 Changes in habitat

Predicting ecological consequences of changes in habitat driven by sedimentation is more complex than just conducting the studies mentioned in the previous sections. It requires incorporating those results with a number of different approaches. These approaches range from monitoring actual changes to spatial surveys of community and species preferences at a number of scales. A number of studies have been conducted to help us predict ecological changes that might accompany increased mud habitats:

- Stable isotope tracking of sediment movement.
- Potential effects of geological-scale and medium-scale sedimentation patterns on communities- conducted in Mahurangi, Okura, Waitemata, Wairoa, Puhoi, Whitford, and Te Matuku – Waiheke Island.
- Long-term monitoring in Mahurangi.
- Mangrove progradation.
- Seagrass as a habitat in the estuary.
- Whitford habitat survey.
- Relationship between % mud content of sediment and macrofaunal species in 19 estuaries.
- Models of habitat disturbance.

These studies have looked at sedimentation patterns, long term changes and predicting the effects of changes in habitats.

4.1 Sedimentation patterns

Sedimentation patterns can be studied using a number of different tracers. Swales et al. (2003) uses pollen, caesium-137 (^{137}Cs), lead-210 (^{210}Pb), Zinc (Zn) and sediment particle size to determine sediment accumulation rates (SAR) in mudflats mainly over time periods greater than 25 years. Gibbs et al. (2001) used stable isotope techniques to track the movement of terrestrial sediments throughout the Whitford Embayment. The work suggested that stable isotopes may be a valid technique for estimating the % terrigenous clay in estuarine sediments. Determination of recent events was beyond the scope of the study, but would be possible if very thin surface layers only of sediment were analysed.

4.1.1 Effects of geological scale and medium-scale sedimentation patterns on communities

Although muddy areas are generally thought of as being of low diversity, this is not necessarily the case. A study of intertidal and subtidal muddy sites in a number of different estuary types (drowned river valleys, tidal lagoons and coastal embayments Swales et al. 2002) found a range of community types in Auckland estuaries, with diversity and community type responding to rates of sediment accumulation (Lundquist et al. 2003). All three types of estuaries studied were comprised of diverse, variable communities at early stages of estuarine infilling (corresponding to low or natural rates of sediment accumulation). The three types of estuaries then appeared to converge to a similar low diversity, stress-tolerant community as sediment accumulation rates increase and estuaries became infilled.

4.2 Long term changes

Long-term monitoring of Mahurangi harbour carried out for the ARC has recently noted trends in the abundance of several species consistent with increased sediment accumulation rates (Cummings et al. 2003). The amount of fine sand increased at all sites sometime between April 1996 and April 1997. However, instead of a 'pulse' response by macrofauna, gradual declining or increasing trends have been observed. Changes in *Atrina* abundance at the subtidal sites occurred prior to this time, but work by Ellis et al. (2002) and Hewitt and Pilditch (2004), suggest this species is particularly sensitive.

Changes in fringing vegetation, particularly mangroves, and the distributions of seagrass beds are often associated with increased sedimentation. Mangrove progradation has been observed in many Auckland estuaries (De Lange & de Lange 1994, Morrisey et al. 1999), although it is not always clear whether the progradation is driven by increased sedimentation or causes the increased sedimentation. Regardless, Ellis et al. (2004) observed decreased diversity of macrofauna inside mangrove areas versus the mudflats surrounding mangroves and this decrease was more apparent in older stands of mangroves.

Highly turbid water can restrict light transmission influencing primary production and the relative importance of water column versus benthic flora. Seaweeds and seagrasses typically require more sunlight for photosynthesis than phytoplankton; this, combined with their constraint of being attached to the seabed, makes them particularly susceptible to elevated suspended sediment concentrations. While it is recognised that increased turbidity leads to decreased seagrass habitat, the effect of *Zostera* (New Zealand's major seagrass genus) habitat on macrofauna is inconsistent between studies with communities being more similar at a site within and outside a *Zostera* patch than among sites in the same estuary (Turner et al. 2000, Hewitt et al. 2003).

4.3 Predicting the effects of changes in habitats

Large-scale spatial surveys enable us to relate ecological variables to environmental factors so that models of species responses to increased muddiness can be made. Two surveys conducted by NIWA, one for the ARC and one under FRST funding contain particularly useful findings.

4.3.1 Whitford habitat survey

Amongst the 38 taxa selected for sensitivity assessments by Norkko et al. (2001), there was large variability in the distribution patterns in relation to the silt/clay content of the sediment. For example, low abundances of cockles were found in sediments containing up to 60% silt/clay in the sediment but their highest abundances were found in sediments containing less than 10% silt/clay. Similarly, the mud crab *Helice* is found in different sediment types but occur in highest numbers in sediments containing high silt clay (e.g., > 90%; Fig. 4). In contrast some taxa, such as nereid polychaetes, have very broad distribution ranges. To create sensitivity curves or make predictions on such taxa is very difficult as their distribution is variable and not easily modeled statistically (Fig. 4).

Norkko et al. (2001) present an overall compilation of species sensitivity based on their peak abundance, and their range of distribution across different sediment types (Table 3). Of all the 38 taxa assessed, 26 were found to prefer sandy sites, 5 were found to be intermediate and 7 were found to prefer higher mud content of the sediment.

Table 3:

Table adapted from Norkko et al. (2001). Response of macrobiotic taxa to increasing mud content. Optimum range = the percent mud where taxa exhibit their highest abundances. Disturb. range = total range of occurrence over different mud concentrations. *SS* = strong sand preference; *S* = sand preference, *I* = prefers some mud but not high percentages; *M* = mud preference; *MM* = strong mud preference.

Taxa	Faunal group	Optimum range (%)	Disturb range (%)	Sensitivity
Aonides oxycephala	Polychaete	0 - 5	0 - 5	SS
Travisia olens	Plicate	0 - 5	0 - 5	SS
Paphies australis	Bivalve	0 - 5	0 - 5	SS
?Waitangi sp. off. W. chelatus	Amphipod	0 - 5	0 - 5	SS
Notoacmea helmsi	Gastropod	0 - 5	0 -10	SS
Cominella glandiformis	Gastropod	5 - 10	0 - 10	SS
Anthopleura aureoradiata	Anemone	5 - 10	0 - 15	SS
Diloma subrostrata	Gastropod	5 - 10	0 - 15	SS
Macomona liliana	Bivalve	0 - 5	0 - 40	S
Orbinia papillosa	Polychaete	5 - 10	0 - 40	S
Colurostylis lemurum	Cumacean	0 - 5	0 - 60	S
Boccardia syrtis	Polychaete	10 - 15	0 - 50	S
Nucula harvigiana	Bivalve	0 - 5	0 - 60	S
Scoloplos cylindrifer	Polychaete	0 - 5	0 - 60	S
Austrovenus stutchburyi	Bivalve	5 - 10	0 - 60	S
Syllid	Polychaete	25 - 30	0 - 40	S
Waipirophoxus waipiro	Amphipod	0 - 5	0 - 70	S
Macroclymenella stewartensis	Polychaete	10 - 15	0 - 60	S
Paracalliope ?novizealandiae	Amphipod	35 - 40	0 - 50	S
Goniada emerita	Polychaete	50 - 55	0 - 60	S
Cirratulid	Polychaete	10 - 15	5 - 70	S
Aricidea sp.	Polychaete	35 - 40	0 - 70	S
Arthritica bifurca	Bivalve	55 - 60	5 - 70	S
Cossura sp.	Polychaete	20 - 25	5 - 65	S
Musculista senhousia	Bivalve	55 - 60	0 - 60	S
Tanaid	Crustacean	10 - 15	0 - 100	S
Glycerid	Polychaete	10 - 15	0 - 95	I
Heteromastus filiformis	Polychaete	10 - 15	0 - 95	I
Aquilaspio aucklandica	Polychaete	65 - 70	0 - 95	I
Nemertina	Nemertean	55 - 60	0 - 95	I
Macropthalmus hirtipes	Crab	45 - 50	0 - 95	I
Lumbrinereid	Polychaete	30 - 35	0 - 65	M
Theora lubrica	Bivalve	45 - 50	5 - 65	M
Nereid	Polychaete	55 - 60	0 - 100	M
Oligocheate	Oligochaeta	95 - 100	0 - 100	MM
Scolecolepides sp.	Polychaete	25 - 30	0 - 100	MM
Helice crassa	Crab	95 - 100	5 - 100	MM
Paracorophium excavatum	Amphipod	95 - 100	40 - 100	MM

4.3.2 Nineteen estuary survey

To enable forecasting of the response of macrofaunal species to long-term changes in sediment type, Thrush et al. (2003) developed a novel strategy to rapidly collect data on macrofaunal densities and sediment characteristics by sampling mud-to-sand transition zones. One such zone was sampled in each of nineteen estuaries, the locations of which cover much of the North Island. Species-specific models that predict probability of occurrence relative to sediment mud content were developed for thirteen common macrofaunal species. However, the roles played by many macrofaunal species are influenced by density, not just occurrence. Over broad spatial scales, the constraint an environmental variable places on density can be represented by the upper (or lower) limit on density. Thus, the distribution of maximum density along the gradient from mud to sand was also modelled. The models developed for the different species exhibited a wide variety of functional forms highlighting the potential variation in response to habitat change even from closely related species with similar natural history characteristics (Table 4).

Table 4:

Summary of density responses observed to increased mud content from 19 North Island estuaries of 13 macrofaunal species (Thrush et al. 2004a). *SS* = strong sand preference; *S* = sand preference, *I* = prefers some mud but not high percentages; *M* = mud preference; *MM* = strong mud preference

Preference	Faunal group	Taxa	Optimum range (%)	Distrib range (%)
MM	Decapod	*Helice crassa*	80	0-80
SS	Anenome	*Anthopleura aureoradiata*	0 - 5	0-40
S	Polychaete	*Aonides oxycephala*	0-5	0-80
S	Polychaete	*Scoloplos cylindrifer*	0-5	0-60
S	Bivalve	*Macomona liliana*	0-30	0-75
S	Bivalve	*Austrovenus stutchburyi*	0-10	0-85
S	Bivalve	*Nucula harvigiana*	0-5	0-60
I	Bivalve	*Arthritica bifurca*	20-40	0-75
I	Polychaete	*Aquilaspio aucklandica*	20-50	0-85
I	Polychaete	*Boccardia syrtis*	15-35	0-50
I	Polychaete	*Heteromastus filiformis*	20-40	0-80
I	Polychaete	*Scolecolepides benhami*	20-30	0-85
I	Polychaete	*Nicon aestuariensis*	35 – 55	0 - 80

Apparent differences between Tables 3 and 4 are likely to be due the restricted locations summarised in Table 3. Major differences are discussed in section 4.1 and summarised in Tables 5 and 6.

5 Relevance to resource management

5.1 Approaches

Documenting real effects on ecosystems and assessing how changes are likely to influence biodiversity and ecosystem values are key elements of ecological science, but once the magnitude and scope of a particular problem has been identified, it is also important that scientists provide information to help managers minimize risk and reduce threats. Estuaries are often areas of intensive and diverse human use, emphasizing the need for high quality information and open decision making to facilitate effective environmental management. Important applications of ecological knowledge relate to defining threshold effects, prioritizing actions, and forecasting ecological responses.

An approach used to provide information on the magnitude and scope of likely sedimentation effects in estuaries that has been used successfully by the ARC is a combination of modeling, surveying and experimentation. Experiments on effects of terrestrial sediment deposits on macrobenthic communities in different habitats are combined with models of sediment runoff from the catchment and particle dispersal models within the estuary, to assess the relative ecological risk to different estuarine habitats under different development scenarios. These risk assessments allow managers to contrast the threats posed by various scenarios of land development and thus improve decision-making.

Another approach is the use of statistical models that relate ecological variables to environmental factors enabling forecasts of species responses to increased muddiness or changes in the relative proportion of habitats to be made. This approach assumes that the relationships apparent in the observed spatial patterns match those that will occur over time. Such models take a top-down view of ecological systems and seek to identify general patterns and reveal species with different sensitivities to habitat change.

A third approach is to use species that are sensitive to increased sedimentation. Such species can be identified both by experiments and the models developed from surveys. These species, once identified, can be used in a variety of ways. Large sedentary species, such as *Atrina*, can be transplanted and their growth, health and mortality measured. Even non-sedentary species that are reasonably robust can be used in such a way. This has been done successfully for *Atrina*, *Austrovenus, Aaptos* and *Paphies* (Ellis et al. 2002, Hewitt et al. 2001, Lohrer et al. 2003). Monitoring programmes can use changes in the abundance of species identified as sensitive to indicate whether observed changes are consistent with increased sedimentation (Cummings et al. 2003). The sensitivity of species, the relative changes observed in different species and the number of species exhibiting changes are all ways of building a picture of the potential cause and its magnitude.

The work that has been done on the effects of increased sedimentation rates, suspended sediment concentrations and mud content can be summarized to produce a list of sensitive species. Table 5 presents a list of species that have provided consistent responses across a range of studies, together with their likely value to ecology. Generally, most species provided consistent responses across studies, except for two *Nucula hartvigiana* and *Orbinia papillosa*. *Nucula* is mobile and capable of fast recolonization. Interactions between its dispersal and scale of the studies might have prevented consistent responses being observed. The response of *Orbinia* was consistent across all field studies (surveys and experiments) and was only non-detectable in one laboratory experiment, so has been included in Table 5, with a footnote. Table 6 presents a list of species for which we only have responses from one study. Due to this, changes in these species need to be supported by changes in species listed in Table 5.

Table 5:

List of taxa sensitive to changes in sedimentation rate and increased %mud content. NB Species listed as Bioturbators are all likely to increase sediment reworking, affect porosity and benthic productivity. Expt = experimental, Distrib range = range of % mud contents taxa observed over. Opt range = range of highest abundance. *SS* = strong sand preference; *S* = sand preference, *I* = prefers some mud but not high percentages; *M* = mud preference; *MM* = strong mud preference. (ID = Insufficient data).

Preference	Faunal group	Taxa	Description	Functional value	# expt studies	#survey studies	Distrib and opt ranges[2]
MM	Amphipod	*Paracorophium excavatum*	Small[3] burrowing scavenger/deposit feeder	Semi-permanent burrows oxygenate the sediment to depth	1	1	40 – 100 95 - 100
M	Decapod	*Alpheus*	Large[4] burrower	Permanent burrows oxygenate the sediment to depth	1	0	
MM	Decapod	*Helice crassa*	Large burrower, grazer or generalist	Semi-permanent burrows oxygenate the sediment to depth	1	2	0 – 100 80 – 100
M	Oligochaete	Oligocheate spp.	Small sub-surface deposit-feeder, free living in sediment to 10 cm	Bioturbator	4	1	0 – 100 95 - 100
SS	Anenome	*Anthopleura aureoradiata*	Small predator	ID	0	2	0 - 40 0 - 10
SS	Asciidian	*Styela plicata*	Large epifaunal suspension feeder	Affects hydrodynamics, stabilises sediment	1	0	

[2] Missing data are species for which laboratory experimental studies only are available.
[3] Small species have adults sized <1cm long and <3mm wide.
[4] Large species have adults sized >2cm long and >8mm wide.

Preference	Faunal group	Taxa	Description	Functional value	# expt studies	#survey studies	Distrib and opt ranges[2]
SS	Bivalve	*Atrina zelandica*	Large epifauna suspension feeder	Affects hydrodynamics, stabilises sediment, increases oxygen and nitrogen fluxes between water and sediment, provides refuge and growth area for other animals, affects infaunal diversity, provides habitat structure for juvenile fish	2	0	
SS	Bivalve	*Paphies australis*	Large surface-dwelling suspension feeder- highly mobile	Important food source for birds and humans	2	1	0 – 5 0 - 5
SS	Bivalve	*Pecten novaezelandiae*	Large surface-dwelling suspension feeder	Important food source for fish and humans	1	0	
SS	Gastropod	*Notoacmea helmsii*	Large, common soft-sediment limpet, grazer; Attaches to cockle shells and Zostera blades	ID	1	1	0 – 10 0 - 5
SS	Polychaete	*Asychis* sp.	Large tube-dwelling, sub-surface, deposit feeder	Key role in re-working and turn-over of sediment- prey item for birds and fish	1	0	
SS	Sponge	*Aaptos* sp.	Large epifaunal suspension feeder	Has the potential in dense patches to affect hydrodynamics, stabilise sediment, and increase oxygen and nitrogen fluxes between water and sediment,	1	0	
S	Amphipod	Lysianassidae	Small surface deposit-feeder	Bioturbator- prey item for fish and birds	1	0	
S	Amphipod	Phoxocephalidae	Small surface deposit-feeder	Bioturbator- prey item for fish and birds	1	0	

Preference	Faunal group	Taxa	Description	Functional value	# expt studies	#survey studies	Distrib and opt ranges[2]
S	Cumacean	*Colurostylis lemurum*	Semi-pelagic detritus feeder	Bioturbator- prey for birds and fish	1	1	0 – 60 0 - 5
S	Echinoderm	*Echinocardium australis*	Large burrowing deposit feeder	Strong bioturbator, affects porosity, increases oxygen penetration and increases nutrients and oxygen fluxes between sediment and water	1	0	
S	Echinoderm	*Fellaster zelandiae*	Large surface-dwelling grazer	Bioturbator, affects benthic productivity	1	0	
S	Gastropod	*Amphibola crenata*	Large surface-dwelling grazer/deposit feeder	Bioturbator, affects benthic productivity, prey item for humans, fish and birds	1	0	
S	Polychaete	*Aonides oxycephala*	Surface deposit-feeder, free living in sediment to 10 cm	Bioturbator- prey item for fish and birds	3	2	0 – 80 0 – 5
S	Polychaete	Exogoninae	Small scavenger/predator, free living in sediment to 10 cm	Bioturbator	1	0	
S	Polychaete	*Scoloplos cylindrifera*	Large sub-surface deposit feeder, free living	Bioturbator, prey item for fish and birds	2	2	0 – 60 0 – 5
S[5]	Bivalve	*Macomona liliana*	Large surface deposit-feeder, sedentary adults live ~ 10 cm depth, highly mobile juveniles.	High densities of adult Macomona affect other macrofauna, affect nitrogen and oxygen fluxes between water and sediment, important prey items for fish and birds.	2	2	0 – 75 0-30[2]

[5] Juveniles have been found to be more sensitive

Preference	Faunal group	Taxa	Description	Functional value	# expt studies	#survey studies	Distrib and opt ranges[2]
I, S[1]	Bivalve	*Austrovenus stutchburyi*	Large, highly mobile, surface suspension-feeder	Important food source for birds, fish, and humans, affect the distribution of predator species, affect nitrogen and oxygen fluxes between water and sediment	4	2	0 – 85 0 – 10
I	Bivalve	*Arthritica bifurca*	Small deposit feeder	ID	2	2	0 – 77 20 – 60[6]
I	Bivalve	*Theora lubrica*	Invasive species, selective deposit feeder	ID	0	2	5 – 65 45 - 50
I	Polychaete	*Aquilaspio (Prionospio) aucklandica*	Surface deposit-feeder, free living in sediment to 3 cm	Bioturbator- prey item for fish and birds	4	2	0 – 95 20 - 70[2]
I	Polychaete	*Scolecolepides benhami*	Large surface deposit-feeder, free living in sediment	Bioturbator- prey item for fish and birds	0	2	0 – 100 20-30
I	Polychaete	*Heteromastus filiformis*	Sub deposit-feeder, free living in sediment to 10 cm	Bioturbator- prey item for fish and birds	3	2	0 – 95 10-40
I	Polychaete	Glyceridae	Highly mobile predator or scavenger	Bioturbator	1	1	0 – 95 10 - 15
I	Polychaete	*Lumbrineris* sp. (*Aeotearia*)	Highly mobile predator or scavenger	Bioturbator	1	1	0 – 65 30 - 35
I	Polychaete	*Boccardia syrtis*	Tube-dwelling, surface deposit feeder- can switch to suspension feeding	Can form dense mats which stabilize the sediment surface	2	2	0 – 50 10 – 35

[6] Optima have been observed to differ between locations

Table 6:

List of taxa sensitive to changes in sedimentation rate and increased %mud content but only observed in one survey (Whitford). NB Species listed as Bioturbators are all likely to increase sediment reworking, affect porosity and benthic productivity. Expt = experimental, Distrib range = range of % mud contents taxa observed over. Opt range = range of highest abundance. *SS* = strong sand preference; *S* = sand preference, *I* = prefers some mud but not high percentages; *M* = mud preference; *MM* = strong mud preference.

Preference	Faunal Group	Taxa	Description	Functional Value	Distrib and opt range
SS	Gastropod	*Cominella glandiformis*	Large, surface-dwelling, highly mobile predator scavenger	Bioturbator, prey item for fish and birds	0-10 5 - 10
SS	Gastropod	*Diloma subrostrata*	Large, highly mobile, surface grazer	Bioturbator, prey item for fish and birds	0-15 5 - 10
SS	Polychaete	*Travisia olens*	Large, slightly mobile	Probably prey item for fish and birds	0 – 5 0 - 5
SS	Amphipod	*Waitangi* sp. aff. *W. chelatus*	Small surface deposit-feeder	Bioturbator- prey item for fish and birds	0 – 5 0 - 5
S	Amphipod	*Waipirophoxus waipiro*	Small surface deposit-feeder	Bioturbator- prey item for fish and birds	0 – 70 0 - 5
S	Polychaete	*Goniada emerita*	Highly mobile predator scavenger	Bioturbator, prey item for fish and birds	0 – 60 50 - 55
S	Polychaete	*Orbinia papillosa*	Large sub-surface deposit feeder, free living	Bioturbator, prey item for fish and birds	5 – 10

Preference	Faunal Group	Taxa	Description	Functional Value	Distrib and opt range
I	Polychaete	Cirratulidae	Predator scavenger	Bioturbator- prey item for fish and birds	5 – 70 10 - 15
I	Polychaete	*Macroclymenella stewartensis*	Large tube-dwelling, sub-surface, deposit feeder- key role in re-working and turn-over of sediment- prey item for birds and fish	Large tube-dwelling, sub-surface, deposit feeder- key role in re-working and turn-over of sediment- prey item for birds and fish	0 – 60 10 - 15
I	Polychaete	Syllidae	Predator scavenger	Bioturbator- prey item for fish and birds	0 – 40 25 - 30
I	Crustacean	Tanaid	Small tube-dweller	Likely to increase oxygen penetration to sediment	0 – 100 10 - 15
I	Polychaete	*Aricidea* sp.	Small sub-surface deposit-feeder, free living in sediment to 15 cm, bioturbator	small sub-surface deposit-feeder, free living in sediment to 15 cm, bioturbator	0 – 70 35 - 40
I	Polychaete	*Cossura* sp.	Small deposit feeder	ID	20 - 25
I	Crab	*Macropthalmus hirtipes*	Large burrower, probably a scavenger	Semi-permanent burrows oxygenate the sediment to depth	45 - 50
I	Nemertean	Nemertina	Large, highly mobile predator	Large individuals are strong bioturbators	55 - 60
I	Nerid Polychaete	*Nicon aestuariensis*	Large, predator scavenger	Bioturbator- prey item for fish and birds	35-55
I	Amphipod	*Paracalliope ?novizealandiae*	Small surface deposit-feeder	Bioturbator- prey item for fish and birds	35 - 40

5.2 Tools

5.2.1 Physiological models

Physiological models relate changes in environmental variables and animals' physiological condition and growth. Scope-for-Growth models are relatively simple, relating the potential for growth to the difference between energy input (absorption rate) and energy output (oxygen consumption and nitrogen excretion). More complex eco-physiological models can be developed, however, the amount of information required by these models generally restricts their use to commercially valuable species. Also, at present, such models are unable to include event-driven variations in the duration and/or food quality of elevated suspended sediment levels, or site-specific differences caused by environmental history, food preferences or algal composition of the water. An eco-physiological model and a simple scope-for-growth model have been derived by NIWA for the relationship between Atrina and suspended sediment concentrations. Simple Scope-for-Growth models have been derived for Austrovenus and Paphies response to suspended sediment concentrations. These models are held by NIWA.

5.2.2 Conceptual models

Elevated sedimentation regimes tend to reduce the overall ecological heterogeneity. In estuaries, multiple habitat types, such as saltmarsh, seagrass and unvegetated intertidal flats promote diversity by enhancing recruitment and maintaining species with requirements for multiple resources. The modification of available habitats due to elevated sedimentation has been shown to lower diversity and abundance with functional differences including reductions in the abundance of suspension feeders (Ellis et al. 2004). More generally, the loss of large macrofauna could have important implications for ecosystem function in estuarine and marine ecosystems. But, in order to understand ecosystem effects, we need to be able to visualize flow-on effects, interacting processes and potential thresholds. Conceptual models are important resources for our understanding of complex effects and for our ability to pass this information on to others.

For example, terrestrial sediment can influence estuarine and coastal ecology, both through increased suspended sediment concentrations and sedimentation rates. Increased suspended sediment concentrations can influence primary production and the benthic animals that feed by filtering water. These effects can flow through the communities and ecosystem along a variety of pathways (Fig. 7). Less complex conceptual models can also be derived. For example, Lundquist et al. (2003) produces a model for the effects of increased sedimentation rates over a long-time scale on communities in Auckland mudflats (Fig. 8).

Thrush et al. (2004b) summarises all of the work presented in this report in a single conceptual model (Fig. 9). This model assumes that changes in the estuarine sediment-loading regime will, by favoring some species and habitats over others, influence estuarine biodiversity. Event frequency, extent and magnitude will influence the recovery response of the benthic community by affecting habitat suitability and the possibility for undisturbed areas to provide colonists to disturbed areas. The result is that, with increasing frequency, extent and magnitude, recovery time increases and depletion of sensitive species occurs. Finally a depleted community or estuary occurs, with low diversity and low function.

Figure 7:

Deposited or suspended terrestrial sediment can trigger a variety of changes in estuarine soft-sediment communities. As the disturbance regime increases, more effects are likely to occur. Thick lines mark strong effects determined by our field studies. Modified from Thrush et al (2004b).

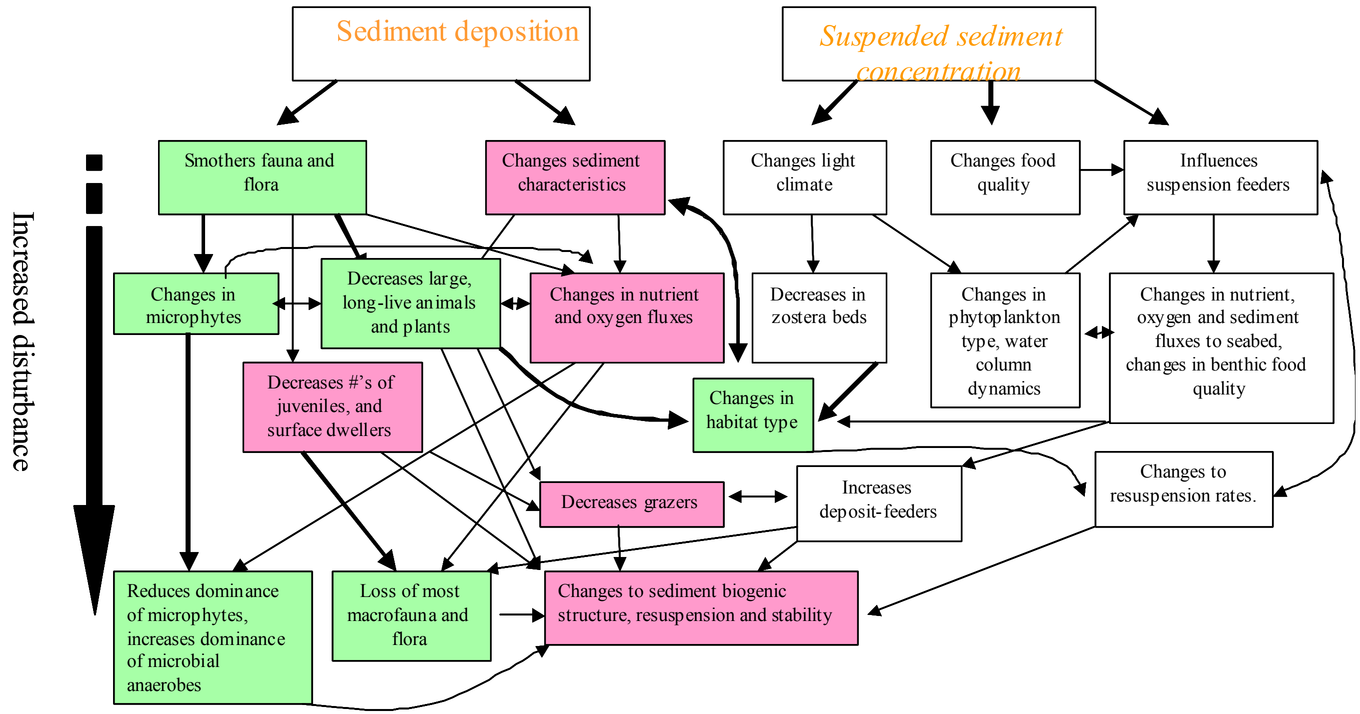


Figure 8:
From Lundquist et al. (2003). Conceptual model of macrobenthic community structure as sediment deposition increases, ranging from 'young' estuaries with low SAR to 'mature', highly infilled estuaries with high SAR. Each of the three types of estuaries in this study (coastal embayment, drowned valley, tidal lagoon) consists of a diverse community with high functional diversity and varied ecosystem roles under low SAR. High SAR (combined with natural aging of estuaries) results in a convergence of all estuarine types to a single, low diversity community of disturbance-tolerant species with similar functional roles.

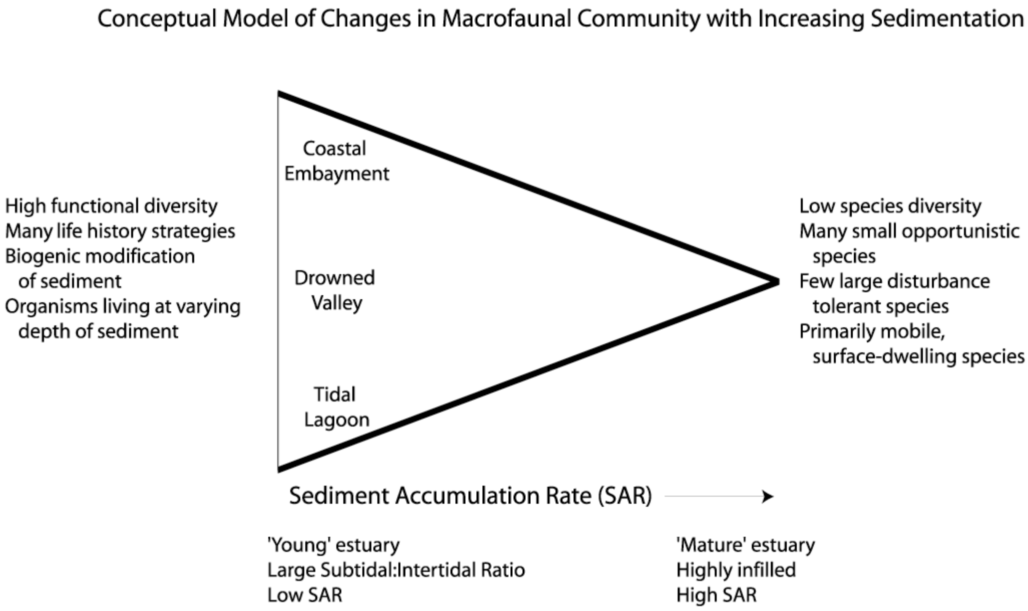
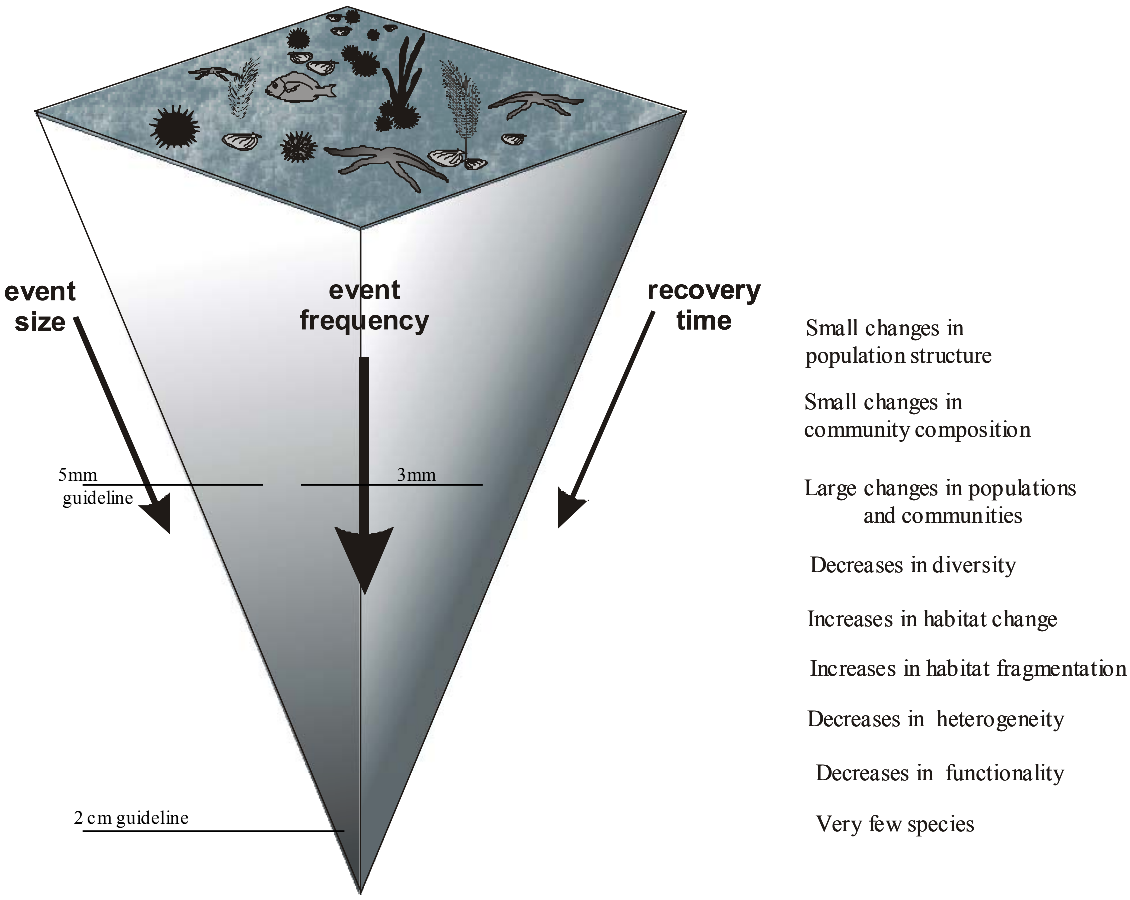


Figure 9:
Conceptual model modified from Thrush et al. (2004b) with guidelines overlain, showing broad-scale changes as biodiversity slides down the slope of increasing homogenisation and exclusion of slow growing and colonizing species to low diversity and function.



5.2.3 Guidelines and caveats

An important role for ecologists in environmental management is the provision of guidelines, based on thresholds of response or percentages of ecological response. Four guidelines have been produced by the sedimentation work:

- In general, the thicker the layer of mud, the more animals will be killed and the longer recovery will take. This will affect both the number of species and the number of animals within each species, however some species are more sensitive than others.
- If mud that has been washed down a stream to one of the tributary estuaries or the embayment results in a mud layer greater than 2 cm thick, remaining for longer than five days, then all the resident animals in that area (with the exception of mobile crabs and shrimp) will be killed due to lack of oxygen.

- A mud thickness of around ½ cm, persisting for longer than 10 days, will reduce the number of animals and the number of species, thereby changing the structure of the animal community.
- Frequent deposition of mud, less than ½ cm, may still have long-term impacts that can change the animal communities.

Another important role for ecologists is to inform managers as to the limitations of knowledge, either in terms of information gaps, underlying assumptions of studies and models and the effect of simplification of results. Caveats for particular studies will be found in the references given in this report, but some caveats are probably worth reiterating here:

- Problems with transferring results across spatial and temporal scales are particularly important for manipulative experiments and one-off-studies.
- Most of this work concentrates on lethal responses (i.e., declining abundances). There has been little work on sub-lethal effects such as organism health, growth or reproductive output. All of these are, however, likely to be important when making long-term forecasts of population and community changes.
- Interactions between the stress caused by increased sediment inputs and other factors, whether natural (e.g., predation) or anthropogenic (e.g., contaminants) are likely to be multiplicative.
- Little knowledge has yet been generated on the effect of duration and frequency of events over long-time scales, or on large-spatial changes, to the distribution of estuarine and coastal habitats.

6 Conclusions

While estuaries are transitory features in geological time, over ecological time and at scales generally relevant to humanity, they are significant features from which we gain a variety of important benefits. Within estuaries, sedimentation is natural and provides some important functions such as supplying nutrients. Even many coastal systems are adapted to the passage (and deposition) of some sediment. However, environmental problems occur when the rate at which sediment is being transferred to, and resuspended and deposited within, estuarine and coastal regions is increased. These increases have the potential to profoundly alter the structure and function of both estuarine and coastal ecosystems, even in soft-sediment habitats. This report summarises work done by NIWA, both ARC and FRST funded, on ecological responses of soft-sediment macrofauna to increased terrestrial sediment inputs.

7 List of reports and papers available

7.1 Reports to ARC

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Cummings, V.J.; Nicholls, P.E. & Thrush, S.F. (2003). Mahurangi Estuary ecological monitoring programme - report on data collected from July 1994 to January 2003. NIWA Client Report: HAM2003-066 prepared for Auckland Regional Council. (NIWA project No. ARC03207). 68 p.

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