New Zealand's Estuaries: how they work and the issues that affect them

Over the past decade, NIWA has published many popular articles that deal with estuaries, mainly in its magazine *Water & Atmosphere*. Included in these articles is information on how estuaries work, the problems they are affected by, and some solutions to those problems. This overview is intended to bring together and make whole sense of the information published to date in the various popular articles.

The target audience is the layperson, such as individuals who have come together in community groups to find ways to deal with particular issues. The purpose is to inform, and thereby empower individuals and groups to act. Specialists might find something of interest in here as well in the way the information is brought together.

Throughout this overview you will find red links to the original articles. After you've read an article or publication, just use the Return to text link at the end to return to the overview. References to external websites are coloured blue; these links take you to a list of the web addresses. Click on the **Bookmarks** tab (to the left of this document) for a linked table of contents to help you navigate.

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Additional text by Mark Morrison and Anne-Maree Schwarz. All articles reproduced with permission. Support from the Foundation for Research, Science & Technology is acknowledged (Effects-Based Protection and Management of Aquatic Ecosystems, C01X0307).

How to cite this overview:
Green, M.O. (2006). New Zealand's estuaries: how they work and the issues that affect them. NIWA Information Series No. 59. 101 p. ISSN 1174-264X.

Okura estuary, north of Auckland.

The Life of an Estuary

Estuaries have a life: they are born, they age, and they die. Birth occurred gradually from around 10,000 years ago, when the ocean began rising from about 150 m below its present level. As the ocean rose, it also marched across the landscape, drowning everything in its path. Around 6,500 years ago, the sea stabilised at more or less its present level, the coastline as we know it today began to become recognisable, and New Zealand's current quota of around 300 estuaries was established.

An estuary is a semi-enclosed embayment, with a free connection to the sea at one end and a freshwater supply at the other, and within which fresh and salty waters mix.

The Estuary Environment Classification (EEC) categorises New Zealand's estuaries based on climatic, oceanic, riverine and catchment factors which, together, broadly determine physical and biological characteristics of estuaries. The EEC is utilised in NIWA's Freshwater Information New Zealand.

Like all of today's estuaries, Tairua harbour was formed by the sea rising and spreading across an older landscape. From this vantage point, it is easy to visualise. Photo: Terry Hume.

With sea level stable, our estuaries then began to age: they have filled out with sediment, and grown an ecology. The article How estuaries grow old describes how sediment infilling ages estuaries.

In essence, estuaries fill with sediments from both ends: muddy "terrigenous" (derived from the land) sediments, eroded from the land and delivered mainly by rivers and streams during floods, fill the upper reaches; and marine sands, washed in through the mouth on a regular basis by tides and waves, fill the lower reaches. Today, many of our estuaries are largely infilled with sediment, and mud meets with sand in the middle reaches, and a fight for dominance ensues.

You will read a lot in here about the "sediment threat" to estuaries. Indeed, most of the issues that are going to be described in a later section relate to that threat. But why is sediment such a problem in estuaries? Isn't it natural?

Think of it this way. The number-one control on an estuary's ecology is its physical configuration: depth, pattern of subtidal (submerged at all stages of the tide) and intertidal (emerges from the water at low tide) habitats, and the nature of the substrate (mud, sand, or some mixture of the two). For example, you don't see mangroves growing in deep channels, and you don't find pipis in mudbanks that are submerged only for an hour or two every tide. In other words, everything likes to live in a particular kind of special place. If you change the physical nature of the estuary, then changes in the ecology inevitably follow.

So, how would you go about changing the ecology of an estuary if you had to?

The easiest way would be to increase **sediment runoff** from the land, which would increase the rate of infilling and alter the balance between terrigenous muds and marine sands in the estuary. It turns out that this is exactly what we have been doing for several centuries now.

For example, before people arrived in New Zealand, a typical **sedimentation rate** was 1 mm per year. But, with widespread removal of native forest, agriculture, roadbuilding and urban development accelerating soil erosion on the land, that figure is now some ten times or more higher (see What happens in estuaries during floods?). This means our estuaries are getting shallower – which affects what lives where.

At the same time, eroded soils spread out over and smother previously sandy areas of the estuary, and also turn the waters more **turbid**. Again, the result is a changed ecology, which we will see in detail shortly.

Every time we "**disturb the catchment**" – for example, by roadbuilding and site development without controlling silt runoff, by logging without revegetation or proper management of access roads, by poor agricultural practices – we change the estuary. As we shall see, there is an ecological price to pay.

There are many other ways that we stress our estuaries: we discharge sewerage into them; we inadvertently fertilise them; we design buildings that leach heavy metals into them; we overfish them; and we let invasive species invade them. Still, it is fair to say that accelerated sediment erosion on the land has done, and is still doing, the most damage to our estuaries.

It is worth noting that the estuary aging metaphor is comprehensive: estuaries can also die by completely filling with sediment. We know that this has already happened in New Zealand (Hot Water Beach and Waikawau on the eastern Coromandel Peninsula are mentioned in How estuaries grow old), and increasingly rapid mangrove expansion might be signalling onset of old age for many other North Island estuaries.

Sediment runoff: sediment eroded from the land and transported down to the coast by flowing water.

Sedimentation rate: rate at which sediment permanently settles on the bed of an estuary, causing it to get shallower. Sedimentation rate will normally vary throughout an estuary, being highest in sheltered areas.

Turbidity: roughly, the clarity of the water. "Cloudy" or "dirty" water is turbid, which is usually caused by large amounts of particulate matter suspended in the water, e.g., fine sediments eroded from the land.

Photo: Malcolm Green.

The term "**disturbed catchment**" indicates a catchment that is losing sediment faster than it would under native forest.

Photo: Malcolm Green.

The Physical World

Sea-level rise, with all of its projected adverse effects, is beneficial when it comes to counteracting the shallowing of estuaries in disturbed catchments. Other physical processes might also stall the inevitable, perhaps even indefinitely in some circumstances. For instance, as an estuary becomes shallower, small waves kicked up by winds become more effective at lifting sediments – grain by grain – off the bed and mixing them into suspension in the water column. Once suspended in this way, sediments can be dispersed and possibly flushed from the estuary by tidal currents, thus slowing down the rate at which the estuary grows shallower. What regulates sedimentation in estuaries? describes how this works, and also gives a broader overview of waves and currents and how they do their business in the different parts of an estuary.

Small waves scour these sandflats of mud, and build these ripples while they are at it. Photo: Malcolm Green.

It's a good trick, really: the shallower the estuary becomes, the better it gets at flushing itself of sediments. Still, it cannot always work, otherwise we wouldn't have those Coromandel cases just mentioned. We might ask ourselves this: should we leave the ultimate fate of our estuaries to these little waves which may or may not be their ultimate saviour? Perhaps not, when the cause of the problem – increased sediment runoff from the land – is decidedly manageable.

Those small waves kicked up by the wind – "wind chop" – actually do a lot more than most people realise (including scientists, at least until recently). In deeper waters, they just upset boaties, but in the shallower waters around the estuary fringes they create a different type of havoc. The dance of the turbid fringe explains how, and also explains some of the implications for dispersal of contaminants such as heavy metals and pesticides. These "fringe processes" are currently the subject of intense research, for they may hold a key to understanding and predicting how our estuaries are going to continue to change in this next, possibly crucial, phase of their lives in the face of rising sea level and continued sediment runoff from the land.

Waves in shallow water explains how waves in estuaries are generated and what they do. Photo: Malcolm Green.

The Living World

We turn now to the ecology of estuaries: the biota (living things, including fish, shellfish, worms, birds, algae, seagrasses and mangroves), the habitats the biota live in, and the interactions between the two.

Healthy seagrass habitat. Photo: Anne-Maree Schwarz.

Seagrasses

Seagrasses are flowering plants that occur around the world. There are about 12 genera and 50 species worldwide, but all the evidence currently available points to there being only one seagrass species in New Zealand, *Zostera capricorni*, which was recently re-classified as *Zostera muelleri*. Apart from its common intertidal habitat, *Zostera muelleri* can also grow as subtidal fringes in New Zealand estuaries if water clarity is high enough. Seagrass beds provide a number of "services": they stabilise sediments; they provide habitat for a range of other organisms including bivalves and fish; they provide food; they participate in complex geochemical processes that cycle nutrients and gases within sediments and the water column; they act as nursery areas for fish; and they provide grazing areas for waterfowl.

Pipefish. Photo: Crispin Middleton.

Fish

Until quite recently, not a lot was known about the importance of estuarine habitats to fish in New Zealand. Recent research, however, is now filling in the gaps and answering some basic questions, such as what fish species are present, what parts of estuaries fish inhabit and what they do when they are there, and what fish feed on.

An interesting – and very useful – sidebar to this research is the discovery that fish sampling is often best done at night. This is because fish sleep, and while they do they are quite readily collected using dip nights or observed under torch-light and counted! This can provide a way to estimate absolute numbers and size distributions of fish, which is not so easily done with traditional sampling methods. Let sleeping fish lie explains why, and also describes a new research tool, the DUV or "drop underwater video".

It is now widely accepted that New Zealand's estuaries do play an important role as nurseries for many fish species (see Intertidal flat estuaries: are they useful to fish?). In the upper North Island, recreationally and commercially valued species include snapper, trevally, kahawai, sand and yellow-belly flounder, grey mullet, rig, and school sharks. Highly abundant forage species include yellow-eyed mullet, anchovies, soles, gobies and triplefins, along with other less well-known species such as ahuru, northern bastard red cod, estuarine and spotted stargazers, and sepia squid.

Some fish species are permanent residents of estuaries, others reside in estuaries only as juveniles, and others migrate in and out of estuaries with the seasons. Factors that strongly influence fish distribution and abundance include sediment type, water clarity, and the presence of "biogenic" habitats (produced by living organisms) such as seagrass meadows, horse mussels, Neptune's necklace, brown kelps, and mangrove forests. For instance, it is likely that horse mussel beds provide increased invertebrate prey as well as protection from larger fish predators. A similar role is provided by seagrass meadows, which support high abundances of juvenile snapper, trevally, parore, spotties and pipefish. Subtidal seagrass patches seem to be especially important, even those of very limited extent or modest quality.

Estuaries of the west coast of the North Island are thought to be particularly important as nurseries, since they provide shelter from the high waves along the open coast. Larger harbours probably provide the majority of recruits for the coastal snapper stock. For instance, Kaipara Harbour, with 432 km^2 of subtidal area, may provide almost three-quarters of all snapper recruits.

Mangroves

There are a couple of unusual things about New Zealand's mangroves, or manawa.

Firstly, there is only one species of mangrove present (*Avicennia marina*, the grey mangrove), which is not usually the case in other parts of the world. Secondly, the global southern limit of mangrove occurrence is in New Zealand: Ohiwa Harbour on the east coast and Kawhia Harbour on the west.

Mangroves not only accumulate fine sediments around them, by slowing water currents, but they also help to permanently stabilise those accumulated sediments, by providing habitats for microbes that excrete substances that stick sediments together (see, for example, Bugs 'n' mud – a sticky problem). This is well and good, since it helps to reduce turbidity and improve water clarity and quality throughout the estuary. However, it also helps to bring on the natural fate of the estuary: death by infilling with sediments.

As far as the ecology goes, mangroves contribute to the species and habitat diversity of New Zealand's estuarine ecosystems. For instance, they are a key source of organic material and nutrients, which go towards fuelling the estuarine food web, and they provide habitat for a wealth of animals, including bacteria, crabs, snails, cockles, worms, black mussels, barnacles, rock oysters, whelks, shrimp, fish and birds.

Photo: Malcolm Green.

At the risk of being overly dramatic, the appearance of mangroves in an estuary that sits within a disturbed catchment is something akin to the arrival of the grim reaper. The question, which is addressed shortly, is whether you deal with the problem by going after the mangroves or by fixing what fuels their spread.

Life in the soft sediments

There is a world of life intimately associated with the "soft sediments" in estuaries: microbes, plants and animals that live in, burrow through, track across, sit on top of, stick together, eat, excrete in and mix the muds, silts and sands that floor an estuary. Some of these are well-known and obvious – shellfish, for example – and others are less so – for instance, bacteria. Taken as a whole, these assemblages, through the ecosystem services that they provide, are the real engine room of the estuary ecology.

Some species are considered to be "key", meaning that they have an important effect on the structure and functioning of the ecosystem; were they to disappear, the ecosystem would significantly change (see Determining impacts on marine ecosystems: the concept of key species). An example of a key species is the bivalve *Atrina zelandica*, or horse mussel, which tends to occur in patches, with individuals sitting partly buried in the sediment and facing upwards. Horse mussels affect the estuary in a surprising number of ways. For instance, they feed on particulate matter suspended in the water column by pumping water through a mantle, which clears the water of suspended matter; they provide physical shelter and hiding places for other animals who live in close association with patches of horse mussels; their shells provide points of attachment for sponges and soft corals; their excretions help to bind sediments and provide food for smaller organisms; and their very presence can affect the way water flows.

Photo: Rod Budd.

This is actually an artificial patch of horse mussels that was planted as part of an experiment to determine how water flow near the bed is affected by the presence of the shells. The instrument in the picture is an acoustic current meter that measures currents and turbulence.

Burrowing by heart urchins: an important function in soft-sediment ecosystems describes an equally important but much more secretive and cryptic species common in soft sediments. *Echinocardium australe*, the heart urchin, is a seldom seen animal that "bioturbates" – or mixes – sediments through its burrowing activities. In so doing, it alters the chemistry of the sediments and associated "pore waters" (water that fills the gaps, or pores, between sediment particles), which has a profound effect on nutrient cycling and the estuarine food web.

It works like this. Sediments are generally rich in particulate organic matter – the remains of plants and animals – that continuously rains down as detritus from above, and which feeds life both directly and indirectly. Directly, animals ingest the detritus. Indirectly, bacteria break down the detritus, which then releases locked-up nutrients, which then fertilise the growth of microscopic plants called algae. These algae are, in turn, at the base of the entire marine food web. The cycle is closed when plants and animals die, the remains rain down on the sediments as detritus, and so on. There is a catch here, and it is this: bacteria need oxygen, and oxygen does not readily diffuse very far into sediments without assistance. That assistance is, in fact, supplied by bioturbators such as the heart urchin, who literally pump oxygen deep into the sediments. In this way, the heart urchin, and other bioturbators like it, is an essential cog in the estuary nutrient-cycling machine. Marine soft sediments: more diversity than meets the eye provides more details.

Microbial life in the water column

Floating in the water column are countless "micro-organisms" (less than 0.2 mm across) that have developed a bewildering variety of ways to feed, get about and reproduce (see Estuarine microbial food webs). This includes phytoplankton (single-celled organisms that, like plants, obtain their energy from the sun by photosynthesis), zooplankton (predatory animal-like organisms that graze on phytoplankton and other micro-organisms), and bacteria. This is a complex world and, tiny though these organisms are, they can affect water quality and, indeed, human health. For instance, phytoplankton can form blooms that kill fish, contaminate shellfish, produce surface scums, and deplete the water of oxygen when they die *en masse* and rot. Phytoplankton are thought to be kept in check naturally through grazing by shellfish, zooplankton and microzooplankton. However, excessive nutrients in the water (from agricultural runoff, for example) in combination with the right amount of light can stimulate blooms.

Algal scum washed up on a beach.
Photo: Malcolm Green.

Sediment bioturbation is one of those things that is both mundane – it's just a bunch of bugs digging around in the mud, after all – and profound. If you are not convinced, read More than just a crab hole, which describes how *Helice crassa* (the tunnelling mud crab; below) goes about "engineering the ecosystem" by digging holes in the mud.

Photo: Kay Vopel.

The burrowing shrimp *Callianassa filholi* is another bioturbating ecosystem engineer. The picture below shows mounds of sediment exhumed from below and piled on the surface by this creature.

Photo: Pip Nicholls.

Bioturbators clean up some of the messes that we make. For instance, heavy metals that are washed off roads and buildings when it rains attach to sediment particles in stormwater and ultimately deposit in estuaries. They do so at very high concentrations (mass of metal per mass of sediment that the metal is attached to) which would be toxic to most marine life. However, bioturbators mix those highly contaminated layers down into pre-existing sediments, thus diluting the metal concentrations and, in so doing, keeping the bed sediments habitable for marine life.

Algae in the water column are called phytoplankton, and algae in the sediment are called phytobenthos (or, sometimes, microphytobenthos).

Birds

Birds are an obvious inhabitant of our estuaries. Less obvious, and pretty remarkable when you think about, is where a lot of them come from. Are our estuaries wader-friendly? tells the story: New Zealand's estuaries are important destinations for many waders that migrate each year from the other side of the world. For instance, about 30% of the summer population of bar-tailed godwit are thought to have flown in from the East Asia–Alaska–Australasia migratory route. In addition to the itinerants, there are many local bird species.

What Ails Our Estuaries – Problems and Solutions

Let's start with a few words about solutions. Estuaries are at the bottom of the freshwater drainage network and, effectively, are a part of it. This means that every time we act to protect and enhance streams and rivers we are also benefiting the estuary at the downstream end. There are lots of such actions available to us. For instance, we can keep stock out of streams, protect riparian margins, plant steep slopes with trees to control landslips, apply fertiliser at recommended rates (this is not just farmers: city gardeners, take note), and restrain ourselves from tipping paint into stormwater drains. Some of these things are clearly within the ability of the individual to achieve, whereas others require a "higher level" of action. This is where various local, regional and national authorities and agencies come in, usually acting under the umbrella of the Resource Management Act.

Whaingaroa (Raglan) estuary. Photo: Alastair Senior.

When it comes to curing estuary ailments, there is not a lot you can actually do inside the estuary. Why is this? To continue the metaphor, it is because estuary illnesses are caused by what happens on the land, so this is where the cure must be applied. In a very real way, if you look after the land, the estuary will look after itself.

The Resource Management Act 1991 (RMA) dictates how we are to manage our physical environment, including the coast and estuaries. A number of key concepts underpin the Act:

- Sustainability: focuses on ecological considerations and, in broad terms, is intended to ensure future generations access to the natural resources and services that we benefit from today.
- Effects-based management: effects of activities, rather than the activities themselves, are to be managed. This opens the way, in principle, for developing innovative solutions to problems.
- Integrated management: can mean many things. From a physical point of view, it means management should be "catchment-based". For example, decisions regarding landuse must take account of the downstream effects of that landuse, all the way down to the sea. From an institutional point of view, it means that the various agencies involved in resource management must not contradict each other.

The Ministry for the Environment is responsible for administering the RMA and ensuring that it is being implemented effectively. Implementation is achieved at a number of levels and in a number of ways. Regional councils have responsibility for environmental management of the coastal marine area (CMA), which is the foreshore and seabed below the level of Mean High Water Springs (MHWS). This includes estuaries. City or district councils have responsibilities for activities above MHWS (i.e., land outside the CMA).

You might now be thinking of a clear delineation of responsibilities around MHWS, but that is not so. Here is where the Act starts to show its true nature. For instance, regional councils can require territorial local authorities to act on the land to protect the waterways that are in the regional councils' jurisdiction, if those land-based activities are having effects on waterways.

The Environmental Defence Society website has a guide to the RMA for informing and assisting individuals and community groups.

The Ministry for the Environment's website has more information on the RMA, including the full text of the Act.

Decline of seagrasses

Seagrasses have diminished worldwide – and this includes within New Zealand – which is of some concern because it has been found that it is very difficult to restore seagrass beds once they have become degraded. Common causes of degradation, which are discussed in some detail in The role of sediment in keeping seagrass beds healthy, include unnaturally turbid water, high sedimentation rates, and gradual replacement of sandy habitats with muddy sediments. All of these are symptoms of disturbed catchments.

Mangrove spread

It was mentioned previously that New Zealand's mangroves are unusual in a couple of respects. This turns out to be true when it comes to issues concerning mangroves as well: New Zealand is one of the few (perhaps only) places in the world where people are concerned about the spread of mangroves. Spreading mangroves: a New Zealand phenomenon or a global trend? explains that in most parts of the world, areas of mangroves are diminishing and mangrove ecosystems are under threat. Furthermore, people are concerned about that and are trying to prevent the rot. In contrast, New Zealand's mangroves are expanding, with consequent unwelcome effects including reduced boat access, spread of smelly mud, loss of water views, poorer fishing and shellfish gathering, and decreased property values. Many New Zealanders are concerned about these issues, and are taking steps to actively control mangrove spread. The difference in the perception of the value of mangroves must stem, at least in part, from the different ways mangroves are used. For instance, mangroves are widely used overseas for timber, food, shelter and protection, which is not so much the case here. There is also a perception that New Zealand's mangroves do not play a significant role in the larger estuarine ecosystem.

Mangrove spreading in New Zealand in recent times is widely attributed to accelerated silt runoff from developing and deforested catchments (see Fringing habitats in estuaries: the sediment–mangrove connection), which reduces water depth and expands the areas that are suitable for mangroves to colonise. Recent experimental work has indicated that you can stimulate mangrove growth by fertilising them with nitrogen (see Nutrient enrichment in mangrove ecosystems: a growing concern). This discovery implies that elevated nitrogen levels in the water – from agricultural runoff, for example – may be fertilising mangroves and thereby assisting them to spread. This occurs through faster growth, and increased production of reproductive propagules.

A discussion intended to inform the mangrove-control debate is provided in For and against mangrove control, which includes an assessment of

Photo: Anne-Maree Schwarz.

various management options. It's not a straightforward issue: although mangroves are a natural part of the ecosystem, and it is in their nature to spread, there may be valid reasons for controlling them. For example, retaining and restoring the sandy habitats that are being consumed by mangroves might lead to an overall increase in estuary biodiversity, and human amenity undoubtedly would be improved in many cases. On the other hand, mangrove control would prevent the estuary from "ageing naturally", although just what this means in estuaries that already have unnaturally high sediment inputs is open to debate.

It is interesting to wonder why it is that mangroves are expanding here but retreating overseas. In both cases, change in landuse is the root cause, but with different results. Here, catchment development has resulted in increased soil erosion and consequent larger sediment inputs to estuaries, which stimulates mangrove spread. In contrast, in Micronesia, India, Pakistan and Brazil, for example, damming of rivers has resulted in reduced sediment load to the coast, which starves mangroves of sediment. In India, extreme siltation has changed the paths of freshwater inflows so that mangroves no longer receive sufficient tidal flushing, which causes them to decline.

Photo: Malcolm Green.

It is time to mention monitoring. Monitoring is often an expensive exercise, but it does not have to be. For instance, a regional council may need to collect data that stand up under scientific attack in Environment Court, which may well be expensive, but a community group's aim may be different. For instance, monitoring data can be used to persuade authorities to take action locally. Or, it might be used to show the effectiveness of local action at restoring and enhancing the environment, which is good ammunition for seeking further support to broaden those actions. Simple and cheap monitoring methods may suffice in these cases. Useful guides for monitoring by community groups of sedimentation and mangrove spread are available in Estuary monitoring by communities.

Turbid water

As far as shellfish go, turbidity – or, more precisely, suspended particulate matter (SPM) in the water column – is both necessary and fatal, depending on how much of it there is. The article Effect of increased suspended sediment on suspension-feeding shellfish explains why.

Most shellfish are suspension feeders, meaning that they suck in water and filter out particles that, until sucked in, were suspended in the water column. Some of these particles are organic in origin and so have value as food. These are ingested. Other particles are mineral in origin (silt or "dirt"), have no food value, and so are excreted. We can deduce two things from this. Firstly, a certain amount of SPM is required for shellfish to survive, for if the water column is perfectly clear, then there will be no food and the shellfish will starve. Secondly, some portion of the SPM must have food value or, again, the shellfish will starve.

Here, then, is where increased turbidity levels (more precisely, increased concentrations of SPM in the water column), which are characteristic of estuaries within disturbed catchments, can have an effect: the increased supply of fine mineral silt that is eroded from the catchment reduces the ratio of edible to inedible particles suspended in the water column, and the shellfish have to work harder at filtering to feed themselves. The more energy they spend on feeding, the less they have available to grow and reproduce, which can lead to loss of condition and, ultimately, death. Modelling the effects of muddy waters on shellfish shows how this works: there are different optimum levels of SPM for different species of shellfish.

Here is where we see what "effects-based management" under the Resource Management Act really means: if some proposed landuse change is going to result in levels of SPM in an estuary exceeding the level that is known to be harmful to shellfish, then the proposed landuse may be denied consent because it will have an adverse effect (on the shellfish). The proposer is free to take steps to reduce the adverse effects, by installing settling ponds to trap silt runoff while a road is being built, for instance. Remember, the RMA intends us to manage on the basis of effects, not the activities *per se* that cause those effects.

So, how can we know if a proposed landuse is going to change SPM levels in an estuary? This is what models are for.

Increased turbidity also reduces light levels, which can reduce primary production, including the growth of phytoplankton (which fuels the estuarine food web) and "macrophytes" such as seagrasses. In addition, lower water clarity can reduce the ability of visual predators (such as snapper) to hunt.

Sediment slugs

When it rains, soil is eroded from the catchment, washes into streams and rivers, and makes its way down to the coast, where it is dispersed and ultimately deposited. If the conditions are right, then some part of that load of eroded sediment may deposit in a noticeably thick "slug" in some parts of the estuary. If the slug is thick enough and covers a wide-enough area, then estuarine plants and animals unlucky enough to be under the slug can be smothered and killed. This process is natural enough, but, like many natural processes, can be magnified in estuaries that sit within disturbed catchments.

In time, the slug may be washed away by waves and currents or mixed down into pre-existing sediments by bioturbating creatures like crabs. Rehabilitation will depend on these factors and the availability of colonising animals (see, for instance, Winds, waves, and recovery from sedimentation in estuaries). If this kind of thing happens too often, or slugs cover a wide enough area, then there may be a long-term shift in the estuary sediments and its ecology.

Sediment dumps in estuaries: filling in gaps with a risk map is a step-by-step guide to identifying estuaries and parts of estuaries that are prone to this kind of impact, by looking for key dump signs, threat indicators and ecological changes.

Assessing human impacts on estuaries: it's a risky business describes a model that has been used by regional authorities to estimate risk of sediment slugs occurring during the earthworking phase of greenfields development. This phase of development is particularly targeted for two reasons. Firstly, it is when soils, which lie naked before the elements, are most liable to erode. Secondly, it is relatively easy to take steps to reduce the vulnerability of the soils. For instance, silt fences can be installed, unstable slopes can be ruled out of bounds for development, and slopes can be grassed and left alone during the wet season. So, here we have a potential problem, and potential solutions to that problem. How, then, is a risk assessment used in this kind of situation?

In the case of the greenfields development example, the developer needs to approach the authorities in advance (in order to gain consent) with a plan for how the greenfields are to be developed. The plan will include not only the final look of the development (lot size, housing density, road network, stormwater services and so on) but also how the development is actually going to be executed. This will include plans for things like staging the development, building access roads, and

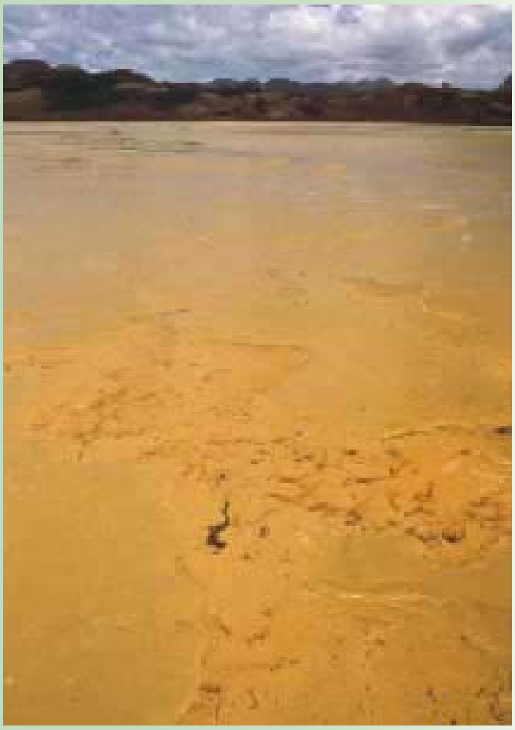


Photo: Don Morrisey.

Quite a few factors must come together for a sediment slug to be deposited, but it is not impossible. For example, discharge of freshwater containing a large sediment load generally needs to occur on an incoming tide, so that sediment is not immediately flushed out to sea. The slug usually can only occur in a sheltered part of the estuary, where waves are not able to wash it away. Finally, the water depth will be fairly shallow so that suspended sediment does not have too far to settle down to the bed.

Photo: Simon Thrush.

NIWA scientists have conducted a series of experiments that involved depositing artificial slugs of sediment to determine the effect of the slug on the underlying flora and fauna and how recovery occurs.

controlling erosion during earthworking. As part of the consenting process, the model is applied to estimate risk of sediment slugs occurring during the proposed development. If the risk is considered to be too high, the developer can be required to alter the plans. The process of putting forward a proposal and assessing its ecological consequences may be iterated until a plan with acceptable ecological risk can be found.

Because rehabilitation of impacted habitats and the communities they support is difficult, prevention of damage in the first place remains the best option. You might as well carve that statement in stone: it's always true.

Change in substrate

How will habitat change affect intertidal areas in estuaries? describes how most species have habitat preferences when it comes to how muddy the bed sediments are. For example, the mud crab is more likely to occur in areas with a high mud content; cockles prefer little mud; and the polychaete worm *Boccardia syrtis* likes the middle ground (but other polychaetes get on fine in muddier sediments).

This kind of information rings alarm bells, for it tells us how the ecology – particularly abundance and distribution of sediment-dwelling animals such as shellfish, polychaete worms, crabs, snails and anemones – are going to change in response to a long-term change in sediment type that is characteristic of estuaries in disturbed catchments. It is worth noting that when we seek to limit immediate impacts, such as those associated with sediment slugs that get deposited in the aftermath of rainstorms, then we are also reducing the rate, over the long term, at which bed sediments become muddier.

Photo: Malcolm Green.

In disturbed catchments, the balance between fine sediments (eroded from the land) and marine sands (swept in through the mouth of the estuary by waves and tides) is tipped in favour of the former, with the result that bed sediments of the estuary get muddier. The ecology changes as a result. For instance, mud-sensitive species such as shellfish and the polychaete *Aonides* will decline in abundance.

Urban contaminants

When it rains, zinc is leached from galvanised iron roofs (by design), gets washed into stormwater drains, and for the most part attaches itself to fine sediment particles that are also travelling in the runoff. The sediment with its attached zinc load makes its way down to the coast where it is dispersed and, ultimately, deposited. If the zinc in the deposited sediments reaches a certain high concentration, then it can be toxic to the biota (see SWAT's up Doc?).

Zinc, of course, is just one type of urban contaminant, with others being copper (from abrasion of car brake pads), lead (from lead-based petrol) and polyaromatic hydrocarbons (from the inevitably incomplete combustion of hydrocarbons). These are "big problems" and, as such, require "big solutions", such as the banning of the sale of leaded petrol in 1996, after a long process that began in the mid-1980s. This, by the way, has already resulted in widespread reduction in lead concentrations in estuarine sediments.

Photo: Alan Blacklock.

If you are really paying attention here, you will notice that most problems in the estuary start "when it rains". Why? Remember, estuaries are at the bottom of the freshwater drainage network, which means that "what ails our estuaries" often comes from the land, carried down streams and rivers by rainwater..

A page on the Ministry for the Environment's website notes, ironically, that "Lead was first added to petrol in the 1920s as a cheap and convenient method of boosting octane (which enhances fuel combustion) and reducing engine 'knock' (caused by faulty combustion). The General Motors research engineer who made the discovery, Thomas Midgley, went on from this triumph to develop a non-toxic, non-flammable alternative to ammonia as a refrigerant – chlorofluorocarbon or CFC. Today, both of these substances are recognised as major pollutants."

Invasive species

Some nuisance and pest species invaded; others were invited. An example of an invited species is cordgrass (genus *Spartina*), which was planted in estuaries in many parts of New Zealand in the early 20th century to prevent shoreline erosion and as part of reclamation schemes to extend pastures. It has since established quite successfully, forming islands that stand above the intertidal flats in some areas, and dense barriers along the shoreline in other areas. The Department of Conservation and some regional councils have programmes to eradicate *Spartina* by spraying with Gallant, which is a herbicide that acts on grasses, but not on native species such as mangroves.

Spartina eradication by spraying with herbicide.
Photo: Andrew Swales.

With the rise of international trade and travel, and widespread decline in the resilience of native ecosystems, other species have truly invaded.

New alien mudworm now becoming a pest in longline mussels describes a shell-boring polychaete worm, *Polydora haswelli*, that damages the shell of the green-lipped mussel, making it less attractive – and in some cases repellent – to consumers. It came to scientists' attention in mid-2003 after worm-inhabited blisters were found inside the shells of farmed green-lipped mussels, although it has probably been in the country at least since the mid-1990s. It is not clear how it got here, although the best bet is via ship ballast water, which is discharged offshore before entering port to load. Native shell-borer worms do exist, but are not capable of damaging the hard, shiny green-lipped shell.

The Asian kelp *Undaria pinnatifida* invaded in the late 1980s, arriving in ballast water in ships from Asia. Given its success so far – it is found widely throughout southeastern New Zealand – and the fact that its impacts vary from location to location, management is focused on slowing its spread around the mainland and, particularly, reducing its ability to penetrate remote regions and areas of special significance such as Fiordland and Abel Tasman National Park. This is being achieved by educating people on how to avoid spreading the kelp when moving boats and marine-farming equipment, investigating ways of treating boats and equipment, and operating early-detection and surveillance systems.

Some invaders may be riding on the back of climate change. For example, the southern saltmarsh mosquito (*Ochlerotatus camptorhynchus*), which is a tropical beast known to carry a number of viruses including that responsible for Ross River fever, has been found around the Kaipara Harbour. The Department of Conservation believes the mosquito arrived on vessels from Australia, and was able to withstand border fumigation control that is targeted at freshwater container-breeding mosquitoes, not saltmarsh species.

A new goby species, *Acentrogobious pflaumii*, was recently discovered in Whangapoua Harbour, Coromandel. The most striking feature of the new species is the many iridescent blue spots along its sides, which the native goby does not have. Photo and text: Rudi Kuiter.

Vigilance is the key to protecting New Zealand's biosecurity. The Department of Conservation website gives an account of who is involved in guarding our borders, the law pertaining to this, international treaties and obligations, how the defences work, and the role and duties of the individual in keeping our borders secure. (Go to the DOC website and follow the trail to "Guarding the Borders".) Information on some of the technical aspects of surveillance and reporting can be found at NIWA's National Centre for Aquatic Biodiversity and Biosecurity.

Faecal contamination

As noted in Flood flushing of bugs in agricultural streams, pastoral agricultural streams in New Zealand are chronically contaminated by livestock faeces. These may be washed by rainfall from pastures into streams, or deposited directly into streams by animals, where they come to be bound up with the streambed sediments. However, those same streambeds are disturbed by floods or livestock trampling, which mobilises the sediments and their attached faecal contaminants, sending them on their way down to the coast. Here, they can be a danger, since faeces of all warm-blooded animals – which includes us – can contain disease-causing micro-organisms (or "**pathogens**").

It is difficult and expensive to screen water samples for the presence of pathogens, and so screening for more-easily detectable "indicator species" is done instead. For instance, Environment Waikato routinely monitors a number of coastal swimming beaches for enterococci (a bacterium that lives in animal guts) for an indication of whether water quality is suitable for swimming. Suspension-feeding organisms such as shellfish (the ones that feed by filtering suspended particles from the water column) are a problem here, since filter-feeding causes micro-organisms to accumulate in the flesh of the animal. Although not necessarily harmful to the shellfish, these can be very harmful to a human consumer of the shellfish. Different indicators may be used, and different standards applied, for assessing contamination of shellfish beds.

As far as agricultural **diffuse-source** contamination goes, the best mitigation strategy is fencing to exclude livestock from streams, which precludes direct deposition of faeces into waterways and trampling. Planting riparian buffer strips is also a good option, since these can trap sediments and faecal microbes in overland flow that would otherwise make their way into waterways.

Agriculture is a "**diffuse source**" of faecal contamination; other diffuse sources include wild animals (for instance, possums and deer) and birds. "Point-source" faecal contamination comes from piped discharges of treated and untreated effluent, including domestic sewerage, and abattoir and farm waste.

Photo: Alan Blacklock.

A **pathogen** is a disease-causing micro-organism. Pathogens include bacteria (e.g., *Camplylobacteria*, *Leptospira*, *Salmonella*, *Yersinia enterocolitica*), viruses (hepatitis A and E) and parasites (*Giardia*, *Cryptosporidium*).

What Now?

Estuaries are more than just the mudflats that we cross on the way to the beach. Of course they have intrinsic value – what natural environment doesn't? – but they also provide us humans with a range of ecological services that help to sustain the quality of our environment, and with amenities that we all enjoy, and sometimes profit from. Estuaries are also threatened – and worse – by the things we do. But here's the good part: we can manage the threat, and in some cases eliminate it. The first step is awareness, which is what this publication is all about.

Action – also described in this publication – needs to follow awareness, and this can occur on many levels: there is the individual, who can take biosecurity seriously when travelling overseas; the community group, who can plant stream banks and the estuary foreshore to intercept sediment runoff; the farmer, who can apply fertiliser at recommended rates; the regional authority, who can use predictive models to plan catchment development rationally; and central government, who can frame laws and provide resources to give teeth to resource management. We all can, and need to, play a part.

Photo: Nicki Green.

Waikaraka Estuary Managers: The Story of a Successful Landcare Group (available from the New Zealand Landcare Trust website) may inspire anybody wondering how they might go about organising their neighbours to clean up the estuary down the road.

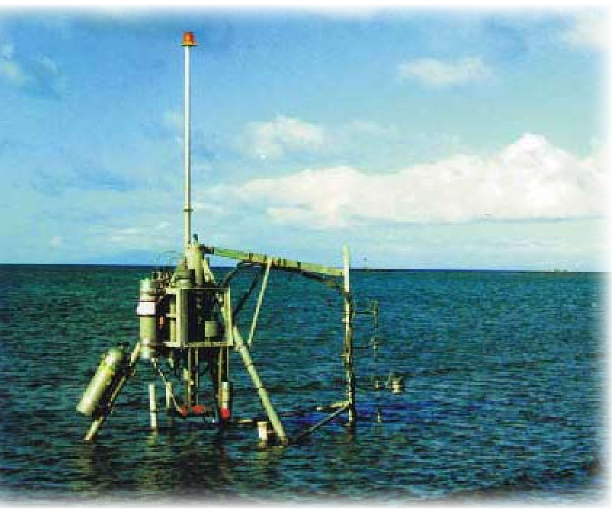
Models

What is a model?

A model is a representation of a "real thing". Usually, the model is simpler in some or many ways than the real thing; the model simulates the behaviour of the real thing; and the model can be used to predict the future behaviour of the real thing. Scientists usually mean a mathematical model when they talk of models – which means that the representation is made out of mathematical equations – but there are many other kinds of models.

For instance, there are tide models that are mathematical, but there are also tide models that are, literally, machines built of gears, cams, shafts, pulleys, and so on. You can see one of these marvels at the website of the Proudman Oceanographic Laboratory. Both types of model do the same thing: they simulate tides. They don't do this by causing water to actually rise and fall, however. Instead, they might, say, print a graph showing tidal variations in water level.

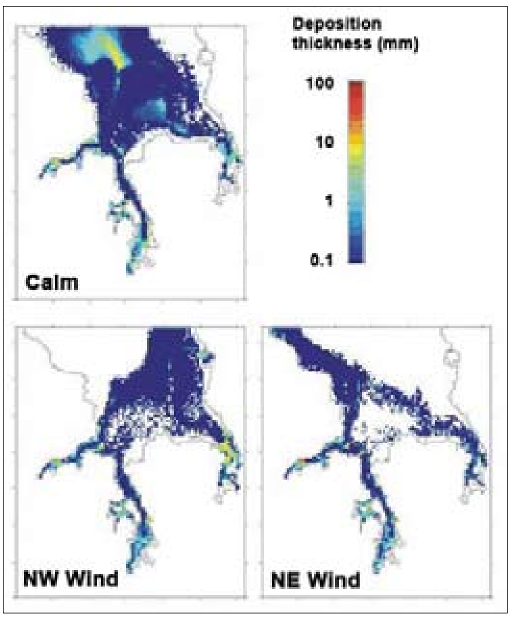
Wave gauge. Photo: Malcolm Green.



Instrument for measuring boundary-layer flows and sediment dynamics. It is submerged at high tide. Photo: Malcolm Green.

Much research today is aimed at continually expanding and improving models. To do this, we need to understand how things work, so that mathematical equations can be written, which are subsequently installed in the models. This is achieved by making field measurements with a range of sophisticated instruments (see photos, and SCAMP: measuring turbulence in estuaries, lakes and coastal waters). A particular area which we do not understand all that well is how sediments eroded from the land are delivered to estuaries during floods, and what happens to that sediment once it reaches the estuary. This is now receiving special attention (see What happens in estuaries during floods?).

Models can be used to predict. For example: a model of tides in an estuary can predict current patterns throughout an estuary and how these change as the tide rises and falls. A sediment-transport model can be linked to the tide model to show how sediments are eroded from the bed by the tidal flows, how they are dispersed around the estuary by the tidal currents, and where in the estuary those sediments ultimately settle. The same estuary sediment-transport model can be linked to a model of sediment erosion in the catchment to show how suspended-sediment levels in the estuary change as a result of erosion in the catchment, and how that same erosion increases the rate of sedimentation in the estuary.



Model predictions of sediment deposition thickness in Whitford embayment, Auckland.

Big solutions to big problems: planning catchment development to minimise contamination of urban estuaries

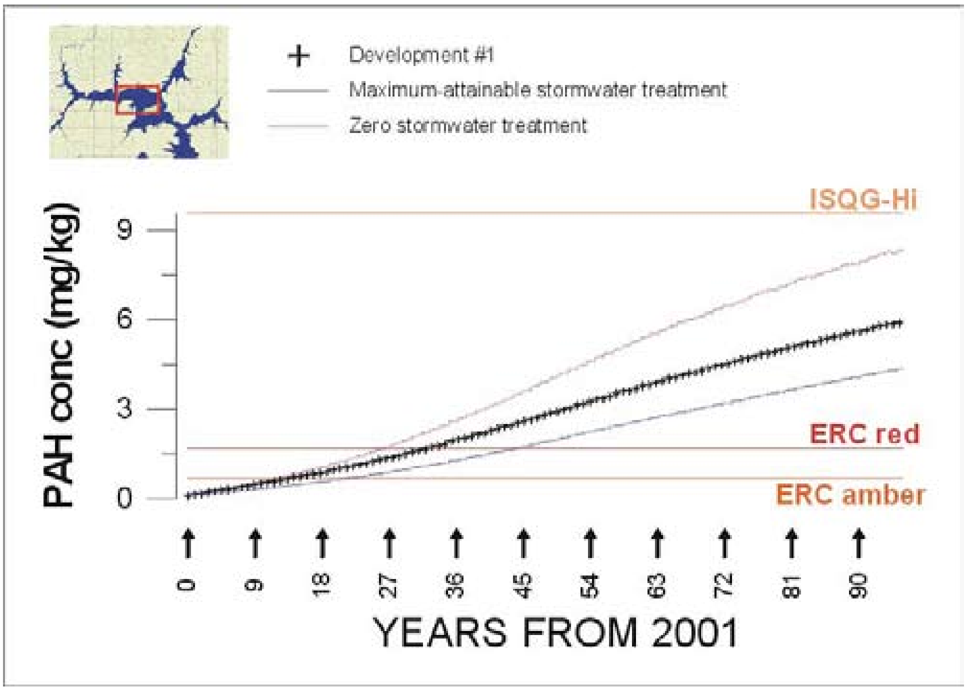
The USC-2 (Urban Stormwater Contaminant) model has been developed to make predictions of contaminant accumulation in estuaries over the next 50–100 years. Given a description of how the catchment is expected to develop, the model can predict where in the estuary and at what rate contaminants will accumulate.

The model has been applied recently as part of planning development of the catchment surrounding Auckland's Upper Waitemata Harbour (UWH). Build-up of zinc, copper and polycyclic aromatic hydrocarbons (PAHs) in the bed sediments of 11 "subestuaries" of the harbour under a number of scenarios has been predicted. The "Existing" scenario provides baseline information against which future trends can be compared. The "Development #1" scenario is one possible way that is being considered for catchment development over the next 50 years, which includes a certain level of stormwater treatment.

The figure below shows an example of predicted PAH concentrations in the surface sediments of the middle main body of the harbour. PAHs are predicted to exceed the Environmental Response Criteria (ERC) "red traffic light" sediment-quality guideline within the next 30 years under Development #1, which indicates probable biological impacts. That curve is bracketed by two other curves, one showing PAH build-up under the Development #1 pattern and intensity of urban development but with maximum-attainable stormwater treatment (which may come at considerable cost), and the other with zero stormwater treatment (which demonstrates the environmental gains made by the level of stormwater treatment already within the Development #1 scenario). A considerable gain in "time to traffic-light exceedance" (about 15 years) is won by improved stormwater treatment, which might justify the extra expense, given that new technologies for mitigating or avoiding contamination could emerge in that time.

It is worth noting that this is not true of every subestuary in the UWH. In some parts, the shift to maximum stormwater treatment on the land gains virtually nothing in the estuary, and in yet other parts a very small improvement in treatment is predicted to avoid guideline exceedance entirely. The difference lies in the complex connections between the various sensitive parts of the estuary and the various contaminant hotspots in the catchment, which is precisely what the model is intended to capture.

The model is run in a kind of iteration, with discussion of results after each loop, until an acceptable – and no doubt compromise – development strategy can be found. As part of this iteration in the Upper Waitemata study, it has been found that stormwater treatment alone may not deliver acceptable environmental outcomes in some critical parts of the harbour. This has turned attention to benefits that could be derived by new methods of source control, such as regulating galvanised building materials. The USC-2 model is providing the information needed to develop regional planning policies aimed at protecting estuarine receiving waters in developing catchments.



Return to text

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Ministry for the Environment (RMA text): www.mfe.govt.nz/laws/rma/

Ministry for the Environment (lead levels): www.mfe.govt.nz/publications/ser/ser1997/html/chapter6.9.html

National Centre for Aquatic Biodiversity and Biosecurity: www.niwascience.co.nz/ncabb/

New Zealand Landcare Trust: www.landcare.org.nz

Proudman Oceanographic Laboratory (tide model): www.pol.ac.uk/home/insight/doodsonmachine.html

ESTUARIES

How estuaries grow old

Terry Hume

Andrew Swales

Have you ever wondered how estuaries have formed and if they will eventually fill up with sediment and die?

Estuaries in New Zealand have not always looked like they do today. These semi-enclosed coastal water bodies, where land drainage mixes with the sea, began life about 6500 years ago, when climatic warming caused sea level to rise some 150 m to its present level. The sea level rise drowned an ancient and varied landscape. So, in the Auckland region, the seabed of present-day Hauraki Gulf was once a broad alluvial plain with meandering river channels incised into it and the coast was out beyond Great Barrier Island. In south-west New Zealand, the landscape was dominated by deep U-shaped valleys cut by glaciers. The "proto-estuaries" that formed as sea-level rose were very different from those we see today because since that time they have filled with sediment and grown old.

The aging process

The geomorphology of today's estuaries depends on the shape of the landscape that was flooded by the sea, and on how estuaries have been subsequently modified by sediment infilling. First, the shape and size of the flooded basin determine how much sediment can accumulate. Second, the pattern of infilling is controlled by the interaction of stream/river processes, tidal exchange and waves. An important point is that estuaries infill with sediment derived from both the land and the sea.

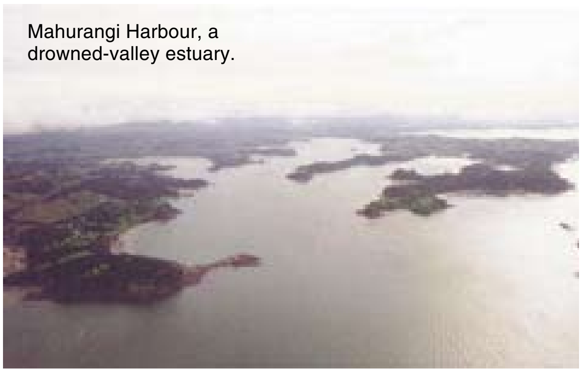
Map showing locations of estuaries mentioned in the text.

The variety of landscapes that were flooded by the sea and the many paths the aging process can take are the primary reasons we have so many different types of estuaries in New Zealand, as the following examples show.

- There will have been rapid aging where the sea drowned deeply incised landscapes and there has been abundant soil runoff from the land. Examples are drowned valleys such as the Mahurangi, Waitemata and Otago harbours. Here, thick sequences of sediments have accumulated rapidly in deep basins to develop into low-gradient intertidal flats. Tidal creeks in the upper reaches of such estuaries have infilled with many metres of mud.
- In contrast, the drowned valleys of the Marlborough Sounds have aged more slowly despite runoff from large catchments. Infilling has been most visible in the headwaters, where marshes have developed. But the steep-sided, deep Sounds provide copious storage space for sediment. Furthermore, estuarine flow and stratification of the water (layering according to temperature and salinity) help to ensure that sediment-laden river water is transported as a surface layer and dispersed well down the estuary.

Hellyers tidal creek in the Upper Waitemata Harbour

- Where drowned valley estuaries emerge onto a sheltered coastline with little sediment drift (for example, Auckland's Waitemata and Mahurangi harbours) there is little infilling from the sea and sandy shoals (tidal deltas) don't form at the mouth.
- In contrast, on the exposed west coast, ocean swells and sediment drift build shoals of marine sands at the mouths of large harbours such as the Hokianga.
- Tides and infilling from the sea play a major role in the growth and aging of shallow tidal lagoons such as Tauranga Harbour, Whangarae Estuary and the Avon Heathcote Estuary. In these systems, river inputs are small relative to tidal flows. Here, sand driven along the open coast by



Mahurangi Harbour, a drowned-valley estuary.

Terry Hume and Andrew Swales are based at NIWA in Hamilton.

waves is captured by the tidal flows at the entrance to build sand bodies outside the entrance and inside the bay. A quasi-equilibrium develops between sand being captured and stored in the shoals and sand being released back to the open coast. The middle parts of the lagoons contain a mixture of marine and catchment-derived material, the thickness of which depends on the topography of the original landscape that was drowned. Many of these landscapes were originally shallow embayments and today they have largely infilled so that when the tide goes out extensive areas of intertidal flats are exposed. Interestingly, sedimentation can slow down late in the infilling process because there is no opportunity for deposition when the tide is out, and when wind-generated waves stir the seabed, sand is remobilised and transported out to sea.

- River-mouth estuaries age differently. These systems, such as the Mokau River (right), are short and narrow and have little space for sediment. So it is surprising that these estuaries age slowly, in spite of having large catchments. The reason is that floodwaters and suspended sediment are quickly jetted though the system to the sea, bypassing the estuary. Little sediment enters river mouth estuaries from the sea because the flows in the estuary are directed seawards for most of the time. Floodwaters also scour the bed, prolonging the life of river mouth estuaries.
- Some estuaries don't show their age. The fiords of Fiordland, for instance, have changed little since the "great flood" because sediment build-up is insignificant in these very deep (200–300 m) and steep-sided water bodies. Furthermore, there is relatively little sediment runoff from the heavily forest-clad catchments, despite the very large rainfall and runoff.

Factors that accelerate aging

The aging process can be dramatically accelerated by biological and anthropogenic factors. The colonisation of intertidal areas by fringing vegetation, such as mangroves or salt-marsh rush (*Juncus*, for example), speeds up infilling. Fringing vegetation reduces local currents, which encourages sedimentation. Therefore, fine sediment becomes trapped on the intertidal areas. Fortunately, the infilling slows down in the final stages of this process, prolonging estuary longevity.

Human activities, in particular catchment deforestation and rapid urbanisation in the last 150 years, have had pronounced effect on the aging of some estuaries. Some effects are obvious, such as reclamation of estuary margins for farmland or ports, or construction of causeways for roading and rail. Some anthropogenic effects are more subtle, such as increases in catchment sediment runoff associated with land-use change.

We know that increased runoff from catchment clearance associated with logging, agriculture and urban development has greatly increased sedimentation rates and infilling in estuaries, especially during floods (see pages 11–13 in this issue for more details). However, wise land-use practices such as avoiding large-scale land clearance and maintaining riparian vegetation may help minimise these effects.


Whangarae estuary, a small tidal lagoon near Nelson.


You can watch the daily changes at the Mokau River mouth on NIWA's Cam-Era system (www.niwa.co.nz/services/cam-era/sites/mokaua/)

What does the future hold?

For some very deep estuaries such as fiords there will be little observable change in the next few centuries or millennia. Other small, shallow systems, such as Hot Water Beach and Waikawau (eastern Coromandel Peninsula) will infill with sediment and die. In these situations the upper reaches of the former estuary are now farmland and the lower reaches are so choked with marine sands that the sea only enters at high tide. We expect estuary infilling to be partly offset by sea-level rise associated with climatic warming, which will deepen estuaries by about 2 mm/yr, and by the sea flooding low-lying margins which will evolve to marsh and then tidal flats. However, in many places this will not be allowed to happen as the shores of farmland are stopbanked to prevent flooding and property loss. Thus, anthropogenic processes and climate change make the future for estuaries rather uncertain and human activities mean that some estuaries will not be able to grow old gracefully. ■

Teachers: this article can be used for Biology L7 A.O. 7.3(a) and NCEA AS 2.5, 2.9, 3.2, 3.4. See other curriculum connections at www.niwa.co.nz/pubs/wa/resources

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ESTUARIES

What happens in estuaries during floods ?

Andrew Swales
John Oldman
John Radford
Iain MacDonald

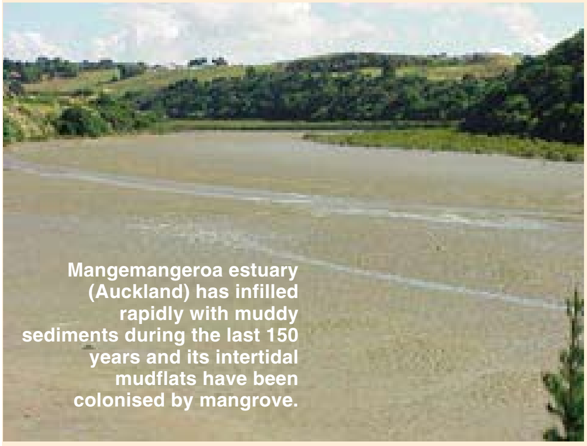
An experiment in Auckland's Mangemangeroa estuary is helping us understand what happens to sediment eroded from the land, how much accumulates and how much escapes during floods.

Most sediment is washed into estuaries during floods. These events are difficult to record because they often only last a few hours and can happen any time. But we need a good understanding of what happens during floods if we are to accurately predict the fate of catchment sediments in our estuaries.

Our aging estuaries

The estuaries that we see in New Zealand today formed only 6500 years ago when rising sea level drowned coastal valleys (see pages 14–15 in this issue). The life histories of some of our estuaries have been pieced together from dated sediment cores, from which we can estimate how fast sediment has been accumulating.

Before people arrived in New Zealand, our estuaries filled gradually – less than 1 mm/year – with sediment from both the land and the sea. However, in the last 150 years, widespread removal of native forest and, more recently, urban development have greatly increased the amount of sediment runoff from the land. As a result, average sedimentation rates in our estuaries today are typically 10 times or more higher than before humans arrived. For example, research in some North Island estuaries has shown that sedimentation rates in their upper reaches have averaged as much as 20 mm/yr over the last 50 years. The effects of such rapid sedimentation on the longevity and ecology of estuaries can be far-reaching. (See pages 14–15 and *Water & Atmosphere 10(4)*: 22–26 for examples.) Today, many of our estuaries have infilled to the extent that they are largely intertidal and much of their beds is exposed at low tide.



Mangemangeroa estuary (Auckland) has infilled rapidly with muddy sediments during the last 150 years and its intertidal mudflats have been colonised by mangrove.

Floods and sedimentation

Information gleaned from sediment cores gives us a good idea of the long-term history of our estuaries but provides only part of the story. Average sedimentation rates calculated from sediment cores can give the impression that sediment runoff to estuaries occurs at the same rate all the time. In reality, most sedimentation occurs in estuaries during episodic floods that may last a few hours and happen perhaps only several times each year. For example, in the Mahurangi catchment north of Auckland a single flood in May 1985 delivered 75% of the estimated 20-year annual average sediment runoff to the estuary.

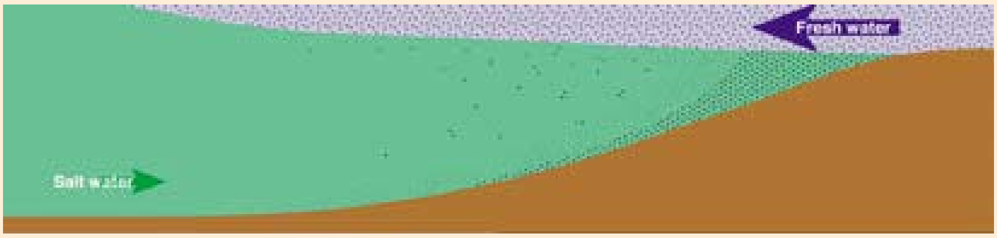
This means that if we want to predict the effects of increased sediment runoff from the land, we need to know what happens in estuaries during floods. One way to investigate this is to make measurements of what actually goes on in estuaries during floods – for example, water flows, sediment dispersal and sedimentation processes in various environments, such as tidal channels, intertidal flats and fringing habitats. We can then use this information to improve predictive models of sediment dispersal and sedimentation.

Modelling to make predictions

Mathematical models are used increasingly to predict the likely consequences of human activities, and several applications have been described in previous issues of *Water & Atmosphere* (such as *8(4)*: 13–16; *10(2)*: 18–19). The value of numerical models as environmental management tools lies in their assimilation of knowledge, integration of the effects of the interaction of many processes in time and space and, as a result, an ability to predict the consequences of future events such as increased sediment runoff during catchment development.

Estuary models are usually built in several steps, and the overall accuracy of the model predictions depends on the degree to which we understand the physical and biological processes which underpin them. Modelling

Andrew Swales, John Oldman, John Radford and Iain MacDonald are based at NIWA in Hamilton.



Salt-wedge stratification: sediment-laden flood-water flows seaward as a surface layer while less turbid near-bed saltwater flows towards the head of the estuary.

sediment dispersal and sedimentation in estuaries during floods is a good example of how our understanding of processes limits the accuracy of models.

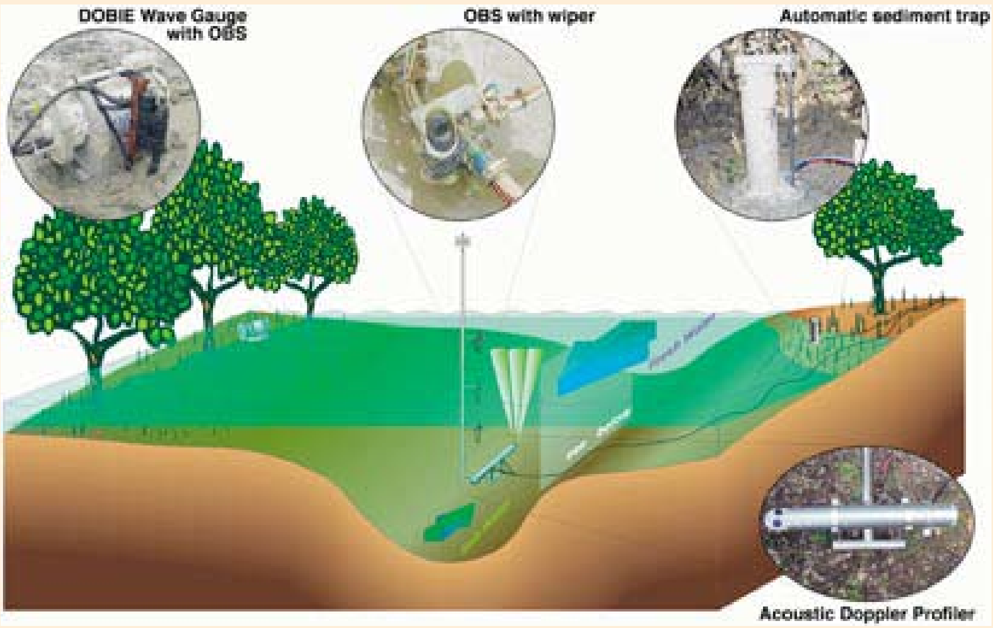
In the first step tidal flows are predicted using a hydrodynamic model – for example, see *Water & Atmosphere 8(4)*: 13–16. The accuracy of these predictions depends mainly on how accurately we know the shape (bathymetry) of the estuary: we can measure this relatively easily.

The second step involves modelling how freshwater flood runoff mixes with the salty estuary water. This step is important because sediment dispersal is primarily determined by this mixing process. Typically, in largely intertidal estuaries, fresh water and salt water are well mixed most of the time because of the combination of shallow water and strong tidal currents. However, during floods, if the river flow is large in comparison to the tidal flow *and* the water is deep enough, then we see two changes. Silt-laden freshwater runoff flows out into the estuary on the surface of the saltier, denser estuary water and sediment from the freshwater can settle out into the incoming "salt wedge" and be transported back to the upper estuary where it is likely to be deposited. This process is called salt-wedge stratification (see illustration above).

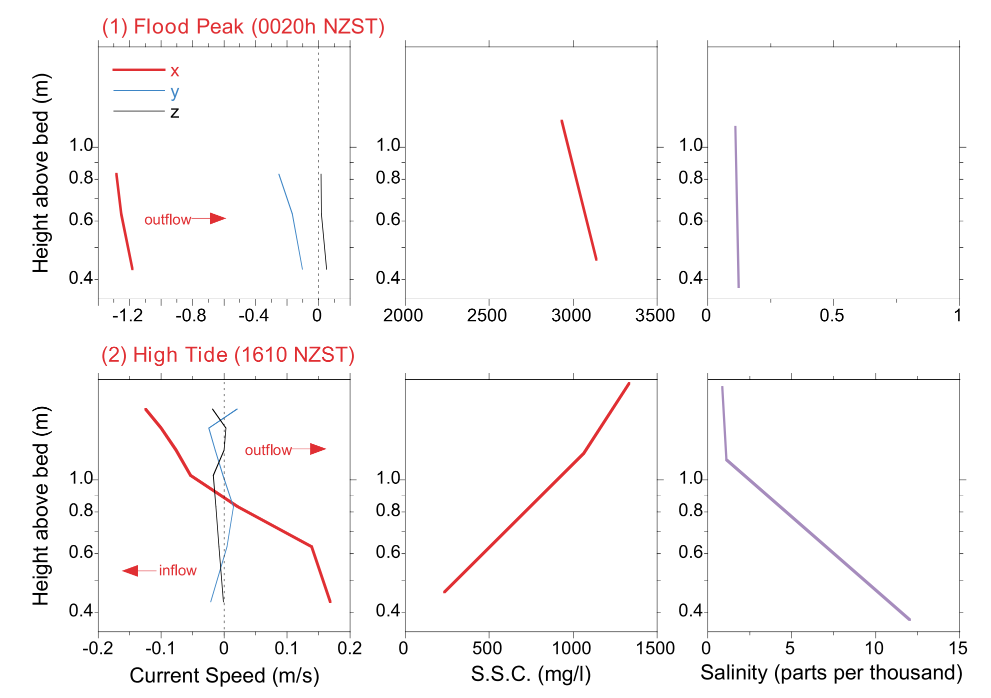
Many estuaries – particularly those formed from drowned river valleys – are fringed with small, shallow tidal creeks (see pages 14–15 in this issue). Such creeks are largely intertidal so their flows are likely to be well mixed, but it is not clear whether salt-wedge stratification occurs in these environments. This could be important because the degree to which salt wedges modify flows in tidal creeks might have a large influence on flood sediment dispersal and sedimentation.

Flood sediment dynamics: an experiment

We are investigating what happens to flood sediments in estuaries through an experiment in Auckland's Mangemangeroa estuary (see photo on previous page), a good example of a tidal-creek estuary which drains to a large, shallow bay.



Measuring salt-wedge stratification and flood sediment dispersal and sedimentation. An acoustic Doppler profiler measures current profiles. Optical backscatter sensors (OBS) and conductivity/temperature probes measure suspended sediment concentration and salinity at different levels in the water column, while other instruments measure sediment processes on the intertidal flats.



Snapshots of the June 2002 "Weather Bomb" storm in the tidal channel during (1) the flood peak and (2) subsequent incoming tide. Our sensors recorded how the salt-wedge evolved and persisted for almost two hours, during which time some flood sediment returned to the estuary in the salt wedge. (In the left-hand plots, x refers to the current speed in the direction of flow; y and z are flow measurements at right-angles to x, and vertically, respectively.)

A "smart" instrument system has been designed to capture what happens during short-lived floods by making frequent measurements in both the catchment and the estuary. We measure catchment sediment runoff using electronic sensors, supplemented by automated sampling of floodwater. In the estuary channel, a sensor mast measures water levels, current speeds, suspended sediment concentrations (SSC) and water salinity at several levels in the water column. (see figure left). Elsewhere in the estuary, other instruments are making similar measurements in mangroves and on the mudflats. By this range of measurements we can build up a detailed picture of how flow conditions change during the flood and how sediments are dispersed and deposited.

Capturing a flood

A severe storm in June 2002 – the "Weather Bomb" – was captured by our instruments at Mangemangeroa and the data demonstrate just how complex flow conditions are during floods. The plots above show suspended sediment, salinity and current-speed profiles measured at the flood peak (which occurred at low tide) and at the subsequent high tide. At the flood peak, silt-rich runoff was transported rapidly down the estuary. As the next incoming tide flowed into the estuary and the storm abated, current speeds and suspended sediment concentration in the channel rapidly declined. Then, as high tide approached, a salt wedge gradually evolved and persisted for two hours. The near-surface freshwater layer flowed down the estuary over an opposing salt wedge travelling up the estuary, transporting with it suspended sediments. We can recognise the salt wedge easily from its tell-tale S-shaped velocity profile, shown in the lower left-hand plot. The upper surface of the salt-wedge is identified by a sharp salinity gradient or halocline about one metre above the bed (lower right-hand plot), which coincides with rapid vertical changes in current velocities and suspended sediment concentration.

New information on salt wedges

Our initial flood "snap-shots" from the Mangemangeroa estuary tell us that salt-wedges do develop, even in shallow, largely intertidal estuaries. Thus, we have answered one of our questions about flood sediment dynamics in our relatively infilled estuaries. Our measurements also suggest that the pattern of estuarine sediment dispersal and sedimentation is likely to change as salt-wedges evolve and decay during floods. Furthermore, flood processes, such as the salt-wedge, must be adequately understood and incorporated into models if we are to make useful predictions about the fate of catchment sediments in our estuaries. ■

Teachers: this article can be used for Biology L7 A.O. 7.3(a) and NCEA AS 2.5, 2.9, 3.2. See other curriculum connections at www.niwa.co.nz/pubs/wa/resources

Acknowledgements
We thank the Auckland Regional Council for their generous support of the Mangemangeroa estuary experiment. This research was part of the programme "Effects of Sediments on Estuarine and Coastal ecosytems" (C01X0024) funded by the Foundation for Research, Science and Technology.

ESTUARIES

What regulates sedimentation in estuaries?

Rob Bell
Mal Green
Terry Hume
Richard Gorman

Why don't estuaries fill up with all the sediment that is carried in from both the land and the sea? We are developing a picture of what goes on in estuaries to keep them from silting up, and of how we can slow down infilling by managing land use.

ESTUARIES ARE THE MEETING PLACE of land drainage with the sea. They contain many different habitats: shallow open waters, salt marshes, sandy beaches, mud and sand flats, rocky shores, mangrove forests, seagrass beds, river deltas and tidal pools. These habitats form the most productive areas on earth, creating more organic material each year than comparable areas of forest or farmland.

But estuaries are very vulnerable to the effects of human activities and require careful management to keep them in reasonable shape. One of the biggest issues is sediment. In an ongoing research programme we have been examining the various factors that affect sediment in estuaries.

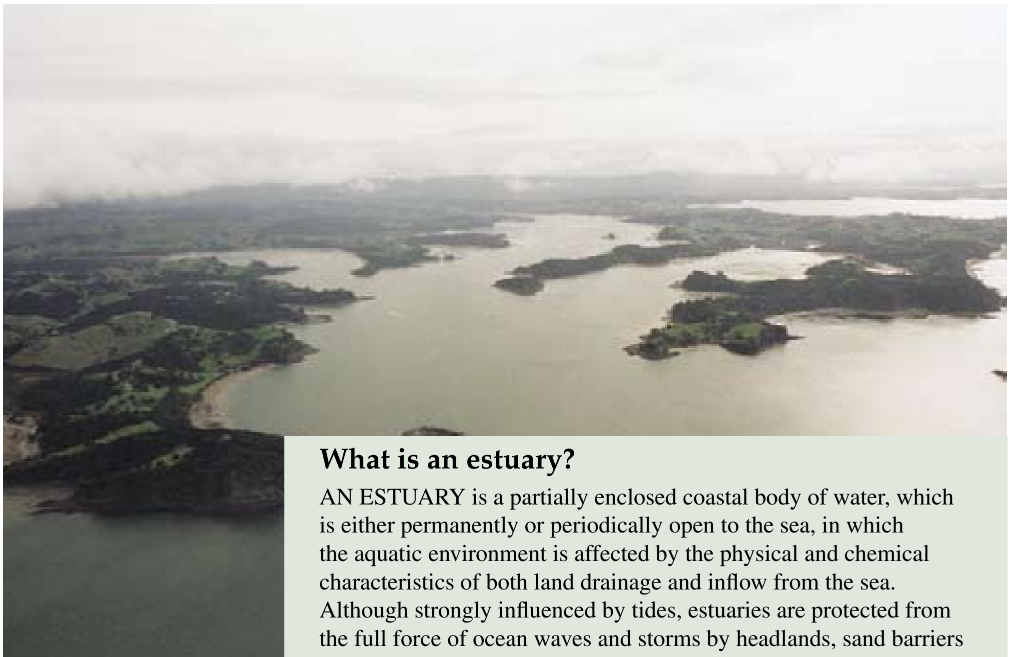
A little history

Today's estuaries in New Zealand are quite recent in geological terms. They formed when river and glacial valleys were flooded as sea level rose quickly during the Holocene – the geological period that started about 10,000 years ago, at the end of the last major ice age. Sea levels stabilised about 6000 years ago and ever since then estuaries have been catching up on their sedimentation. Waves and tides have combed coarse marine sediments from the seabed offshore and built sandy barriers and spits at estuary entrances, which in turn supply sand to an estuary. Meanwhile, rivers have carried in finer sediments. So why haven't all our estuaries simply filled up with sediment?

A changing balance

Whether an estuary fills in or remains deep depends on the balance between sediment entering and leaving the estuary, and on water inputs from rivers or from sea-level rise.

Human activities have changed this balance in estuaries in various ways – mainly by increasing



Mahurangi Harbour (north of Auckland) viewed from above the Hauraki Gulf at high water.

What is an estuary?

AN ESTUARY is a partially enclosed coastal body of water, which is either permanently or periodically open to the sea, in which the aquatic environment is affected by the physical and chemical characteristics of both land drainage and inflow from the sea. Although strongly influenced by tides, estuaries are protected from the full force of ocean waves and storms by headlands, sand barriers and/or tidal deltas (partially submerged sand shoals) at the mouth. Estuaries are also known as harbours, bays, lagoons, inlets or sounds. New Zealand has nearly 300 estuarine systems spread along 11,000 km of coastline. They range in size from a few hectares to over 95,000 hectares (Kaipara Harbour), although most are less than 6000 hectares.

Diagram of long-term balance for estuaries between rates of sea-level and river-flow change and sedimentation in coping with sediment inputs from land and sea.

erosion and by changing water-flow patterns and sediment movements. For example, port or marina developments trap fine sediment, and regular dredging may be required to prevent sediment accumulating. Causeways for roads can change both current patterns and the way sediment is carried in and trapped. Erosion can be caused by the clearfelling of forests and by construction projects such as new subdivisions; the fine particles in eroded material may end up in estuaries. In fact, any activities that lead to extra mud and silt settling on estuary floors pose a threat to New Zealand estuaries. Overdosing on fine sediments can easily push the sedimentation balance towards irreversible infilling. In addition, the estuarine ecosystem may suffer: the many animals that live in estuaries may be harmed if sediment inputs and patterns change too quickly.

Sustaining the balance

To manage an estuary so that it doesn't undergo rapid alterations, we need to know how the estuary responds to changes in sediment input from both the land and the sea. Computer models can then help in assessing whether land use or other changes may upset the fine sedimentary and biological balance.

In the past decade, New Zealand researchers have unravelled part of the complex story of how estuaries handle sediments. Three important physical features play a part: tides, waves and rivers.

Tides

Tidal currents provide the steady supply of energy that moves sediments into and out of estuaries. Most of New Zealand's estuaries have a tidal range of 2–4 metres.

Waves

Especially during storms, waves and swell at the entrances to estuaries can stir up large amounts of sediment, which can then be moved into the estuary by the incoming tide.

Inside the estuary basin, smaller waves can comb sediments off the shallow intertidal banks.

Rivers

Fresh river water floats over seawater. So when sediment-laden floodwaters enter an estuary the finer particles that stay in suspension may be flushed out to sea quite quickly. But heavier particles sink to the bottom as the flow meets salt water. This is why sediment deposition is greatest near the upper reaches of an estuary.

Within estuaries we can identify distinct sub-environments in which tides, waves and rivers interact differently.

Tidal inlet

Inlets on sandy shores have narrow entrances to the sea, with sand shoals – tidal deltas – just inside and outside the entrance. These shoals are moulded by waves and by strong tidal currents. Sand circulates in the tidal inlet between the shoals and adjacent beaches and the shallow seabed offshore. The amount of sand in the inlet depends on how much water passes in and out of the estuary during a tidal cycle. The shape of the delta depends mainly on the shape of the bay and on the energy produced by waves. So, on New Zealand's west coast, where waves tend to be big and powerful, deltas are squashed against the shore, but on the more sheltered east coast, deltas can protrude farther offshore.

Channels, sandbanks

Channels are the sediment highways in estuaries and sandbanks are areas where sediment builds up. Channels carry in suspended sediment but are themselves scoured out when currents are stronger. The rush hour for sediment movement occurs around mid-tide on both ebb (outgoing) and flood (incoming) tides, when currents are strongest. Over time, fine material is washed out from channel beds, leaving behind a layer of gravel and shells that stabilises the channels.

In a simple estuary with no sandbanks, flooding tidal currents are stronger than ebbing ones and this leads to gradual infilling. As sandbanks develop, ebbing currents become stronger so that excess sediment can be flushed out again. This changing interaction between the tide and the shape of the estuary floor helps to regulate long-term sedimentation.

The illustration on page 16 shows the result of modelling tidal currents in the interconnected channels of Manukau Harbour, Auckland. The

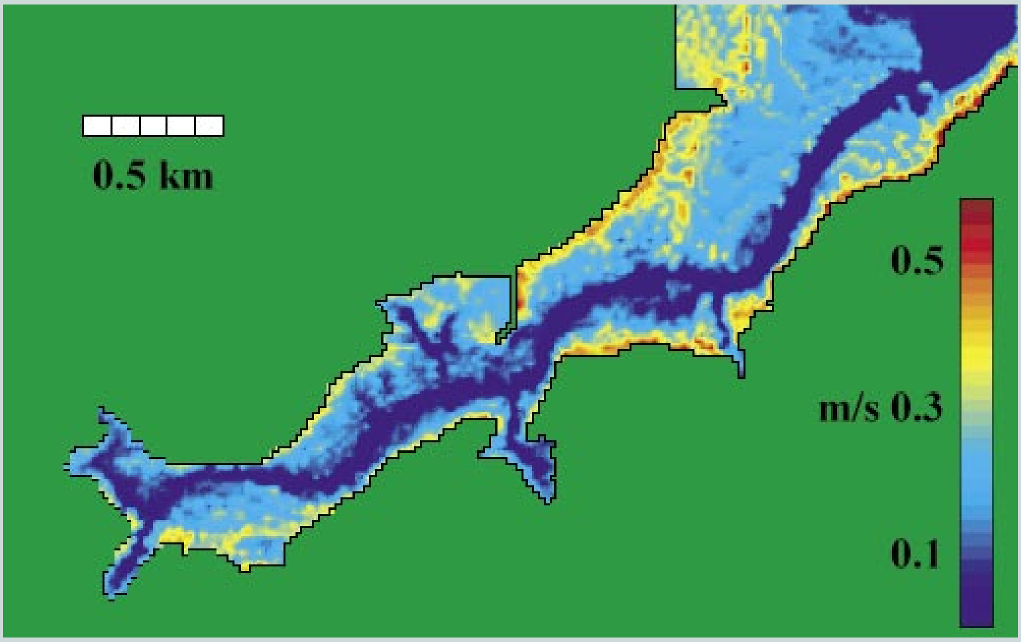
Tools of the trade in estuarine research

Sophisticated instruments are deployed in estuaries to measure sediment processes. The photograph (left) shows the instrumented tripod ALICE, with a full suite of sensors for measuring waves, currents, turbulence, bedforms and sediment movement (see *Water & Atmosphere* 4(2): 8–10). The lower photograph shows a DOBIE wave gauge deployed on an intertidal flat.

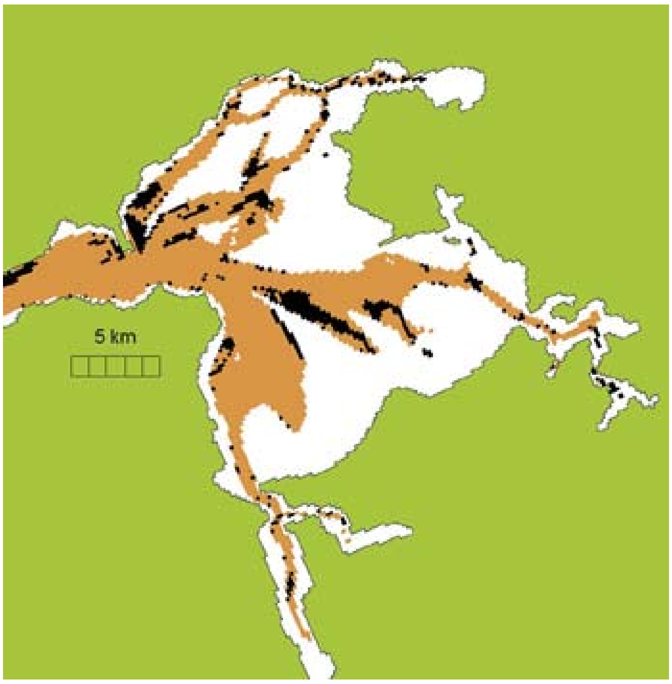
Numerical models simulate water movements caused by tides, winds, waves and rivers, and the resulting sand and silt transport over an entire estuary. Near-bed current velocities predicted by a hydrodynamic model and wave orbital velocities predicted by a wave generation model are used to compute sediment transport, both as migrating bedforms and by picking up and re-depositing suspended sediment. Changes in transport of sediment lead to a change in bed levels (either erosion or accretion). The illustration below shows output from a wave model of Okura Estuary, Auckland.

Instrumented tripod (ALICE) at Okura to measure near-bed currents, turbulence and sediment transport.

DOBIE moored in Okura Estuary (North Shore) for measuring waves on the intertidal flat.



Prediction of the wave velocity (m/s) at the bed in Okura Estuary using the WGEN computer model (developed by Prof. Kerry Black). The channel has low wave stirring, whereas the upper intertidal flats have high values.



Model simulation of the tidal channels of Manukau Harbour (see Green et al. *2000). Brown indicates ebb-tide dominance and black indicates flood-tide dominance. White areas are intertidal sandbanks.*

modelling showed that there was net seaward transport almost everywhere, except in the short side arms of main channels.

Intertidal flats

Outside the channels, tidal currents are weaker and water on the incoming tide gently floods adjacent shallow intertidal flats. Thus sediment falls out onto the flats, except when waves resuspend it. As the water deepens the waves have less and less effect on the sediment. Some fine silts and muds may be carried out to sea on the outgoing tide through the drainage channels.

Fringes

Along the intertidal margins, the incoming tide can move turbid plumes (originating from intertidal flats or catchment run-off) up into small, sheltered, tidal creeks or side arms. If conditions are calm then fine sediments settle out. These fringes are where mangroves love to grow, further enhancing sedimentation by slowing water movement.

Headwaters

The sediment carried by streams and rivers increases enormously following heavy rainfall. Some of this load is discharged directly into the ocean, but most settles down on intertidal banks and in shallow tidal creeks. Any sediment deposited in channels is soon scoured and re-deposited on intertidal flats and around the fringes of the estuary.

How do estuaries digest their sediment diet?

Despite all the sediment coming in, many New Zealand estuaries have remained as open-water bodies, even after 6000 years. This suggests that, in the long term, sediment build-up is limited by a dynamic balance between the effects of tides, waves and rivers on sediment inputs and outputs in different parts of an estuary. An important effect is the increased stirring of bottom sediment by waves as estuaries get shallower, which curtails further sediment deposition. Storms and floods can sometimes cause siltation, but this is usually washed out quite quickly.

However, there are cases where some of our estuaries have suffered from infilling because of excessive sediment run-off, either from urban development (e.g., Mangere Inlet in the Manukau Harbour) or from clearfelling of forests (e.g., Mahurangi Harbour). Clearly there is a very fine balance in the sedimentary "digestion system" of our estuaries. Their equilibrium can be easily upset by inputs arising from human disturbance, and also by any future changes in sea level. ■

All authors are based at NIWA in Hamilton.

Acknowledgements

This work is part of the FRST-funded research programmes "Effects of Sediments on Estuarine and Coastal Ecosystems" and "Physical Processes Affecting Estuaries, Coasts and the Continental Shelf".

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ESTUARIES

The dance of the turbid fringe

Malcolm Green

Waves at the edge of an estuary can cause surprisingly large amounts of sediment to disperse over quite long distances: what are the implications for the estuary ecosystem?

When out in a boat in the middle of a large estuary, we see wide expanses of deep water and we feel strong tidal currents. When we walk along the shoreline of the same estuary, however, we wade through shallow water that creeps sluggishly up and down the intertidal flats. Is there a connection between the two?

Certainly, the waves that break upon the estuarine shoreline are generated by wind blowing over the open expanses of water in the middle of the estuary, so that's one kind of connection. This can be inferred from an interesting phenomenon: when the tide drops and sandbanks in the middle of the estuary start to emerge from the water, waves along the downwind shoreline get smaller. What is happening is that the emerging sandbanks break up the "fetch" of water over which the wind blows to generate waves. In effect, the wind has to start all over again building waves every time it encounters an emerging sandbank (see figure below, right, and *Water & Atmosphere 10(2)*: 20–21).

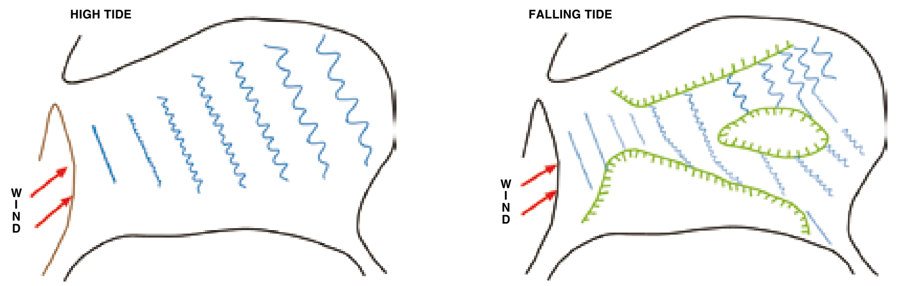
Wave action and the turbid fringe

What happens when the waves arrive at the estuary shoreline? Just like on an open coast, the waves stand up as they enter shallow water and then eventually break. Back-and-forth water movement underneath waves (the wave orbital motions) can stir up (suspend) bed sediments into the water. In the estuary, this happens in the so-called turbid fringe (see panel, opposite page, top), named because estuary bed sediments are usually muddy and the water turns brown and turbid when they are stirred up by waves.

The outer edge of the turbid fringe coincides with the depth at which wave orbital motions touch down on the bed. The inner edge of the band coincides with the depth at which waves have spent all their energy and decayed away to virtually nothing. This might be right at the shoreline, in which case "fringe" is accurate, or it might be somewhat offshore, in which case it is really a "turbid band".

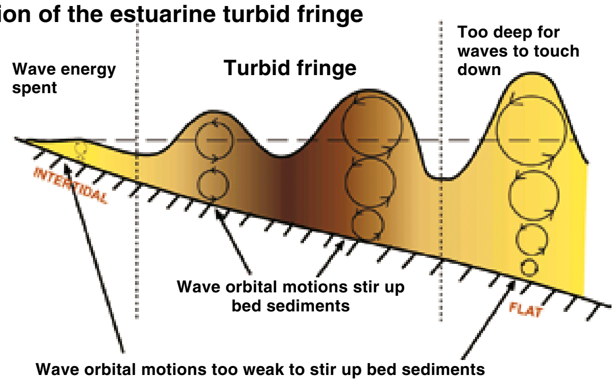
As the tide goes up and down in the estuary, the turbid fringe moves across the intertidal flats, expanding and contracting in a complicated dance that is controlled by the interaction between such factors as wave height, water depth, shape of sandbanks, and gradient of the intertidal flats. For instance, at low tide the fringe can be tiny or nonexistent since emerging sandbanks in the middle of the

Diagram of waves at high tide and low tide.



Malcolm Green is based at NIWA in Hamilton.

Formation of the estuarine turbid fringe



Cross-section of waves stirring up a turbid fringe. Interestingly, the same kind of thing happens on ocean beaches, but we are less aware of it for a couple of reasons. Firstly, the open-coast turbid fringe extends way past the seaward limit of the surf zone to depths of 10–20 m or more under the larger ocean waves. Secondly, the seabed is typically not as muddy as in an estuary, hence the fringe is not as muddy and is therefore harder to see. Note, there is still plenty of sand in suspension in the water, but it doesn't cloud the water like mud does, and it also stays closer to the seabed.

estuary prevent downwind wave growth, which switches off the turbid fringe. And at high tide it may be too deep for waves to penetrate down to the bed anywhere except right at the estuarine shoreline, which will also cause the fringe to contract.

Dispersal of sediments

Now we come back to connections. It turns out that the estuarine turbid fringe can stray from the intertidal flats where it is born, into the deep heart of the estuary. We know this from experiments in Manukau Harbour, Auckland, in which we have identified remnants of a turbid fringe moving down a deep tidal channel into the interior of the estuary on an outgoing tide. This has an interesting implication: sediments on an intertidal flat might be widely dispersed throughout the estuary by becoming suspended in a turbid fringe that then escapes down a deep tidal channel. If the sediments are contaminated, then such dispersal could spread environmental harm. On the other hand, dispersing sediments may not always be such a bad thing. For instance, sediments brought down in rainstorms can dump on and smother shellfish beds (see *Water & Atmosphere 10(4)*: 22–23). However, under the action of a turbid fringe, the dumped sediments may be picked up and dispersed in time to limit damage – a kind of natural defence against sediment attack. Either way, this connection between the centre and the edges of the estuary has implications for the health of the estuarine ecosystem.

We don't understand a lot about how turbid fringes get dispersed in the wider estuary. Part of the reason is that our numerical tidal-current circulation models, which we use to visualise and understand circulation patterns in the estuary, are weakest around the edges where we have wetting and drying. This means that they don't depict processes in those areas very accurately. We are presently working on improving our understanding of processes at work in the turbid fringe by making wave, current and suspended-sediment measurements. Our experiments are expanding our knowledge of connections and what these mean to the health of the estuary. ■

How much sediment is suspended in the turbid fringe?

Consider a round estuary, 10 km wide, with a 10-m wide turbid fringe running all the way around the edge. The area of the interior of the estuary is about 500 times that of the turbid fringe. If sediment is suspended to about the same height above the bed and the suspended-sediment concentration (SSC) is the same in both regions, then there are about 2 orders of magnitude (100 times) more sediment suspended in the interior than in the fringe. On the other hand, if the SSC is two orders of magnitude greater in the fringe, then there are about equal amounts of sediment suspended in the two regions. The latter is more like reality: SSC in turbid fringes is significantly higher than in the interior, sometimes more than two orders of magnitude greater.

Conclusion: there might be times when as much or more sediment is suspended in the turbid fringe as in the rest of the estuary.

Teachers: this article can be used for NCEA Achievement Standards in Biology (1.3, 2.4, 2.5) and Science (1.6, 3.5). See other curriculum connections at www.niwa.co.nz/pubs/wa/resources

ESTUARIES

Waves in shallow water

Murray Smith
Richard Gorman
Craig Stevens
John McGregor

Waves generated in shallow, enclosed estuaries can have a big impact on marine life. Computer modelling of these wave systems is helping us to predict their effects.

A familiar sight along New Zealand's coast is waves growing, steepening and breaking as they approach the shore. Even to the most casual observer it is clear these waves must have major impacts on any aquatic plants tough enough to grow beneath them. The waves can also stir up sediment, which can smother plants and prevent larvae settling and becoming established.

Waves in estuaries and harbours are less dramatic. While large ocean swells are usually prevented from entering these enclosed systems, local winds can still produce significant waves. Their effects on beaches, structures (e.g., jetties) and boats is well known, but they also play an important part in shaping the habitats beneath the water surface. The ecosystems in these areas adapt to smaller waves – for example, less robust plants can grow there.

In shallow estuaries, waves move the water close to the seabed, stirring up sediment and small animals, which can then be transported by tidal currents. While this process can be a problem in some situations, it can also be a blessing. For example, extreme rainfall events in the hills can send large amounts of clay down rivers, smothering estuarine plants and animals. NIWA studies have shown that without waves to stir up and remove the sediment, the marine life on the seabed can quickly die.

Waves, and the sand and mud they stir up, strongly affect the settlement and viability of plants along coasts and in estuaries. Kelp can survive in high wave-energy coastal settings such as this, where it is the dominant plant.

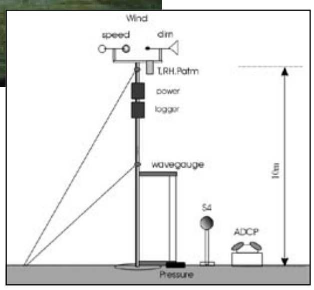
Manukau Harbour as an experimental site

Field experiments are essential in understanding wave processes and developing better wave models. Only by comparing model predictions with real life can we discover any missing elements of the models. Improvements based on these comparisons increase our confidence in the models' capabilities.

We used Manukau Harbour, adjacent to Auckland Airport, as a test-site for our modelling work. Manukau Harbour is one of New Zealand's largest intertidal estuaries. Like many other estuaries around the country Manukau Harbour has:

- a complicated bathymetry (bed shape);
- tidal variations in depth (up to 4 m);
- tidal variations in fetch;
- strong tidal current flows;
- adjacent rough and hilly landscape.

We took measurements at six sites along a 15-km line across the estuary using pressure sensors, current-meters, and high-frequency wire wave gauges. We also measured the wind speed at four sites across the estuary, which changed significantly according to the surrounding topography.



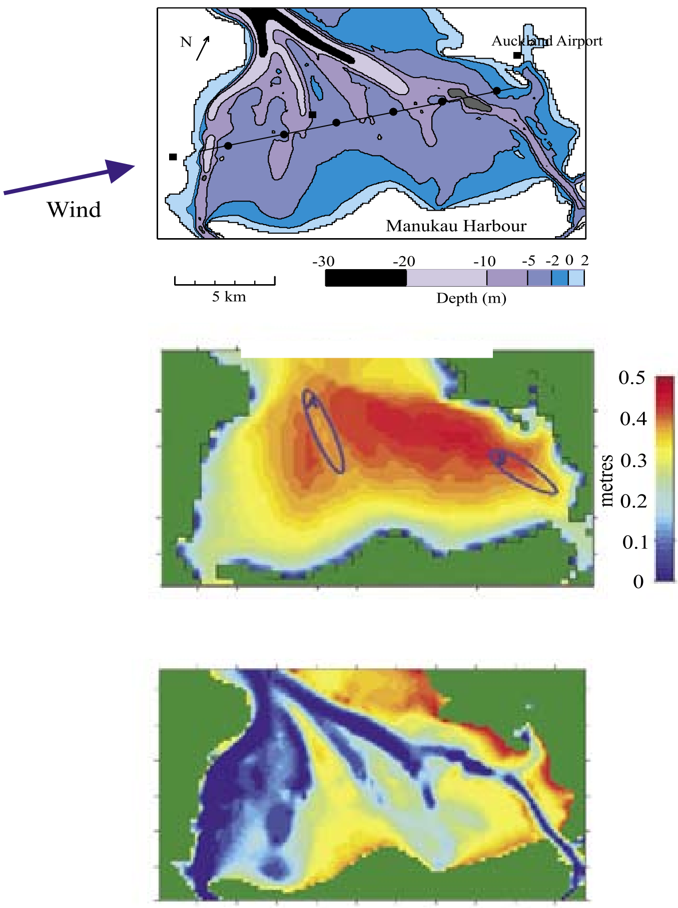
One of the recording sites – on a calm day. The diagram shows some of the instruments used: wave gauges, current meters (S4), current profiler (ADCP), and meteorological sensors.

Murray Smith, Craig Stevens and John McGregor are based at NIWA in Wellington; Richard Gorman is based at NIWA in Hamilton.

Wave modelling

The ultimate test of how well we understand wave processes comes when we compare our attempts to model and predict waves with actual wave measurements. We recently implemented the SWAN model for shallow-water studies. This model was first developed in the Netherlands, but researchers around the world can now use it and suggest improvements. SWAN is the current state-of-the-art tool for modelling waves. What sets it apart from earlier models is that SWAN aims to describe the physics of such processes as forcing and attenuation without making any assumptions about the structure of the waves that eventuate. **Forcing** is applied by the wind; **attenuation** refers to the reduction in size of waves by wave breaking and friction with the seabed.

For tidal estuaries we also have to model the changing water depth and currents. This allows us to predict the effects of wave action on the seabed as it changes through a tidal cycle. We can then determine how much sediment is being stirred up, or the effect of the waves on structures and plants. The results can be displayed on maps (below).



top: The complicated bathymetry of Manukau Harbour strongly affects wave development. The circles and squares show the position of the wave and wind measurement sites.

middle: The model provides maps of wave height across the estuary for various wind conditions. It clearly shows the reduction in size of waves across the shallow intertidal banks near the centre of the image (region A), and the movement of waves up the channels (region B) for a typical south-west wind.

bottom: The pattern of wave motion at the seabed is shown here using different colours: blue shows where there is little motion, and yellow-red shows where velocities are strongest. The seabed sediment is stirred up the most when high waves occur in shallow water.

Waves, wind, tides, turbulence

The wind initially feeds energy into small waves, increasing their height. When the waves have had enough time and distance to build up, they keep pace with the wind and stop growing. Waves with long wavelengths are more energetic than waves with short wavelengths: they not only travel faster, but also grow larger than short waves before toppling over and breaking.

In deep water, wave height depends on wind speed and on the distance (fetch) and duration over which the wind blows. This all changes in shallow water because waves interact with the seabed, causing them to slow down and lose energy, resulting in a reduction in wave height. Tidal currents are also important in estuaries. When the current is moving in the opposite direction to the waves, the waves slow down, more energy builds up, and the waves get steeper. This is why estuaries such as the Manukau Harbour, which has a large tidal range, can be deceptively dangerous for boaties.

It is common to assume that the wind is constant when trying to predict waves, but this is seldom the case. The land around estuaries like the Manukau Harbour can be hilly or have large vegetation that slows down wind-speed and makes it more variable.

In complex situations like this we need to use sophisticated computer models; it is not realistic to rely on simple relationships between wave growth and fetch. Models can be used to map variations in wave forces and sediment re-suspension, and to test the effects of different wind conditions (e.g., predicting the effects of waves during extreme weather events). These models can greatly improve our ability to predict and manage changes in our coastal environment. ■

Further reading

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Acknowledgements

This work is part of the FRST-funded research programme "Effects of Sediments on Estuarine and Coastal Ecosystems" (C01X0024).

MARINE FISHERIES

Let sleeping fish lie

Mark Morrison

Glen Carbines

Video photography of sleeping fish has proved to be an effective way of estimating fish population sizes.

Many small marine fishes can be difficult to visually count and measure because of a mixture of cryptic colouration patterns and behaviours designed to avoid larger predators. We have experienced this trying to count juvenile snapper (less than 10 cm long) within habitats such as seagrass and horse mussel beds. We know that they are there because we have sampled them using other methods, but we see virtually none during daylight SCUBA searches of these habitats.

We need information on the absolute numbers of fish in an area to underpin applications such as management of fisheries and marine protected areas, habitat protection, and assessing habitat degradation. However, most sampling methods measure relative rather than absolute abundances. In other words, they account for only a portion of the fish in the sampled area, and we don't usually know the size of that portion.

During work on juvenile snapper and their habitats in Mahurangi Harbour (Auckland) we made an important discovery while doing some night diving. We encountered numerous small snapper sleeping on the seafloor. They were oblivious to the divers' powerful torch-lights, and could be measured in-situ. If we were careful, they could even be collected using small aquarium dip nets. The behaviour was also observed for other common inhabitants of estuaries including larger snapper, goatfish, gobies, and sand and yellow-belly flounders.

A goatfish (about 7 cm long) on open sediment. (Photo: Richard Taylor, Leigh Marine Lab)

This finding was significant as it meant that we now had a means of estimating the absolute numbers and size distributions of fish. With good water clarity, counts could be done by divers at night. However, dive counts are logistically difficult and time-consuming.

New research tool

To apply our finding more efficiently, we turned to a fish-sampling system originally developed to collect fish and habitat information in the difficult and diver-hostile environment of Foveaux Strait. The system, called a DUV (drop underwater video), consists of an underwater camera system attached to a towed device with a live cable link back to the support boat. Laser scaling of the seafloor, digital image recording, and video-linked GPS positioning allow the device to be towed just above the seafloor. This enables accurate measurement of seafloor features and fish abundances over almost all terrains, with no physical impacts on the seafloor.

A juvenile snapper (about 6 cm long) photographed at night. (Photo: Richard Taylor, Leigh Marine Laboratory)

We deployed a DUV system in Mahurangi Harbour during darkness. With oven-proof wax paper taped over the dive-torches to provide diffuse illumination, the system worked very well. The fish were completely unaware of its presence until the last moment (or not at all). The video laser system allowed us to determine the area surveyed, as well as fish lengths. We could also obtain habitat information from the video images.

Our new system yielded valuable information on snapper densities, population size frequencies, and habitat associations. Other data collected at the same time using different techniques will allow us to assess the effectiveness of the new approach. Preliminary work on adjacent coastal areas has shown that the system works well in other habitats. For example, trial night tows in a rocky reef area have allowed us to count snapper, John Dory, and big-eye (a nocturnal plankton feeder that hides in crevices during the day).

New technology combined with a better knowledge of fish behaviour makes this night-time underwater video system an exciting addition to our fish research tool-box. All our methods contribute to a better understanding of how juvenile fish use nursery habitats, with the eventual aim of ensuring that fish populations remain productive and healthy. ■

Mark Morrison is based at NIWA in Auckland and Glen Carbines is at NIWA in Dunedin.

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MARINE FISHERIES

Intertidal flats in estuaries: are they useful to fish?

Mark Morrison
Malcolm Francis
Bruce Hartill
Derrick Parkinson
Michelle Wilkinson

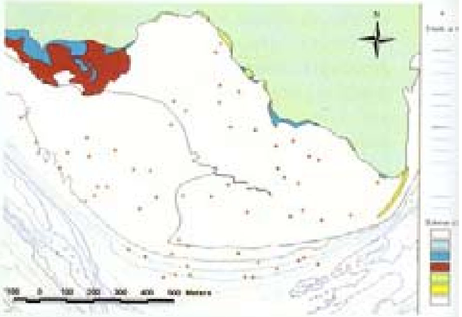
New Zealand has more than 300 estuaries spread along its coastline. The role these play in the life-cycle of coastal fish species is very poorly understood. Research is underway to improve our knowledge of how fish use these potentially important – yet vulnerable – areas.

ONE OBVIOUS FEATURE of many of our estuaries and harbours is the extensive areas of intertidal mud and sand banks. For example, 40% (136 km²) of the Manukau Harbour in Auckland is intertidal. These flats can be highly productive, supporting dense concentrations of bivalves and other benthic species. Their importance to fish is considerably less well known, although they may play a major role as nursery habitats. Currently, even basic information is not available. What fish species are present? Which tidal zones and associated habitats are most important to them? What are they feeding on, and when? We wish to answer these questions in order to determine the potential impact of human activities on estuarine habitats. Our eventual goal is to produce habitat risk assessment models that will allow resource managers and other interested groups to incorporate this information into their decision making.

How do you sample an estuary?

To sample shallow waters immediately adjacent to the shoreline, we can use fine-mesh beach seines (9 mm mesh), dragged on to the shore at the end of each tow. This works well for the shore areas but as soon as we want to start sampling fish in deeper waters we run into problems.

Standard fish sampling gear simply doesn't work in such situations. For example, beach seines need a shoreline for retrieval, while standard trawl and gill nets have meshes too large to retain the small fish that we are interested in. Beam trawls (low box nets towed across the seafloor) do catch fish species associated with the sea floor – benthic species (e.g. flounders and soles), but fail to catch those species often found higher up in the water column – the pelagic and semi-pelagic species (e.g., yellow-eyed and grey mullets, piper and anchovies). We need a type of gear that catches all of the species present and that can be deployed in open waters away from the shoreline and in waters too deep and/or on seafloors too muddy to be worked by manually hauled nets.



above right:
Map of Wattle Downs sites, Manukau Harbour, showing substrates, and sampling locations (red dots).

Our solution was to build a hybrid between a beam trawl and a beach seine – an "outrigger" trawl. We already possessed a 6-m sampling barge, the *Patiki*, built to work in shallow estuarine waters. We rigged up a modified form of beach seine on a boom supported by an outrigger on one side of the barge. This net would be pushed, rather than towed, reducing potential boat avoidance by the fish and keeping the net clear of the barge's twin propellers. The net was built to fish depths from 0.5 m (the minimum operating depth of the barge) to 4 m (close to the maximum tide range in northern west-coast harbours).

An 8 hp outboard engine, remotely operated, was added to the outrigger to combat the drag induced by the net, which otherwise forced the

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barge to go around in circles. A long cod-end, with choker rope, was incorporated to allow us to retrieve the catch at the end of each tow without having to haul the whole net from the water.

Sampling location

We knew from previous sampling that large numbers of the juveniles of several fish species live in the Pahurehure Inlet of the Manukau Harbour. A medium-sized tidal flat (approximately 800 m by 1 km) was selected as a study location, and its bathymetry sampled using a manually deployed RTK GPS system which accurately maps position and height. Deep mud over most of the study area made this a very strenuous process. From these data, a tidal elevation model (a contour plot of the tidal heights) was built to assist in designing our fish sampling programme and in interpreting our findings.

Sampling design

Fish usage of tidal flats is likely to be dynamic, driven by the state of the tide (obviously tidal flats are not available at low tide) and other key factors such as the day–night cycle. Therefore we incorporated tidal state (high/low) and time (day/night) into our fish sampling design. Sampling the shallow water near the waterline at low tide is also important, to assess whether juvenile fish might use these areas as "holding areas" when the tidal flats are not available, and then migrate on to the tidal flats as the tide floods in.

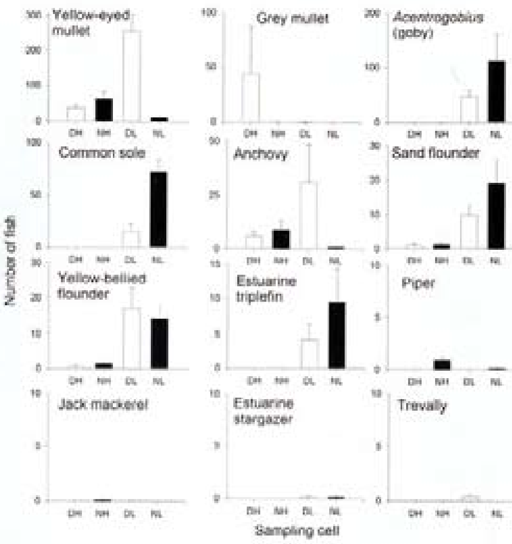
For the beach seine sampling, fish were collected over both high and low tides, day and night. Only the first 20–50 m of water immediately adjacent to the shoreline could be sampled using this method. For the outrigger trawl, sampling stations were placed across the full range of tidal heights over the high-tide periods, while for low tides only the area alongside the low-tide mark was sampled. As with the beach seining, both day and night periods were sampled.

Samples of fish were retained from each of the treatments to assess gut contents and fullness. This allowed us to get a better picture of what fish were actually doing in terms of their feeding over the different times and tides sampled.

Some results to date

Beach seining was completed at eight stations at high and low tide during the day and night. The results showed some clear patterns.

- Species diversity and fish abundance were greater over low-tide periods, for both day and night sampling. This is not surprising, given that fish are concentrated by the falling tide into limited habitat, but it does suggest that some species are not moving fully into the high-tide zone as the water returns (*Acentrogobius* (goby), estuarine triplefin, common sole, estuarine stargazer). Some of these are small benthic species for which large-scale movements over a short time are unlikely. The lower abundance of other fish over high tides (yellow-bellied and sand flounders) suggests that these species may spread widely across the tidal flats at high tide.
- Yellow-eyed mullet and anchovy were caught in highest abundance during low tides, but only during the day. At night, they were almost absent from the immediate sub-tidal zone. Large numbers of mullet were observed feeding further offshore on the surface during the very early hours of the morning. This suggests they may feed nocturnally and may use the shallow zone adjacent to the shoreline at low tide during the day as a holding area only.
- Piper were caught only at night, suggesting some form of net avoidance during the day (they have been taken during daylight sampling with the outrigger trawl).
- Most grey mullet captured were in one large school of 1-year-old fish (14–19 cm), which was only partially sampled (these fish are very fast and many escaped). Grey mullet of this size are seldom encountered in our larger-scale beach-seining programme.



Abundances of fish species caught by beach seining (no. per tow). Eight sites have been sampled for each tide state/day–night combination. Vertical lines above each bar are standard errors. DH, day high; NH, night high; DL, day low; NL, night low.

We used a multivariate statistical technique known as Correspondence Analysis to identify fish assemblages. Grey mullet and three rare species (piper, jack mackerel and trevally) were omitted from this analysis. Yellow-eyed mullet and anchovy contrasted strongly with the other five species along the dimension 1 (i.e., this difference accounted for the greatest proportion of explainable variability in the data set). This results from the low abundance

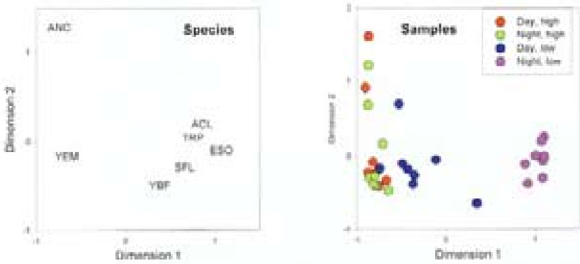
The outrigger trawl net. (Also see front cover of this issue.)

of yellow-eyed mullet and anchovy in the night-time low-tide samples, due to offshore movement. The remaining species were abundant in low-tide samples at night. Yellow-eyed mullet and anchovy separated out along dimension 2. Although these two species had similar patterns of mean abundance among the four day–night/tide combinations, anchovies were more variable in their abundance, and were often uncommon or absent from tows that contained large numbers of yellow-eyed mullet. Not surprisingly, the night-time low-tide samples had a catch composition that was quite distinct from all other samples. Day-time low-tide samples were also distinct from the high-tide samples, which differed little between day and night.

The outrigger trawl data showed clear evidence that different species were accessing different parts of the intertidal areas over high-tide periods. There was a clear decrease in fish abundance at around 300 m above the low-tide mark. Most of this abundance was in the form of high numbers of anchovies. For the flatfish species, yellow-bellied and sand flounders were found across the full extent of the intertidal zone, but the common sole ranged only about 300 m up from the low-tide mark. This result was consistent with the beach seine sampling: no soles were caught during the high-tide sampling, but they were present at the low-tide stations.

Among the semi-pelagic species, anchovies were only found in any numbers up to 300 m above the low-tide mark, while yellow-eyed mullet were more cosmopolitan, occurring across the full extent of the tidal flats. The small benthic-associated species (a goby and a triplefin) only extended in range to approximately 300 m and 150 m respectively into the intertidal flats during high tides. This matched up well with the high-tide beach-seine results, where these species were not present. This is consistent with what we might expect for small benthic species that are not great swimmers and run the risk of being stranded with rapidly falling tides on such low-slope intertidal areas.

Other species were caught, but in numbers too low to make meaningful comments on their distribution on the tidal flat.

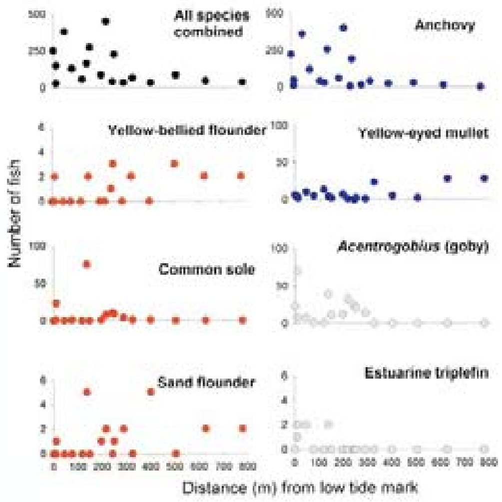


above:
Correspondence analysis plots for species and tide/time combinations. ANC, anchovy; YEM, yellow-eyed mullet; YBF, yellow-bellied flounder; SFL, sand flounder; TRP, triplefin; ACL, Acentrogobius (goby); ESO, common sole.

Outcomes

Once we have completed a formal analysis of this work, we will have a much clearer picture of the dynamics of fish usage of estuarine tidal flats. Those results will be incorporated into ongoing work to determine what fish species are closely linked to estuaries, which habitats are most critical to them, and how potential changes in such systems may adversely impact on fish species and assemblages. For example, in systems where the intertidal flats are several kilometres wide, it may prove that only the lower tidal portions are heavily used by fish, and that areas further away from channels are of little relative importance.

This coming summer, we intend to undertake a large-scale fish sampling survey of about 25 estuaries throughout the northern North Island. The results from the current work clearly show that beach seining at low tide is the best way to maximise the number of species encountered and to allow collection of adequate numbers of fish for estimating juvenile population size structures. ■



below left:
Catch rates of fish by the outrigger trawl for the night/high tide treatment. Distance is measured from the mean low-tide mark. Symbol colour denotes a species functional group: black, all; red, flatfish; blue, semi-pelagics; grey, small benthic species.

Acknowledgements

We are very grateful for the expertise of Dave McIntosh in designing and building the outrigger trawl net. Also, thanks are due to field and measuring assistance from Cameron Walsh, Karen Field, Helena Cadenhead, Virginie Binet-Traineau and Martin Cryer.

Mark Morrison, Bruce Hartill, Derrick Parkinson and Michelle Wilkinson are based at NIWA in Auckland, while Malcolm Francis is at NIWA in Wellington.

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ESTUARIES

Bugs ‘n’ mud – a sticky problem

Sharon Stephens
Mal Green
Conrad Pilditch

The seabeds of our estuaries are inhabited by an array of organisms, including the more obvious crabs, worms and shellfish. But what about the bugs – or, more specifically, the microbes – and why should we be interested in them?

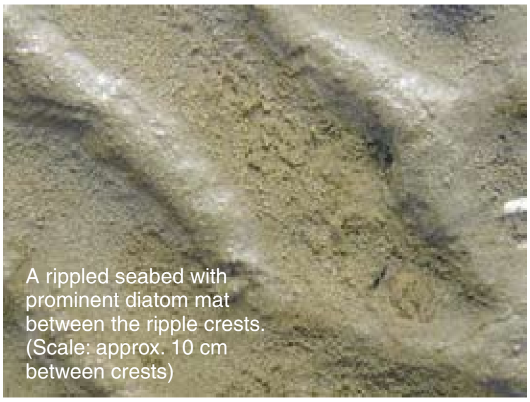
What do muddy water, shoreline erosion, mass kills of shellfish, and siltation of marinas and navigation channels have in common? No, it’s not bugs (they come soon), it’s sediment transport – the erosion, movement and deposition of sediments. Sediment transport affects just about every physical and biological feature of our harbours and estuaries. Hence, the ability to accurately predict sediment transport is a key tool in the maintenance of the integrity of these valued coastal areas. For example, if we know that land erosion associated with forest clearfelling is going to eventually result in a layer of mud on a particularly sensitive estuarine habitat, then we can take steps to protect that habitat. For example, appropriate sedimentation ponds could be established between the site of tree-felling and the estuary.

Microbes in sediment

Although great strides are being made in understanding estuarine sediment transport and in transferring that knowledge to predictive models, progress has been limited by a demonstrably wrong assumption: that the movement of sediment is not affected by biological processes. (The critic would explain this situation by pointing out that biology introduces all kinds of complexities – mathematical and physical – into sediment-transport models, and so it is usually put in the “too-hard basket”.)

Enter the microbes and their mucous secretions that they use for attachment and locomotion in a sediment world. These mucous secretions bind grains of sediment, potentially making its erosion more difficult. Microbes can therefore be viewed as “sediment stabilisers”. Herein lies our interest in bugs ‘n’ mud: a more accurate picture of the forces needed to start erosion – taking microbial processes into account – can be used to build more accurate sediment-transport models, which in turn can be applied in real-world problems with more confidence.

How have we gone about it? The first hurdle was to find a way to measure something we cannot see with the naked eye. Microbes in abundance are often noted as green-brown patches on the estuary floor, but even then we cannot count them. We can, however, collect small samples of sediment and estimate microbial activity using proxies: the amount of chlorophyll *a* (a light-capturing pigment used in photosynthesis) and carbohydrate in the samples. These are indicators for microbial biomass and sediment mucous content, respectively. Both measurements are necessary because different species of microbes produce different amounts of mucous, hence measurements of chlorophyll *a* and carbo-hydrate will not necessarily correlate.



A rippled seabed with prominent diatom mat between the ripple crests. (Scale: approx. 10 cm between crests)

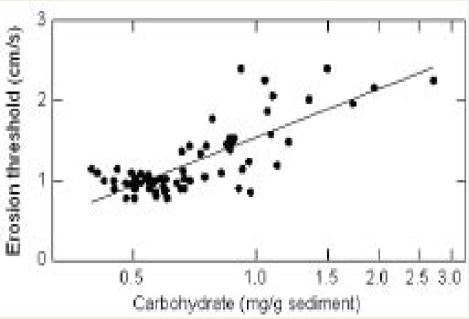
Mud stabilisers

As well as microbial abundance and sediment mucous content, we can also measure erosion threshold (see “Measuring sediment erosion...”). So it is now possible to determine how effective bugs are at stabilising seabed sediment. This has involved making many measurements in different kinds of estuaries – sandy vs. muddy and sheltered vs. exposed. We expect the type and number of microbes to differ between sandy and muddy sediments. Thus the amount of mucous produced and therefore the degree of sediment binding will differ both within and between estuaries. In addition there will be variability through time because seasonal changes in both weather and macrofauna are likely to

Sharon Stephens is a University of Waikato PhD student based at NIWA in Hamilton, under the supervision of Conrad Pilditch (Department of Biological Sciences, University of Waikato) and Mal Green (NIWA Hamilton). Her study is funded by a FRST Bright Future Scholarship (Top Achiever Doctoral) and is a part of NIWA’s FRST-funded programme Effects of Sediments on Estuarine and Coastal Ecosystems (C01X0024). The Sea Carousel project and Mal Green’s participation in that work were sponsored by the Geological Survey of Canada (Atlantic).

affect microbial communities. (Macrofauna are animals larger than 0.5 mm, which live in the seabed. They include worms and shellfish.) Our fieldwork is ongoing.

Next is the number crunching, with the aim of finding a biological predictor of erosion threshold. We are looking for good relationships between the indicators of microbial activity and erosion threshold (see graph below). Indicators with the best prediction potential are being incorporated into sediment-transport models.



A good relationship between bed sediment carbohydrate (indicating mucous content) and erosion threshold, Okura estuary, east coast, 25 km north of Auckland. Incorporating this relationship into a sediment-transport model of the estuary could provide more accurate simulations of turbidity, sedimentation and siltation.

Sound simple? Well of course things are never as clear-cut as they seem, and this study is no exception. Because of disturbances, the presence of microbes does not guarantee sediment binding. For example, storm waves may break apart sediment bound together by microbes, leaving behind the microbes (and the associated indicator) but with no binding effect. To understand this type of stabilisation–distur-bance relationship, we are also measuring erosion threshold and microbial activity before, during and after storms. Another complication is that the animals living in the sediment can interfere with stabilisation by feeding on microbes. We are using experiments in enclosures to investigate these interactions.

Our results have shown that microbes can increase erosion threshold by up to a factor of three compared with abiotic sediments. A pattern emerges: microbial abundance and sediment mucous content increase as sediment grain-size grades from coarse sand to fine mud. In tandem with this change, there is an increase in the erosion threshold over that for equivalent abiotic sediment. This indicates a quantifiable link between sediment stability and microbial activity.

It's time to retrieve this one from the too-hard basket! ■

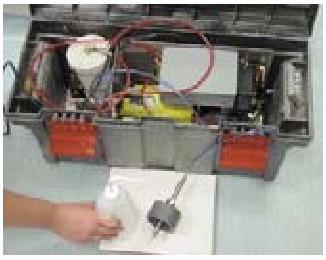
Measuring sediment erosion threshold: the toolkit

Laboratory instrument: Waikato recirculating flume

The Waikato flume is 7.25 m long and 50 cm wide with flow up to 30 cm deep. Cores of estuarine bed sediment are inserted through the base so that they are flush with the flume floor. They are then exposed to increasing flow speeds. We note the instant at which surface sediment grains are first dislodged by the flow. The flow speed at this time is used to calculate the sediment erosion threshold.

Unfortunately, the physical characteristics of the sediment cores (e.g., grain packing, water content) may be altered during transport of the core to the lab. Therefore we complement the laboratory flume with field instruments...

Field instrument 1: Cohesive strength meter (CSM)



The CSM is portable, easy-to-use and gives quick readings. It fires a jet of water at the sediment surface in short pulses. The force of the jet is progressively increased until the erosion threshold is crossed. The CSM is used to survey sediments throughout estuaries and at different times of the year to assess spatial and temporal variability in sediment erodibility.

Field instrument 2: NIWA submersible in-situ flume

The NIWA submersible in-situ flume gives more detailed results than the CSM. It is shaped like an inverted "U", and is equipped with optical backscatter sensors, photodetectors, a water sampler and a current meter. As in the Waikato recirculating flume, water is accelerated through the flume by a propeller. Since the NIWA flume has no bottom, measurements can be made on undisturbed in-situ bed sediments that are exposed to the accelerated flow along the length of the inverted "U".

NIWA scientists participated in a series of North American experiments along Maine's rocky shoreline using the in-situ "Sea Carousel" annular flume, an instrument developed by the Geological Survey of Canada (Atlantic). The purpose of these experiments was to measure the erosion threshold of waste (a combination of unused food and fish faeces) that accumulates below fish farms. The results are being used by GSC (Atlantic) to refine models that predict dispersal of waste by waves and currents and associated effects on the coastal ecosystem.

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MARINE ECOLOGY

Determining impacts on marine ecosystems: the concept of key species

Pip Nicholls

When one marine animal has a large influence on other parts of its ecosystem, we call it a key species. These animals can be very useful in monitoring programmes.

One of the goals of marine ecology is to detect and assess the scale of human effects – such as scallop dredging, heavy metal contamination or increasing turbidity – on marine ecosystems. In these complex systems, making simple predictions can be difficult in all but the most catastrophic circumstances and the search for a quick, foolproof solution for measuring the effects of human impacts has been going on since the 1960s.

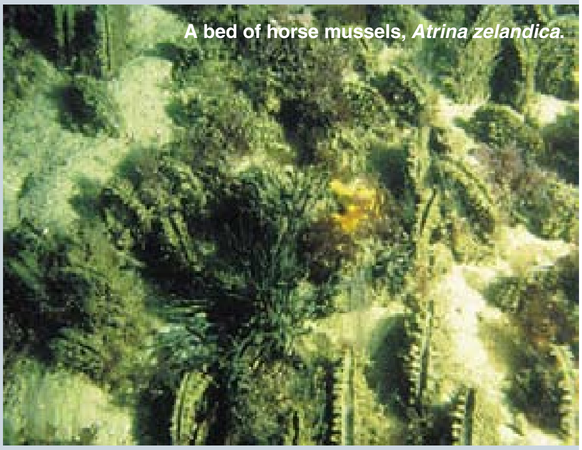
The best information on ecological changes over time comes from research and long-term monitoring programmes that sample the wide range of organisms that make up the marine community. Using **indicator** and **key** species in conjunction with these broad-scale methods adds weight to our predictions and offers a way to reduce costs and time. What are the differences between these two categories of species? And what makes key species so useful in monitoring programmes?

Indicator species

Indicator species change their behaviour, abundance and/or physiology in response to stresses in their environment. Criteria for selecting indicator species will depend on the reason for monitoring. For example, we might want to detect short-term behavioural/physiological responses like the change in the rate of bivalve shell-gaping in response to temperature. Or we might be interested in longer-term chronic effects, like oyster shell deformation.

Many indicator species are chosen on the basis that they are relatively abundant and widespread, so they are easy to sample and are tolerant of a wide variety of environmental conditions.

An important advantage of using indicator species is that extensive research has been done on their responses to certain conditions. For example, they may provide accurate information about the levels of contaminants in an area. A major disadvantage is that they tell us nothing about the potential for impacts on other species or parts of the ecosystem. Indicator species are also not so useful for monitoring disturbance-type impacts, for example, dredging, dumping and changes in water flows.



A bed of horse mussels, *Atrina zelandica*.

Key species

Key species are not linked to the detection of impacts but to understanding ecological processes. Key species are those that either directly or indirectly modify other parts of the community, as in the following examples.

- Key species can exclude or promote other species. For example, even in low densities the wedge shell (*Macomona liliana*) can decrease the abundance of juveniles of a number of bivalve species through its feeding activity. In turn, *Macomona* density can be controlled by shore birds and rays (see Thrush *et al.* 1994, 1997).
- A key species can affect energy flows or transfer food from one part of the ecosystem to another. For example the horse mussel (*Atrina zelandica*) extracts small particles (algae, bacteria, sediment) suspended in the water column. The material excreted by the mussels onto the surrounding sea floor is then used by smaller organisms (see Cummings *et al.* 2001, Norkko *et al.* 2001).
- Some key species are known as ecosystem engineers because they physically modify the environment around them. For example, burrowing shrimp (*Callianassa filholi*) make large burrows beneath the sediment surface and produce mounds on the sediment surface,

Teachers: this article can be used for Biology L8 A.O. 8.1a. See other curriculum connections at www.niwa.co.nz/pubs/wa/resources

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altering the sediment geochemistry and water flow and providing refuge for other species (see Berkenbusch *et al.* 2001).

In general, it seems practical to monitor key species because if they decrease in abundance, size or activity, the rest of the ecosystem will change. For this reason key species can be used not only to monitor impacts, but also to manage ecosystems and to predict effects.

In order to be able to manage and predict, we need to know a lot more about key species than that they affect the organisms around them. We need to know how sensitive they are to various changes in their environment and we need to study their population fluctuations over time. With research, it is possible to turn a key species into an indicator species, combining the advantages of both. This is being done both in New Zealand and overseas.

Key species as indicators

In New Zealand the horse mussel, *Atrina zealandica*, is a good example of a key species that has potential as an indicator. *Atrina* filter their food out of the water column and can remove up to 80% of small particles from the water in the process, affecting phytoplankton concentrations and water clarity. They protrude from the sea floor and this affects how sediment is carried around and settles out on the sea bed. In turn, this affects the structure and diversity of animals living near the sea floor.

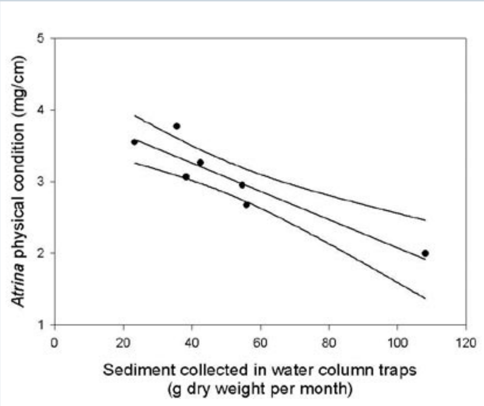
Atrina are sensitive to increased sediment suspended in the water column and transplant experiments have shown there is a direct relationship between increasing sediment concentrations in the water column and decreasing *Atrina* condition (where condition refers to the size and weight of these shellfish). Thus *Atrina* have the potential to offer a reliable and cost-efficient way to monitor increasing sediment loading in estuaries (see Ellis *et al.* 2002).

Our research into using key species to complement community-scale monitoring involves two phases. First we determine the role of a species, and identify how it affects the rest of the ecosystem. Then we investigate the responses of the key species to various changes in the environment.

Already we are using key species as indicators for a variety of environmental changes in long-term monitoring programmes. This is particularly valuable and is helping us to improve our understanding of changing ecological processes so that we can manage habitats and predict changes with greater confidence. ■

Burrows of the shrimp, *Callianassa filholi.*

Research on key species is undertaken in NIWA's FRST-funded programmes: "Effects of Sediment on Estuarine and Coastal Ecosystems" and "Fishing: Ecosystem Effects and Resource Sustainability".



Graph showing the condition of the horse mussel, *Atrina*, at different concentrations of suspended sediment.

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MARINE ECOSYSTEMS

Burrowing by heart urchins:
an important function in soft-sediment ecosystems

Drew Lohrer

Small animals burrowing in the mud at the bottom of the sea could play a key role in increasing the productivity of our coastal waters.

Drew Lohrer is based at NIWA in Hamilton.

Living organisms affect the physical, chemical, and biological aspects of their environment. The complex feedbacks between the environment and its inhabitants have become a major research focus in the last 10 years, as scientists have begun to probe the linkages between biodiversity and ecosystem functioning. One motivation for such research is to improve public awareness of the need to preserve biodiversity. If the loss of species changes the way an ecosystem works to the extent that benefits to humans are affected, then the importance of biodiversity becomes more tangible.

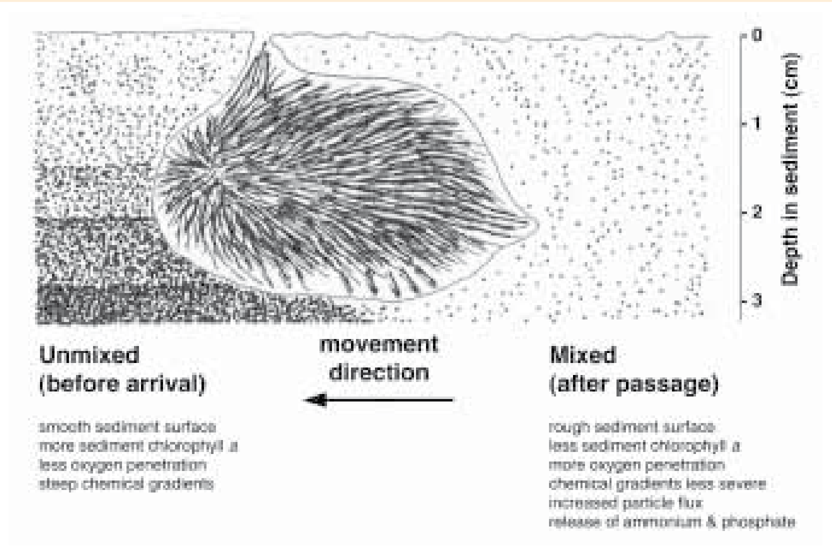
Each species in a community occupies a position in the food web and contributes to community dynamics. The loss of some species may significantly alter ecosystem processes. *Key species* are those whose presence and activities strongly influence the chemical or physical features of the habitat. For example, recent work has identified the native horse mussel (*Atrina zelandica*) as a key benthic species (see *Water & Atmosphere 10(2)*: 22–23). Its large shells create physical structures and vertical relief in marine soft sediments. These provide points of attachment for sponges and soft corals as well as shelter from predators for small fish and invertebrates. Furthermore, the diversity of other animals tends to increase around *Atrina* beds because of sediment enrichment associated with horse mussel feeding.

Horse mussels are a common and conspicuous example of a key species. However, there are other key players in estuarine and coastal marine soft-sediment systems that are not so easily seen.

Heart urchins: nutrient distributors

Heart urchins (*Echinocardium australe*) are common but cryptic animals living in the soft-sediment habitats of New Zealand. A scuba diver with a trained eye may observe a small ventilation slit in the surface of the sediment, or a characteristic track, but even these tell-tale signs are often missing. The sediment-coloured urchins, no more than 4 cm long, move with almost imperceptible slowness beneath the sediment surface.

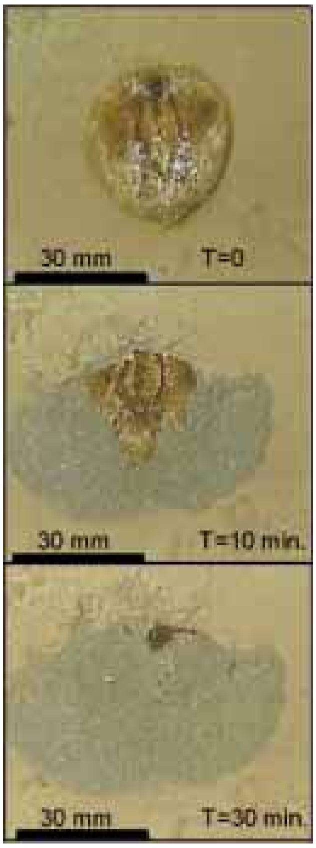
Heart urchins ingest organic matter and microscopic plants as they move horizontally in the upper 3–4 cm of the sediment. As shown below, the movement of the animals displaces sediment particles, a process called bioturbation. This movement can disrupt the chemical gradients in the water within the



Echinocardium movement in benthic soft sediments: a caricaturised cross-sectional view. *Echinocardium* probably influences several variables as it moves and feeds beneath the sediment–water interface. Undisturbed sediment will develop distinct horizons and interstitial pore-water gradients, but sediment will be mixed and the gradients destabilised as the animal moves. The top 3–4 cm of the sediment column will be most affected.

sediments (known as pore water), thus influencing the transport of oxygen and nutrients across the sediment–water interface.

The nutrients in sedimentary pore water are the fuel that supports the growth of microscopic algae both in the water (phytoplankton) and in the sediments (phytobenthos). The algae in turn are an important source of food for soft-sediment organisms and indeed the base of the entire marine food web.



Echinocardium after placement on the sediment surface in a laboratory microcosm (top), and 10 and 30 minutes later (middle and bottom).

Sediments on continental shelf areas (where burrowing urchins are widely distributed) can provide one-third to half of the nutrients in overlying waters. Therefore, these areas contribute significantly to marine primary productivity and support many of the world's fisheries.

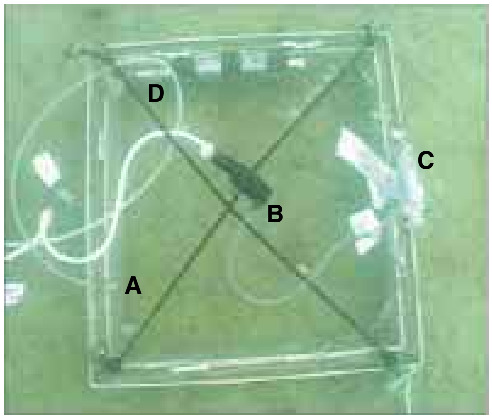
Measuring heart urchin effects

Using underwater time-lapse video recordings, combined with direct measurements in the field, we assessed the rates and patterns of *Echinocardium* movement (left). We found that the urchins generally move less than 1.5 m per day. However, given the large volume occupied by each urchin, a substantial amount of sediment is displaced by each individual. Furthermore, at densities of up to 70 urchins per square metre of seafloor, their collective effects are quite impressive. As much as 15 litres of sediment per square metre can be displaced each day.

Because bioturbation can influence the transport of nutrients across the sediment–water interface, we performed field experiments to measure the ultimate effects of *Echinocardium* on the transport of nutrients between sediment and water. Using incubation chambers, we isolated square patches of seafloor along with about 25 litres of bottom water (illustrated above). Before fitting the chamber lids, we added or removed *Echinocardium*, so that there were treatments with 0, 4, 8, or 16 urchins per chamber. Then, by sampling the chamber water over time, we were able to relate changes in water chemistry to the density of *Echinocardium*.

Flux rates did depend on the density of *Echinocardium* inside the chambers. This was true for oxygen moving into sediments and for dissolved nutrients – phosphate, ammonium and nitrate – moving out into the water.

However, oxygen and nutrients are also used



Benthic flux chamber with clear lid on the seafloor in Mahurangi Harbour. Sixteen chambers (8 with clear lids, 8 with opaque lids) were used in each of two experiments performed in 2003. Densities of *Echinocardium* were manipulated inside the chambers, and nutrient fluxes were measured in response. The area of seafloor enclosed by the chamber is 0.25 m^2 (50 cm x 50 cm).
A, sampling port with tube that extended to surface 6 m above
B, stirring motor used to gently mix chamber water
C, syringe to spike chamber water with tracers
D, oxygen and depth logger.

by organisms in the chambers, and this affects the concentrations that we can measure. Therefore, we also injected an inert chemical tracer into the chamber water at the start of the experiment. The inert tracer allowed us to estimate the amount of sediment mixed by *Echinocardium* movement, because the tracer penetrates faster and deeper into sediments that have been stirred up. The other water chemistry data showed the net effects of *Echinocardium* bioturbation, namely the provision of nutrients (phosphate, ammonium and nitrate) to the water column.

The feedbacks between urchin movement, nutrient efflux, and the growth of marine plants are still not well understood. However, with the data we have gathered so far, we can begin to model the linkages between water and sediment that are influenced by heart urchins. We aim to find out exactly what difference it would make if heart urchins were removed from the system. Since marine soft-sediment habitats support a broad array of desirable finfish and shellfish species and affect global elemental budgets (e.g., the carbon cycle), it is important to study the key species within them and the structural and functional roles they perform. ■

Teachers: this article can be used for NCEA Achievement Standards in Biology (2.5, 2.9, 3.2). See other curriculum connections at www.niwa.co.nz/pubs/wa/resources

This research was carried out as part of NIWA's FRST-funded programme "Fishing: Ecosystem Effects and Resource Sustainability" (C01X0212).

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MARINE BIODIVERSITY

Marine soft sediments: more diversity than meets the eye

Drew Lohrer
Nicole Hancock

Experimental work with sand and mud habitats highlights the importance of biodiversity from the bottom up.

Teachers' resource for NCEA AS: Biology 2.5, 3.2. See www.niwa.co.nz/edu/resources

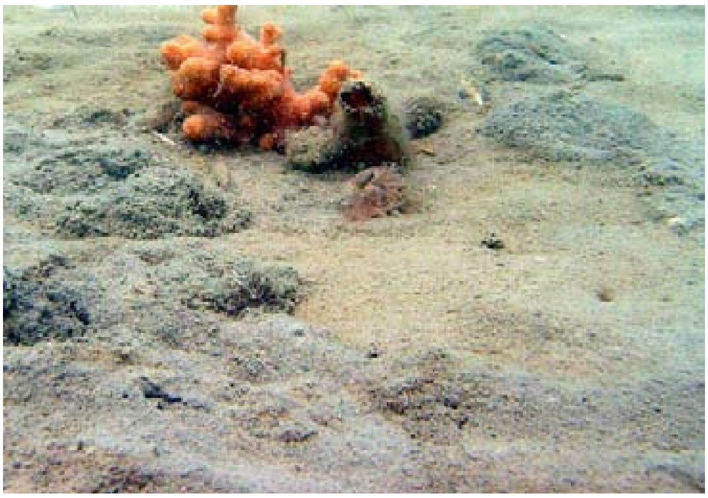
Muddy and sandy sediments cover 70% of the world's seafloor and are found in New Zealand harbours, estuaries and open coastal environments. Sediments have a reputation for being flat and brown, and are certainly less glamourous than the colourful rocky pinnacles, seamounts and coral reefs that get media attention. However, soft sediments host a diverse array of organisms and play a pivotal role in marine ecosystem functioning.

Sediments create a three-dimensional living environment for bottom-dwelling creatures, and animals can burrow deep within the sediment column (up to 2 m below the sediment surface in the case of some crabs and shrimps). This contrasts with rocky systems, where plants and animals are generally confined to hard, impermeable surfaces. Because sediment is an accumulation of particles that have settled to the seabed, it is generally rich in organic matter, with fresh new detritus continually falling to the seabed from above. Animals inhabiting the sediment use this organic detritus as a source of food, but may also graze on microscopic algae that grow on the sediment surface.

Fluxes summarise the system

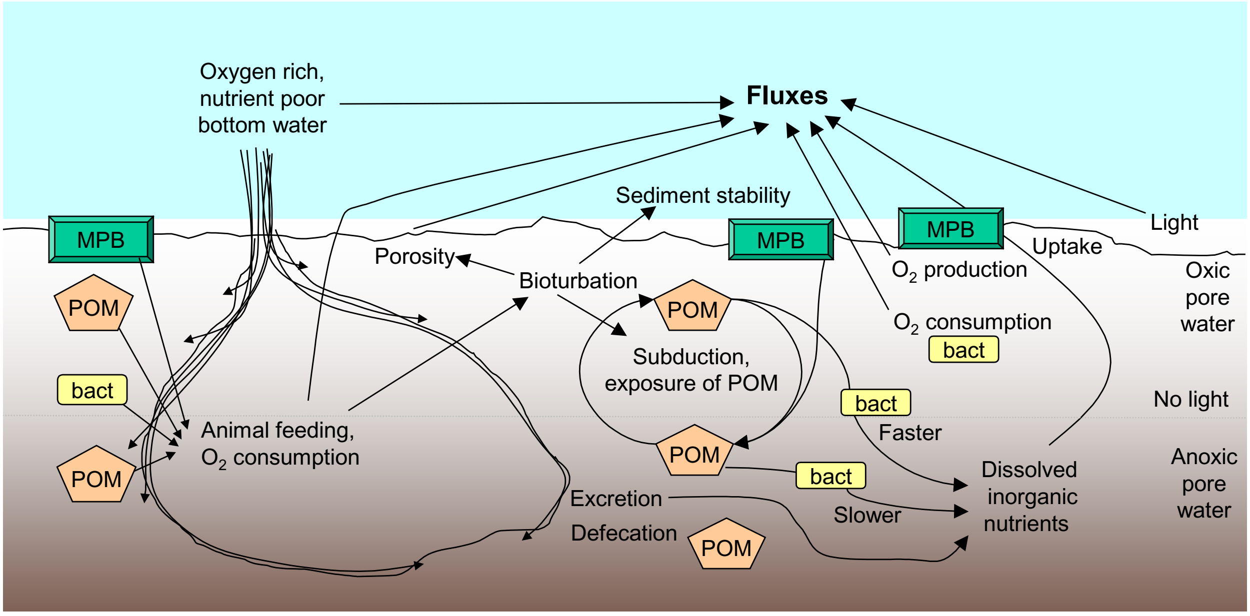
The sediment–seawater interface is permeable, so water fills the small gaps between particles. This sedimentary pore water differs from the overlying seawater in many ways. The concentration of oxygen in pore water decreases rapidly with depth in the sediment, so animals living beneath the sediment surface must maintain access to an oxygen-rich supply. Also, concentrations of nutrients (released by the breakdown of organic matter by bacteria) are generally much greater in pore water than they are in overlying seawater. The nutrients in pore water act as a fertiliser for algal growth, and the algae can only flourish with a combination of both sunlight and essential nutrients. Thus enhanced rates of oxygen and nutrients flowing into and out of the sediment are likely to affect benthic animals and plants. These flows, called fluxes, are measurements of the quantity moved per area per time (for example, grams of nitrogen per m^2 per day). We can learn a lot about how the soft-sediment seafloor functions by understanding the fluxes of oxygen and nutrients.

Although the sophistication of techniques used to measure fluxes has increased dramatically in recent years, the interpretation of flux data is still quite complicated, for many reasons. Soft sediments are inherently complex: bacteria, microalgae, and benthic invertebrates all influence oxygen and nutrient concentrations simultaneously, via direct and indirect pathways (see diagram, right). Fluxes are net results of all such interactions, some of which reinforce each other to increase or decrease flux, and some of which oppose each other. It takes a collaborative, interdisciplinary approach to understand the physical, geochemical, and ecological fac-



A coastal soft-sediment habitat at 6 m depth, in Mahurangi Harbour, north of Auckland. Sponges, tunicates, bivalves, crustaceans, worms, and burrowing urchins (shown bulldozing through surface sediment layers) contribute to the great biodiversity and biocomplexity of soft-bottom seafloors. (Photo: Simon Thrush)

Drew Lohrer and Nicole Hancock are based at NIWA in Hamilton.



Conceptual depiction of complex interactions in coastal seafloor sediments. In this cross-section view the sediment surface is shown as a bumpy line separating bottom water (light blue) and sediment (light brown). Light and oxygen do not penetrate far into sediments. Particulate organic matter (POM), bacteria (bact), and tiny plants (microphytobenthos, MPB) are indicated as different coloured shapes. To the left is a burrow outline of a large sediment-dwelling animal, which is capable of mixing up the sediment. Arrows indicate interactions among components in the system. Movements of oxygen and nutrients across the sediment water interface (fluxes) are the net result of a complex network of interactions.

tors affecting flux rates: a lone scientist in any single discipline will likely overlook key elements in the system, and risk misinterpretation of results.

A biocomplexity framework

The study of fluxes in soft-sediment systems fits well into a "biocomplexity" framework. Biocomplexity is a new buzz word in the natural sciences which acknowledges the interactive (and interdisciplinary) feedback effects that are sometimes difficult to identify and quantify. Proponents of the biocomplexity concept cite the need to study whole systems, as they may exhibit special properties that are not predictable based on the sum of their component parts. Science that reduces complexity and confounding factors in carefully controlled field and laboratory experiments assumes, sometimes without basis, that results can be easily extrapolated to the real world.

Probing soft sediments

NIWA scientists in Hamilton have begun studying biocomplexity in soft sediments. The studies involve measurements of water chemistry over time, the raw data from which fluxes are calculated. However, experiments have also included manipulations of important physical and biological drivers (sunlight intensity, sediment mixing by large invertebrates) so we can separate out the effects of different interacting components in the system. Most importantly, we work with intact soft-sediment communities in order to capture the behaviour of the system as a whole. This requires scuba divers setting up equipment on the seafloor to capture the interactions within natural assemblages of bacteria, algae, and invertebrates. With three experiments run so far and others planned for next year, we are building our base of knowledge and learning how soft sediments perform in different seasons and with differing numbers of invertebrate individuals and species.

We know that disturbance to the seabed can remove key species and reduce biodiversity and that reductions in biological diversity may decrease ecosystem performance. By identifying good measures of ecosystem performance, NIWA scientists are now better positioned to make these linkages and inform coastal managers about the functional importance of marine soft sediments, the most widespread seafloor ecosystem on Earth. ■

This research was carried out as part of NIWA's FRST-funded programmes "Fishing: Ecosystem Effects and Resource Sustainability" (C01X0212) and "Effects Based Protection and Management of Aquatic Ecosystems" (C01X0307).

Marine Ecosystems

More than just a crab hole

***Helice crassa*, the tunnelling mud crab.**

Photo: Kay Vopel

***Kay Vopel** and **Nicole Hancock** explore the labyrinth of burrows beneath mangrove mud and describe the vital chemistry within.*

What's going on down there?

- Crabs in mangroves act as 'ecosystem engineers' when they build complexes of burrows to live in.
- The burrows increase oxygenation of the sediments and set the scene for cycling of nitrogen by bacteria.
- Tides flow through the burrows and flush out ammonium and other nitrogen products.

Mangrove trees trap fine sediment brought in by rivers and the tide. This sediment is the home of various bacteria, algae, protozoa, and invertebrates (such as marine worms) that cope well with the challenges of an intertidal mudflat, including the risk of desiccation, overheating, oxygen deficiency, and regular exposure to air and hydrogen sulphide. These organisms modify their environment and interact with other organisms by exchanging materials in the form of food, waste material, and respiratory gases. However, some larger species are especially important in the ecosystem. Going beyond these relatively straightforward transactions, they alter the nature of the sediment in ways that affect organisms other than their direct competitors, predators, or prey. Ecologists call such species 'ecosystem engineers' because they create new habitats and change the availability of nutrients to other species.

Mangrove crabs and nutrient cycling

One New Zealand example of an 'ecosystem engineer' is the tunnelling mud crab, *Helice crassa*. This species is abundant in the muddy upper parts of our estuaries and is often associated with mangroves. Tunnelling mud crabs create unique habitats for the bacteria that provide nutrients for the primary production of both mangrove trees and microscopic algae. Furthermore, these crabs can enhance the export of nutrients into the coastal zone.

Mangrove mud is often honeycombed with a network of interconnecting passages, occupied by a population of mud crabs. When we stand on the mudflats, the labyrinth of burrows is rarely obvious, but it is revealed at low tide by the amount of water that flows out of crab holes and by the way the rising tide often wells out of crab burrows long before it starts advancing across the surface of the mud. Such burrows can be compared to arteries: the water flowing through the burrows rapidly transports dissolved materials, such as oxygen, through the sediment. Oxygen molecules are transported from the burrow water across the burrow wall and into the surrounding black anoxic (oxygen-free) sediment via diffusion. This process creates a unique habitat for certain bacteria responsible for the cycling of one particular important nutrient, nitrogen.

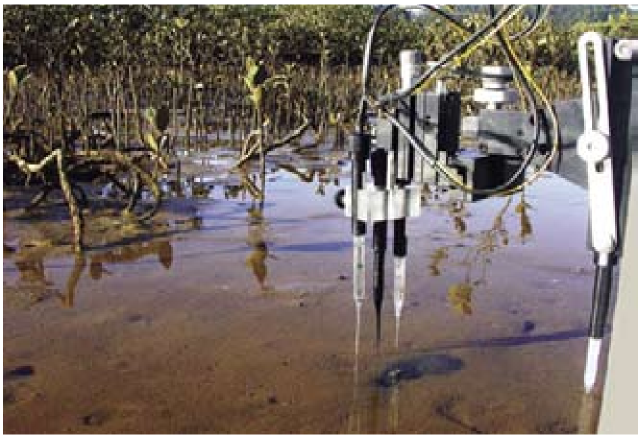
The nitrogen cycle in mangrove mud

Nitrogen is an important nutrient because its availability often regulates primary production. The availability of nitrogen in mangrove ecosystems depends on a complex pattern of bacterial activity within the anoxic mangrove mud, the thin oxic (oxygen-containing) zone at the visible surface of the mud, and the inner oxic linings of animal burrows. Bacteria transform nitrogen in organic material into free ammonium, nitrate, or gaseous nitrogen through three processes: ammonification, nitrification, and denitrification (see box on next page). These processes are closely linked with each other wherever oxic sediment meets anoxic sediment; such conditions occur at some depth below the visible surface of the mangrove mud and around the burrows of mud crabs.

What's so special about crab burrows?

The burrows of the tunnelling mud crabs are the primary sites for both the export of ammonium and the removal of nitrogen from the mangrove ecosystem. Because the bacteria in the burrow wall rapidly consume the oxygen entering from the burrow water, the oxic mud layer around the burrow is usually much thinner than the oxic layer at the visible mud surface. Consequently, the diffusion path for ammonium from the anoxic zone across the oxic wall into the burrow water is very short and ammonium generated in the anoxic mud around the burrow can more easily enter the burrow water and be flushed away by tidal currents.

A NIWA technician measures microprofiles of dissolved oxygen, hydrogen sulphide, and pH in mangrove mud using electrochemical microsensors.



The fragile microelectrodes are inserted into the mangrove mud in increments of 0.1 mm by means of a micromanipulator.

Photos: Kay Vopel

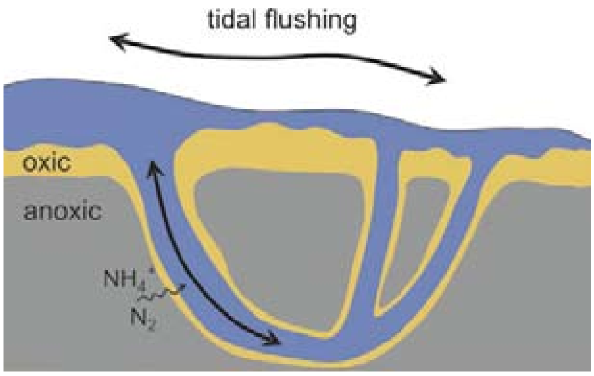
That means crab burrows can be the primary site for the release of ammonium into the surrounding mangrove ecosystems.

Furthermore, the burrow linings seem to offer ideal conditions for both ammonium-oxidising (nitrifying) bacteria and nitrate-reducing (denitrifying) bacteria and thus allow for a tight coupling of nitrification and denitrification. Through this interaction, crab burrows can effectively remove nitrogen from the aquatic ecosystem in the form of gaseous nitrogen (N_2).

The crabs can exert considerable influence on the primary production of coastal ecosystems by modifying the form of recycled nitrogen and by shunting regenerated ammonium out of the system through denitrification. Whether there is a net export of ammonium, nitrate, or gaseous nitrogen from the burrow system depends on the balance of nitrification and denitrification in the burrow wall. Predicting this balance is not straightforward because the coupling of the two microbial processes is mediated by a complex set of factors, including the intensity of the flushing, the burrow geometry, and activity patterns of the inhabiting crabs.

Digging for answers

Our example shows how research on the interactions between the physics of water movement, the activity of bacteria, and the ecology of crabs can improve our understanding of nutrient cycling in New Zealand's coastal and estuarine ecosystems. Incorporated into whole-system models, this knowledge can help predict the consequences of local, human-induced effects or of future scenarios of large-scale environmental change. W&A



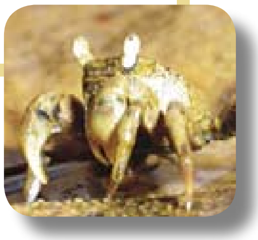
Nitrogen cycling in a crab burrow

This cross section of a crab burrow depicts part of the nitrogen cycle. In both the **oxic** (oxygenated) and **anoxic** (oxygen-free) zones, particulate organic material (dead plant and animal matter) is decomposed by bacteria. During the decomposition, nitrogen in the organic material is transformed to ammonium (NH_4^+). This process is called **ammonification**.

Ammonium in the anoxic sediment is transported to the oxic zone and into the free-flowing burrow water by diffusion. **Diffusion** is the movement of suspended or dissolved particles from an area of higher concentration to an area of lower concentration as the result of random movement of individual particles.

The bulk of ammonium is oxidised by aerobic bacteria, first into nitrite, then into nitrate ions (NO_4^-). This process is **nitrification**.

Nitrate then diffuses from the oxic layer, back into the anoxic layer. Here its fate depends on circumstances. Nitrate may be taken up by bacteria and mangrove roots and become unavailable. Or it may be reduced by bacteria in the anoxic zone of the sediment into either gaseous nitrogen (N_2) or nitrous oxide (N_2O). This process is **denitrification**. Gaseous nitrogen is likely to diffuse through the mud into the atmosphere.



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Dr Kay Vopel is a benthic ecologist with a special interest in biogeochemistry and animal–sediment interactions in coastal ecosystem. Nicole Hancock works in the benthic ecology team. They are both based at NIWA in Hamilton.

Water & Atmosphere 6(2), 1998

ESTUARINE ECOSYSTEMS

Estuarine microbial food webs

Karl Safi

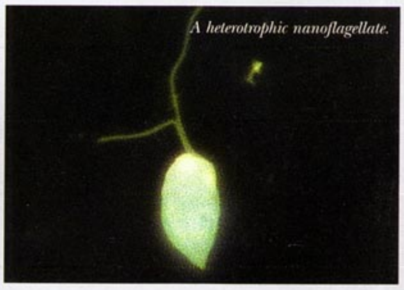
Interactions among the tiny organisms in estuaries can play a major role in maintaining water quality.

GRAZING OF PHYTOPLANKTON and the prevention of phytoplankton blooms in the estuarine environment are traditionally attributed to shellfish and zooplankton populations. It has even been suggested that the shellfish present in some estuaries could filter the entire volume of water present in just a few days.

Both shellfish and zooplankton, however, are often inefficient grazers of small phytoplankton and bacteria as these groups are too small to be consumed directly. In these circumstances small prey may have to pass though additional links in the food chain. In other words, they are "repackaged" via grazing by small organisms into a size which will make them available to the larger grazers.

The microbial food web

In the 1970s the classical model of the marine food web was revised as it became recognised that micro-organisms less than 200 µm across were often as important as larger zooplankton in terms of biomass and energy flows. The term "microbial food web" was introduced in order to describe the complex interactions between organisms within the <200-µm size class.

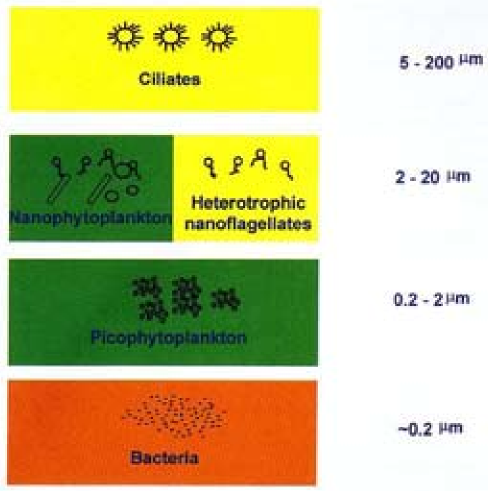


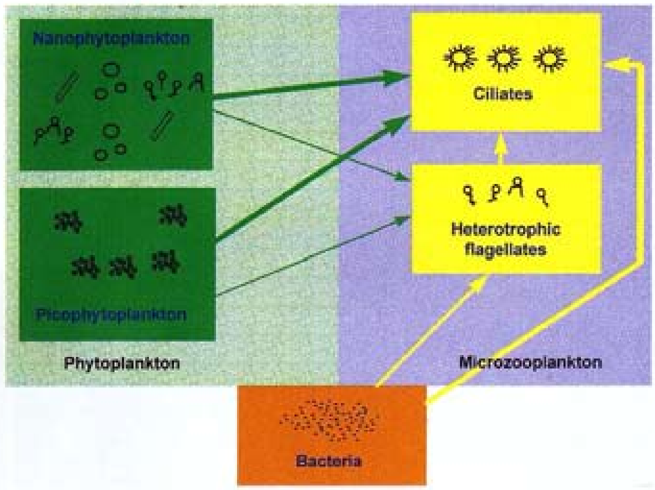
A heterotrophic nanoflagellate.

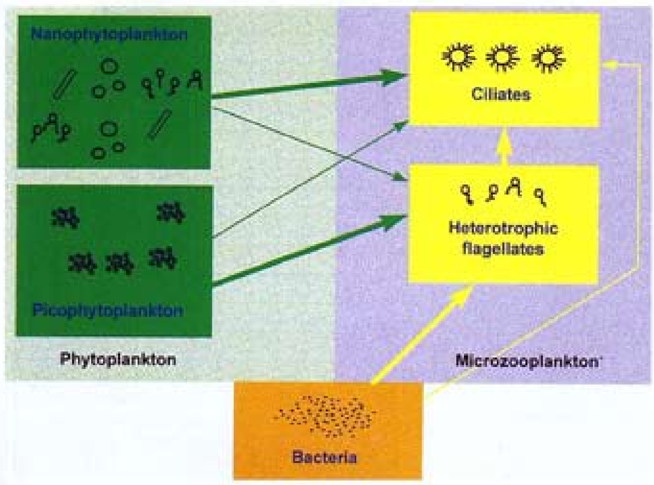
Recent evidence suggests that the microbial food web is a fundamental feature in both coastal and marine waters. It is still largely unexplored in the estuarine environment.

Organisms within the microbial food web can be broken down into groups based on size class and function (see illustrations). The organisms responsible for predation are collectively referred to as the microzooplankton. Microzooplankton have maximum growth rates similar to those of their prey and this can enable them to control assemblages of bacterioplankton and smaller phytoplankton.

It is now recognised that, within the microbial food web, heterotrophic nanoflagellates (see photograph) are the primary grazers of bacteria and picophytoplankton (algae 0.2–2.0 µm in diameter). These protozoa are in turn the prey of large ciliates and dinoflagellates.







The role of microzooplankton in Manukau Harbour

The north-east region of Manukau Harbour represents a eutrophic estuarine environment in which late-summer phytoplankton blooms occur. These blooms consist predominantly of the large diatom *Odontella sinensis*. Despite its large biomass during its blooms, this diatom has no significant nuisance effects.

Collaborative studies involving NIWA scientists have indicated that microzooplankton grazing may be largely responsible for the prevention of bloom formation by the smaller phytoplankton during summer. These studies also found that ciliate abundance in the study area was substantially higher than could be supported by the biomass of the smaller phytoplankton. One explanation for this may be that organic waste has stimulated the growth of natural bacteria already present in the study area. This natural bacterial growth and any introduced bacteria associated with detrital material may have increased food availability and hence enhanced the ciliate abundance.

Activity within the microbial food web in Manukau Harbour.

Studies which focused on phytoplankton biomass (measured by chlorophyll *a*) in Manukau Harbour could not explain the high microzooplankton numbers, nor could they identify which groups of microzooplankton were responsible for the control of the smaller phytoplankton.

In order to answer these questions, experiments were carried out to look at the key predator and prey populations involved in the microbial food web. These studies investigated grazing on phytoplankton prey (represented by chlorophyll *a*) but also investigated grazing on heterotrophic prey within the food web by microzooplankton. Using size-fractionated grazing experiments, we have been able to assess separately the grazing impacts of the two primary predators – ciliates and heterotrophic nanoflagellates.

top:

The different size ranges of organisms found in the microbial food web. This diagram shows that nanoplankton (2–20 µm) consists of two distinct groups the nanophytoplankton and the heterotrophic nanoflagellates.

centre:

A diagrammatic representation of the microbial food web. This figure shows the key members of the microbial (<200 µm) food web with the arrows indicating the pathways of energy and carbon flow.

bottom:

A diagrammatic representation of the microbial food web food observed in Manukau Harbour. This shows that in Manukau Harbour the role of ciliates is less complex than expected with no significant grazing occurring on bacteria or picophytoplankton.

Foodweb terminology

bacteria : microscopic singe-celled organisms that utilise organic matter as an energy source.

chlorophyll *a* : the pigment which plants require for photosynthesis; its concentration is commonly used as a measure of amount of plant material.

ciliates : a group of the protozoa characterised by possessing many fine hairs (cilia).

flagellates : a group of the protozoa characterised by possessing one or more long flagellae (tails) which are used for movement.

- **dinoflagellates** : rigid cells with two flagellae: one passes horizontally around the body usually in a grove; the other often trailing behind the cell. Has photosynthesthic and heterotrophic (see below) representatives.

- **heterotrophic nanoflagellates** : in the size class 2–20 μm; graze to gain energy.

heterotrophs : organisms that obtain energy from organic material.

phytoplankton : single celled organisms that photosynthesise.

- **picophytoplankton** : in the size class 0.2–2 μm.

- **nanophytoplankton** : in the size class 2–20 μm.

protozoa : the scientific name for single-celled grazing organisms; some are also capable of photosynthesis.

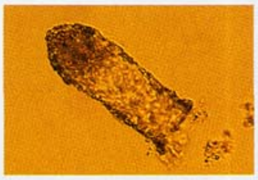
zooplankton : tiny animal-like organisms that graze (consume other organisms, including plants).

- **microzooplankton** : zooplankton less than 200 μm in diameter.

The results of the studies were surprising. Instead of ciliates grazing directly on bacterial populations the results indicated that heterotrophic nanoflagellate grazing removed almost all the bacterial growth. Hence, heterotrophic nanoflagellates were the primary factor controlling bacterial populations. This evidence suggests that bacteria naturally present in the harbour, as well as any introduced bacteria, are controlled by grazing. Heterotrophic nanoflagellates were also capable of consuming ~95% of the picophytoplankton and ~80% of phytoplankton production in the <5-μm size class and therefore also contributed significantly to grazing on the smaller phytoplankton.

Ciliate populations were found to graze scarcely at all on bacteria and picophytoplankton and not heavily on phytoplankton in the <5-μm size class. They appeared instead to be grazing primarily on heterotrophic nanoflagellates and nanophytoplankton populations (<20 μm). The high ciliate numbers in the north-east of Manukau Harbour, therefore, appear to be sustained at least partially by the rapid turnover of the heterotrophic nanoflagellate population. This population was previously unaccounted for in chlorophyll *a*-based experiments which only measured phytoplankton biomass (see centre diagram, page 18).

These findings have, by revealing the complex grazing relationships of the smaller grazers, lead us to a revision of our understanding of the predominant pathways in the microbial food web within the north-east corner of Manukau Harbour.



A loricate ciliate isolated from Manukau Harbour.

Conclusions

These results indicate that the microbial food web plays an important role in the prevention of blooms by populations of the smaller phytoplankton in Manukau Harbour. A significant amount of this grazing can be attributed to the heterotrophic nanoflagellate population. This group is responsible for the rapid repackaging of bacteria and picophytoplankton biomass. In turn, ciliate grazing on heterotrophic nanoflagellates and nanophytoplankton provides a pathway for biomass to be made available to grazers from higher trophic levels such as zooplankton and shellfish. This study has also revealed that high ciliate populations are sustained in Manukau Harbour at least partly by the consumption of heterotrophic prey within the microbial food web. Ciliate populations appear to be enhanced through direct consumption of heterotrophic nanoflagellates and indirect consumption of bacterial biomass.

Implications for the role of the microbial food web

In estuarine and other coastal environments, algal blooms from a variety of size-classes can cause problems including fish kills, contamination of shellfish, oxygen depletion caused by the decay of large amounts of phytoplankton, the production of surface scums and poor water clarity. The current investigations into the role of the microbial food web have shown that in the north-east corner of Manukau Harbour blooms by smaller and possibly more problematic nuisance algae may be prevented by the grazing activity of microzooplankton. In addition to nuisance phytoplankton blooms, problems may arise from the introduction of harmful pathogens including bacteria associated with organic waste inputs. These can cause contamination of shellfish and have detrimental effects on human health. The results of the current study indicate that in Manukau Harbour heterotrophic nanoflagellates may be rapidly consuming any introduced bacteria, reducing detrimental effects that these organisms may cause. Overall these studies indicate that the microbial food web plays an important role in the maintenance of water quality. ■

Karl Safi is based at NIWA in Hamilton.

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ESTUARINE ECOLOGY

Are our estuaries wader-friendly?

Linking estuarine habitat characteristics and wader distributions in New Zealand

David Thompson

Paul Sagar

Some wading birds fly halfway round the world to spend time in New Zealand's coastal areas, alongside many local species. Are changes to our estuarine ecosystems a threat to these remarkable birds?

NEW ZEALAND'S COASTLINE is home to a wide variety of wading bird (wader) species. Outside the breeding season, huge numbers of these birds may gather at estuaries, mudflats and other coastal areas to feed in preparation for the next breeding attempt.

The waders you see in coastal New Zealand are a mixture of local and migrant species. Many of the New Zealand waders – including rare species such as the black stilt and New Zealand dotterel – breed inland, for example on riverbeds or upland areas. They and their young then move to the coast to join Northern Hemisphere species such as bar-tailed godwit and lesser knot. After breeding in the Arctic, these northern waders migrate enormous distances to spend their northern winter here.

New Zealand a major destination

Estuaries and harbours in New Zealand are important destinations for migratory waders from the Northern Hemisphere. During our summer about 30% of the bar-tailed godwit populations that use the East Asia–Alaska–Australasia migratory route (Sagar *et al.* 1999) end up in New Zealand estuaries. The same goes for about 25% of the lesser knot population.

Some estuaries are particularly favoured by some species. For example, almost 40% of bar-tailed godwit occupy only three sites in New Zealand: Manukau Harbour, Kaipara Harbour and Farewell Spit. Manukau Harbour is also a key location for lesser knot and, along with Farewell Spit, it accounts for over 50% of the population.

New Zealand species are also localised. For example, outside the breeding season about 85% of the relatively rare wrybill can be found at just two sites: Firth of Thames and Manukau Harbour.

Unfortunately, humans don't make life easy for waders. Our estuaries are increasingly being modified by the effects of urban development and recreation. Habitat for waders may suffer, for example, through the disturbance of feeding or roosting birds. Habitat may even be lost through land reclamation or when invasive species such as *Spartina* grass and Pacific oysters encroach onto wader feeding grounds.

What can be done to maintain this attractive and internationally important feature of our estuaries?

One important contribution towards the conservation of wading bird populations would be an ability to predict how habitat changes might affect their numbers and distribution.

Northern Hemisphere research

In the UK and north-west Europe researchers have made considerable progress on the idea of linking wader population changes with changes in their environment. Large data sets covering several decades provide detailed information on wader numbers, distributions within estuaries, diets and feeding rates, along with descriptions of estuarine characteristics. Using these data, researchers have devised models that predict how hypothetical reductions in habitat quality might affect wader numbers (Yates *et al.* 1993).

Although these models can be very complicated and require large amounts of data, they have a relatively simple basis:

- the relationships between sediment characteristics of estuarine inter-tidal feeding areas and the numbers and distributions of prey within the sediment (e.g., bivalves and polychaete worms);

- the relationships between prey and the distributions of waders feeding upon them.

It is also possible to incorporate the effects of increases in winter mortality on entire wader populations. Adding a separate model of breeding season productivity produces an integrated picture of the whole population through all seasons and breeding stages (Goss-Custard *et al.* 1995a,b).

A similar approach in New Zealand could provide regional councils and other regulatory bodies with the kind of information they require when faced with planning applications that impinge upon estuarine and coastal ecosystems.

Research for New Zealand

Unfortunately, we cannot simply apply the European models to waders feeding and roosting in New Zealand estuaries because there are too many differences between the systems. For one thing, not all waders that breed in the Arctic fly south for their winter. Imagine, from a wader's perspective, how different conditions are between a bleak, wintry estuary in the UK and a New Zealand estuary in summer. In the north, the birds must feed almost constantly when the tide recedes in order to fulfil much higher energy needs to maintain body condition. When roosting at high tide these waders are particularly vulnerable to repeated human disturbance, and their response of flying off to avoid contact uses up valuable energy.

In New Zealand we have observed that the same species might spend several hours roosting rather than feeding as the tide falls. As well, it is unlikely that energy conservation is so important to birds roosting at high tide. Thus waders in New Zealand have priorities when feeding and roosting that are different from those of their Northern Hemisphere counterparts.

So how do we begin to unravel the links between wader numbers and distributions and habitat characteristics in coastal New Zealand?

In 1998 work began at NIWA on a preliminary investigation of waders and their habitats in New Zealand. First of all, it was accepted that we could not match the scale and scope of the large and well established European studies. So the study initially focused on the links between bar-tailed godwit and lesser knot and their feeding habitats. We also conducted a pilot survey of high-tide roost-site use by waders and of the levels of human disturbance birds typically experience when roosting.

The Manawatu Estuary

The Manawatu Estuary at Foxton Beach, North Island, was chosen for the initial work because it is small enough for a study to be manageable – the accessible north side of the river covers about 68 ha. It is also inhabited by a diverse wader community of New Zealand species (including pied oystercatcher, pied stilt, banded dotterel and wrybill) and migratory species from the Northern Hemisphere (including bar-tailed godwit, lesser knot and golden plover). The area exposed at low tide consists of fine sand and mud, with anoxic conditions within a few centimetres of the surface.

A mixed flock of bar-tailed godwit, lesser knot and Pacific golden plover roosting at high tide on a beach at the mouth of the Manawatu River, Foxton Beach.

Diet studies

We looked at what godwits and knots eat by analysing prey remains in faecal samples collected at low tide. The results were unexpected. At the Manawatu Estuary the birds didn't seem to eat the prey types identified as "favoured" in previous work elsewhere in New Zealand and overseas – that is, small bivalve molluscs for knot, and polychaete worms and bivalves for godwit. Instead we found remains of minute gastropod molluscs (1–2 mm long) in 76% of knot faecal samples and remains of crustaceans, most likely the burrowing crab *Helice crassa*, in 76% of godwit samples (with polychaete jaws, probably from *Nicon aestuariensis*, in another 15% of godwit samples).

It turned out that the "favoured" prey types were just not widely available in the Manawatu Estuary. The next step in the work – now under way – is exploring further whether the prey available at a site actually makes any difference to wader densities, or whether bird numbers and densities are simply a function of estuary/harbour size.

far left:
Map showing the East Asia–Alaska–Australasia migratory route taken by the Northern Hemisphere waders that spend the southern summer (northern winter) in New Zealand. Modified from Riegen (1999).

Relatively common wader species in New Zealand, estimated coastal populations, key sites† and status*

Species	NZ coastal population	Key sites	Status
Pied oystercatcher *Haematopus ostralegus*	113,000	MH, KH, FoT	Native
Variable oystercatcher *Haematopus unicolor*	3,400	Many sites throughout NZ	Endemic
Pied stilt *Himantopus himantopus*	28,000	FoT, MH, KH	Native
Northern New Zealand dotterel *Charadrius obscurus aquilonius*	1,000	Many sites, N and NE North Island	Endemic
Banded dotterel *Charadrius bicinctus*	11,000	FS, LE, PH	Endemic
Wrybill *Anarhynchus frontalis*	5,000	FoT, MH	Endemic
Pacific golden plover *Pluvialis fulva*	650	Many sites throughout NZ	Migrant
Turnstone *Arenaria interpres*	5,100	PH, FS, IE	Migrant
Lesser knot *Calidris canutus*	59,000	MH, FS, KH	Migrant
Bar-tailed godwit *Limosa lapponica*	102,000	MH, FS, KH	Migrant

† When combined, holding > 25%, often much more, of coastal population.

* Endemic: breeds nowhere else other than New Zealand. Native: breeds in NZ and elsewhere. Migrant: occurs in NZ only seasonally, breeds elsewhere. Note that endemic and native NZ species often migrate within NZ between breeding and non-breeding seasons.

Sites: MH, Manukau Harbour; KH, Kaipara Harbour; FoT, Firth of Thames; FS, Farewell Spit; LE, Lake Ellesmere; PH, Parengarenga Harbour; IE, Invercargill Estuary. Sites are listed in order of abundance of the wader species.

Wader distributions

At the Manawatu Estuary it proved difficult to map wader distributions across the inter-tidal area at low tide because the birds were so often disturbed by people fishing, walking their dogs, and driving vehicles across the sand and mud. At high tide, waders and other shorebirds tend to congregate at well-defined sites, often sand or shingle banks, to roost above the high water mark. The birds are sometimes disturbed at these sites as well and this has implications for the "attractiveness" of a site for the birds.

Nationwide survey

Human disturbance was one aspect of our pilot survey of high-tide roost-site use by waders. We wanted to assess what sort of places waders used as roost sites, how often they are occupied, and types and level of human disturbance. Wader enthusiasts throughout New Zealand contributed to a questionnaire, enabling us to cover a wide range of shorebird roost sites. Returned questionnaires covered roost sites from around Whangarei Harbour in the north to Invercargill estuary in the south.

A total of 39 species of wader was recorded, ranging from the relatively common species listed in the table (left) to rare species like large sand dotterel (*Charadrius leschenaultii*) and sanderling (*Calidris alba*).

Nearly 60% of roost sites were sand or shingle banks, but 45% were also vegetated to some extent. Roosting birds also used man-made structures. Thus pied oystercatchers were found roosting on boat sheds in Dunedin, and wrybills used factory roofs in Auckland. The majority (74%) of roost sites were within 5 m of the high water mark, and most (over 70%) were farther than 150 m away from buildings.

The most common cause of disturbance of birds at roosts was "human on foot" (at 52% of roosts covered by the survey). Other important disruptions were motor vehicles (at about 25% of sites) and domestic animals (about 40% of sites). More unusual sources of disturbance included helicopters, jet-skis and dragon boats!

Despite the varied array of disturbance experienced by roosting waders, most respondents thought that the likelihood of disturbance at roost sites was either only "possible" or "very unlikely, almost never" (over 70% of sites). However, 30% of sites were "very likely, almost certain" to experience disturbance.

Future work will add more details to what we already know about how waders use estuarine and coastal ecosystems and will help to refine the relationships between waders and their feeding and roosting habitats in New Zealand. ■

David Thompson is based at NIWA in Wellington and Paul Sagar is at NIWA in Christchurch.

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COASTAL ECOSYSTEMS

The role of sediment in keeping seagrass beds healthy

Anne-Maree Schwarz

Fleur Matheson

Trevor Mathieson

Seagrasses are integral to our estuaries and coastlines, but they are vulnerable to the impacts of development.

Teachers' resource for NCEA AS: Biology 2.5, 2.7, 2.8; Geography 3.2. See www.niwa.co.nz/edu/resources

Anne-Maree Schwarz, Fleur Matheson, and Trevor Mathieson are all based at NIWA in Hamilton.

Seagrasses in the estuarine landscape

Seagrasses are the only flowering plants that grow in the sea. They probably colonised the marine environment about 100 million years ago from freshwater and coastal saltmarsh ancestors, and now they play an important role in coastal ecosystems. Not only do seagrass beds accumulate and stabilise sediments and contribute to food sources for other estuarine animals, but they also act as nursery areas for juvenile fish and serve as an important grazing area for water fowl.

In New Zealand we have one genus of seagrass, *Zostera*, which grows in soft sediments in estuaries and on some intertidal coastal rocky platforms. It is fully adapted to the marine environment, able to tolerate brackish as well as full-strength seawater, and able to withstand being exposed to the air during low tide.

Zostera beds can occupy considerable areas of intertidal sand flats; they can also extend into subtidal fringes in estuaries or form subtidal beds on offshore islands (such as Slipper Island and Great Mercury Island). This is noteworthy as NIWA research suggests that subtidal *Zostera* provides an important habitat for juvenile fish of commercially important species.

Though tolerant of a wide range of conditions, *Zostera* is vulnerable to decline, just as seagrasses have diminished worldwide (see box). What is more, seagrass beds have been proven to be difficult to restore. Therefore it is particularly important to understand what contributes to the maintenance of a healthy seagrass bed.

Identifying healthy seagrass beds

As part of FRST-funded research, and in collaboration with various management agencies, NIWA scientists are studying the conditions that promote healthy seagrass beds in New Zealand. One aspect we have considered is the relationship between sediment conditions, growth, and seagrass health.

Seagrass health can be assessed by a range of measurements that include such things as leaf density and biomass and the photosynthetic

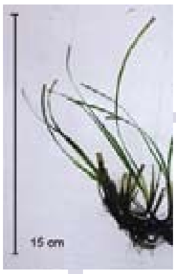
Subtidal seagrass fringe in Whangapoua Harbour. (Photo: Malcolm Francis)

characteristics of leaves. We have measured wide variability in these indicators across a range of estuaries and, while water clarity is an important factor for photosynthetic health, local sediment conditions also contribute to growth performance. We dug deeper to try to uncover the role sediment conditions might play in seagrass health.

Roots: the hidden half

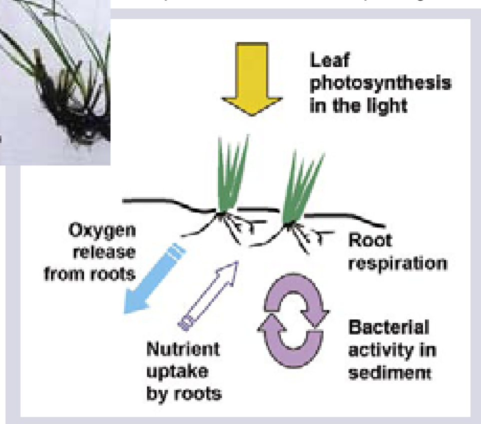
Less visible than leaves but also important, seagrass roots and rhizomes (horizontal stems beneath the sediment surface) can form a considerable biomass beneath the sediment surface. These anchor the plants, preventing them from being swept away by the tides. The roots also extract nutrients for plant growth and can therefore profoundly affect the health of the photosynthesising leaves.

The relative proportion of leaves above the ground to the root and rhizome biomass below



Above-ground leaves and below-ground roots and rhizomes of *Zostera*.

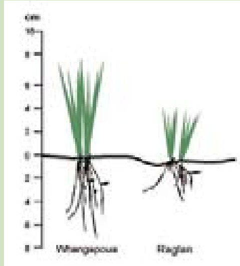
Below, a conceptual diagram of some of the processes that affect plant growth.

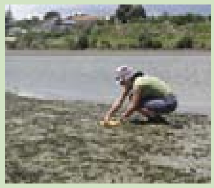


the ground differs from place to place. For example, where *Zostera* grows in sandy sediment in Whangapoua Harbour, there are persistent root layers present down to a depth of 7 cm below the surface. In contrast, a seagrass bed in much muddier sediments in Raglan Harbour has live roots to a depth of only 3 cm. Although leaf biomass is similar at both locations, total root biomass was much lower at the Raglan site.

Relative biomass in two substrates

Sandy substrate in Whangapoua Harbour.





Soft, muddy substrate in Raglan Harbour.

(Photos: A.-M. Schwarz)

How do the plants and sediments interact?

The most likely explanation for differences in root development is related to the characteristics of the sediment. Because estuarine sediments are periodically covered with water, they contain low levels of oxygen; in the picture below the dark-coloured anoxic sediment is evident just beneath the surface. These oxygen-poor sediments can be a hostile habitat: with ample organic matter, sediment bacteria produce reduced compounds like sulphide that are toxic to plants. Nevertheless, healthy seagrasses can counter this stress by transporting oxygen from their leaves to their roots; the oxygen is then used for respiration and nutrient uptake. Since roots are “leaky”, some of the oxygen is also lost to surrounding sediment and helps to maintain an oxidised zone around the plant roots and reduce the likelihood of harmful toxins accumulating.

Anoxic sediment just below the surface of an intertidal seagrass bed in Tauranga Harbour. (Photo: Anne-Maree Schwarz)

As we dig down into the root zone of a seagrass bed, we see expected changes in organic matter, porewater sulphide, and the degree to which the sediment is oxidised. The measure of sediment oxidation is termed redox potential. Atmospheric oxygen can penetrate only a short distance into wet sediment, and so redox potential decreases rapidly with depth according to the depth of the root zone. As expected, our measurements found that concentrations of sulphide increase with depth as oxygen levels decrease.

Sediment processes and healthy seagrass beds

The sediment values we have measured in North Island estuaries fall within the range for seagrasses elsewhere in the world; in general, seagrasses tend to grow in sediments with an organic matter content of below 6%, redox potentials of 100 mV or more, and moderate porewater sulphide concentrations of less than 300 µM.

The leaf health indices that we have measured for plants growing within the desirable ranges of sediment conditions vary. We believe above-ground conditions such as water clarity are at least as important as sediments in determining the health of the seagrass beds. This kind of research can lead to a better understanding of how easily sediment conditions can shift outside of “desirable” ranges and how that affects plant growth. This will enable us to better predict the likely consequences of environmental change, such as changes in water clarity and quality. ■

Worldwide seagrass decline

Seagrasses occur around the world, and in total there are about 12 genera and 50 species. There have been many reports of diminishing seagrass beds and it has been estimated that more than 70% of the reported large-scale declines in the world have been due to human-induced disturbances. Once seagrass beds have been lost through environmental degradation, they are notoriously difficult to restore.

In New Zealand, the area of *Zostera* has been reported as declining over the last 50 years. In some places there is enough historical information to show that subtidal beds in estuaries – such as those in Tauranga Harbour – have undergone the greatest decline.

(Photo: Malcolm Francis)

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Funding for this study came from the FRST research programme “Aquatic Plant Management” (C01X0221), Environment Waikato, and Department of Conservation.

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ESTUARIES / RESOURCE MANAGEMENT

Spreading mangroves: a New Zealand phenomenon or a global trend?

Anne-Maree Schwarz

The spread of mangrove forests – currently seen by some as a problem in some North Island estuaries – is by no means a global trend.

The value of mangrove (mānawa) ecosystems has recently been the topic of public debate in New Zealand, with discussions stimulated by the expansion of mangrove growth in some North Island estuaries. An inevitable question is asked when people are considering the rate of spread of mangroves in New Zealand: *"Is the same thing happening in other places around the world?"*

In this article we take a global perspective and ask how changes in mangrove distribution and related values in New Zealand compare to those elsewhere.

Trends: New Zealand

As a first step, understanding the extent of mangrove spread in North Island estuaries is not straightforward. The Land Cover Database (Terralink, NZ Ministry of Agriculture and Forestry) estimated a total area of mangroves of 22,200 ha for 1996/97. Various initiatives are underway to update this estimate. Although changes in some estuaries have been mapped from aerial photographs no accurate estimate of total change is available.

The value placed on mangrove ecosystems in New Zealand has had a chequered history. While Māori traditionally utilised both mangrove trees and the fish and shellfish from within mangrove forests, during the 20th Century mangroves were often not highly valued by an expanding New Zealand population. The State of New Zealand's Environment Report (1997) describes how *"…seagrass and mangrove ecosystems have declined this century as a result of widespread modifications to estuaries caused by activities such as infilling for agriculture, rubbish disposal and commercial land development"*.

Changing attitudes toward the end of the century are reflected in the New Zealand Coastal Policy Statement (1994), which described a national policy for protecting ecosystems unique to the coastal environment and vulnerable to modification, including mangroves. Around that time there was a move towards conservation and education initiatives and investigations into means of replanting damaged mangrove forests. Now, less than a decade later, local authorities are being presented with applications for Resource Consents to remove mangroves from some areas.

Trends: elsewhere in the world

In 1997 the "World Mangrove Atlas" estimated the total global area of mangroves at ~18 million hectares. However, accurate current estimates remain elusive, complicated by a 2002 estimate by the ITTO (see panel) that, during the last decade, approximately 100,000 ha of mangroves have been destroyed annually. Notably, a survey in 1994/95 to study the global conservation status of mangroves found that *"no mangrove areas were actively expanding"*. (New Zealand was not included in the survey.) However there are examples from specific locations (for example, in Mozambique and Thailand) where, despite an overall reduction in mangrove area in the region, some bays have seen an increase in mangrove coverage. In both these cases, the expansion has been related to increases in sediment loading from the catchment.

International Tropical Timber Organisation (ITTO)

Many different research and interest groups around the world are working on mangrove management and conservation. One of these is the International Tropical Timber Organization, which counts mangrove timber amongst its global products. In 2002 ITTO organised a workshop in Colombia, South America, providing for a New Zealand representative (from NIWA) to attend. The objective of the workshop was to draft a mangrove work plan to guide ITTO members in the development of projects for sustainably managing and conserving their mangrove resources. While New Zealand is a consumer of tropical timber rather than a provider, the presentations made at that meeting provided a useful background for a general discussion of the "global" status of mangroves.

Teachers: this article can be used for Biology L7 A.O. 7.3(a) and NCEA AS 2.4, 2.5 and 2.9. See other curriculum connections at www.niwa.co.nz/pubs/wa/resources

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Values

Mangroves occur at the interface between land and sea and are encroached upon by competing land-use, as well as being indirectly affected by catchment development. From this perspective, the same general considerations for management of mangrove ecosystems apply globally. So what are the values and how do they differ from place to place?

Ecological values

There are over 60 species of mangroves worldwide, of which about a quarter are of the genus *Avicennia. Avicennia marina* (grey mangrove) has the widest latitudinal distribution and is the only species of mangrove represented in New Zealand. Like all mangroves, *Avicennia* forests contribute to marine food webs through production of detritus, and several marine organisms spend all or part of their lifecycles there.

Economic values

Mangroves provide livelihoods for millions of people throughout the world thereby providing tangible economic benefits. The cases summarised below (with examples of relevant countries) include values that, due to exploitation, can also contribute to mangrove decline:

- Mangrove poles are extensively used for the construction of houses because the wood of many species is durable and resistant to termites. However unregulated cutting for timber, firewood, charcoal or pulp results in cleared land being converted to other types of land-use (Micronesia, India, Ecuador, Latin America, Madagascar, Pacific Islands, Thailand, Vietnam).
- Mangrove forests are cleared to make way for brackish-water shrimp farms and salt ponds, sometimes leaving an unsustainable fringe of mangroves between the ponds and the sea (Indonesia, Sri Lanka, Latin America).
- Land colonised by mangroves is reclaimed for housing and resort development (Australia, USA, Malaysia, Belize, Madagascar, South Africa) or is used for dumping rubbish (Venezuela, Pacific Islands).

As recently as the 1970s New Zealand's mangrove forests were being reclaimed for various types of land development including roading, oxidation ponds and agriculture, and were also used as tip sites. There is no mangrove timber industry here, but mangroves continue to support ecological values, traditional Māori values and other community values.

Mangroves come in all shapes and sizes all over the world. Although some species can grow to more than 30 m tall they can also occur as small shrubs. Here Pip Nicholls samples amongst *Avicennia marina* in New Zealand (top) and Dr Candy Feller samples amongst *Avicennia germinans* in Florida (bottom).

Indirect effects on mangrove values

Of other human activities that have indirect effects on these values, catchment management is probably of most relevance in New Zealand.

Here, recent increases in mangrove area have been attributed at least in part to accelerated erosion of catchment sediments into our estuaries, providing more suitable conditions for mangrove colonisation. Compare this with the situation in some other countries, where catchment development has sometimes had the effect of *reducing* the area of mangroves. In Micronesia, India, Pakistan and Brazil, for example, damming of rivers has reduced sediment load, starving mangrove forests of sediment. Elsewhere in India, extreme siltation has changed the path of freshwater inflows so that mangroves no longer receive sufficient tidal flushing.

As in New Zealand, attitudes to exploitation of mangrove forests have changed in other parts of the world. Partly because of the global decline in mangroves (noted above), in some places there is now a strong emphasis on conservation, sustainable management and restoration. The ITTO Mangrove Workplan (2002) stated:

"it is widely believed that after total felling a [mangrove] *forest will regenerate spontaneously. On the contrary this happens under very special conditions and usually with human assistance."*

Because of this, attempts to establish nurseries and re-plant mangroves are the focus of a projects in many regions, including the USA, Thailand, and Latin America (e.g., Colombia, see photographs, right) as well as closer to home in Fiji.

Mangrove spread: a New Zealand phenomenon

It seems there is no hard and fast rule about spread or decline that can be applied to all mangrove ecosystems. There are places where mangrove forests are relatively untouched, are in dramatic decline, have been completely destroyed, are spreading seaward into estuarine areas, or, in places that are affected by sea-level rise, are spreading landward onto adjacent river plains. Nevertheless, it is generally accepted that on a global scale the area of mangroves is in decline and that mangrove ecosystems are under threat.

Thus, with few exceptions, the trend for spread of mangroves that has been recently observed in some of our estuaries does appear to be a relatively local phenomenon at present. This is mostly a result of different values and different degrees of catchment and coastline development, all of which are likely to continue to change in the future, not only in New Zealand but also elsewhere in the world. ■

Nursery-grown *Rhizophora* seedlings ready for planting in a coastal re-forestation project in Colombia.

NIWA continues to research the effects of sediment loadings to estuaries on the rate of mangrove spread, the role of nutrients in mangrove growth, and the relative value of mangrove habitat for estuarine fauna. For further information on any of these topics, contact Anne-Maree Schwarz, Mal Green, or Pip Nicholls at NIWA, PO Box 11115, Hamilton (ph 07 856 7026, fax 07 856 0151, a.schwarz@niwa.co.nz)

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ESTUARINE AND COASTAL ECOSYSTEMS

Fringing habitats in estuaries:
the sediment–mangrove connection

Pip Nicholls
Joanne Ellis

Investigations into changes in salt marsh and mangrove communities are confirming the important role of increasing sedimentation.

Pip Nicholls is based at NIWA in Hamilton; Joanne Ellis was formerly based at NIWA in Hamilton.

Fringing plant communities, such as salt marshes and mangroves, play an important role in our estuaries and coastal ecosystems. These fringing habitats are a key source of organic material and nutrients, which help to fuel the estuarine food web. Stems and leaves of salt marsh and mangrove plants provide a three-dimensional structure in which animals can hide from predators, and they create habitat for fish species and wading birds.

Fringing habitats also act as physical buffers between the land and the sea. Branches and stems of plants reduce water flows and dissipate wave action, while root–rhizome mats stabilise and bind marine sediments, preventing erosion. Reduced water flows enhance sediment settling, and therefore fringing habitats act as sinks for sediments and pollutants that are washed down or leach out from land-based sources.

New Zealand's growing population and the catchment development that goes with it are leading to greater sediment deposition in our estuaries and coastal ecosystems. Estuaries and tidal inlets are particularly vulnerable because these places act as natural retention systems. If sediments from the land are deposited faster than usual, then habitats may be altered. Such changes can kill, displace, or damage parts of the plant and animal communities. The severity of impact depends on the frequency of depositional events and can vary considerably. Ecological repercussions can be both catastrophic (short-term) and chronic (long-term).

In an ongoing research programme we are investigating possibilities for predicting and managing these changes. This includes assessing the impacts of changes on the distribution and functioning of fringing habitats.

Studies in two estuaries

To understand how estuaries respond to long-term increasing sediment inputs we are studying two estuary systems in the Whitford embayment, Auckland: Mangemangeroa and Waikopua Creek.

We have used photographic records along with data relating to sediment deposition, both dating back 45 years, to map historical distributions of mangrove (*Avicennia marina* var. *australasica*) and salt-marsh plants. Using sediment cores, we have been able to quantify sedimentation rates in both estuaries. When combined with information about currents and tides, this has enabled us to make predictions about the influence of mangroves on depositional patterns.

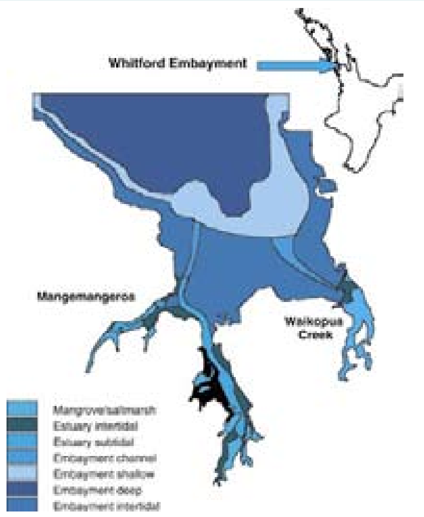
In addition, individual mangrove and salt-marsh plants are being measured routinely at places with different degrees of sedimentation, to determine how fast the plants grow, how many die off and how many new plants establish. Finally, we have been assessing the abundance of large invertebrates such as cockles (*Austrovenus stutchburyi*) and crabs. All this information helps us to determine the relationships between changes in sedimen-tation levels, plant health, and the associated changes in animal communities that live within these fringing habitats.

far left:
Saltmarsh in Mangemangeroa Estuary, Auckland.

left:
Extensive root and pneumatophore system of a mangrove tree, Waikopua Creek.

Long-term changes

Of the two estuaries, Mangemangeroa has the greatest sediment loading and rate of sediment accumulation. Since 1953, 1 m of sediment has accumulated at the inland end of the estuary, but only 0.1 m at the estuary mouth. This difference is the result of varying physical conditions in different locations. At its upper end, the catchment is steep with highly erodible soils. In addition, this part of the estuary is protected from wind and wave activity that would normally resuspend and transport sediments farther downstream. The aerial roots of dense mangroves are likely to reduce water flows further, trapping sediment.



Photographs indicate that changes in the distribution of salt-marsh communities in the Whitford embayment have been slight over the past 50 years. However, between 1955 and 2000 mangrove cover increased by 50% in Mangemangeroa, and by 75% in Waikopua Creek. In Mangemangeroa most of the increase in mangrove distribution has been limited to the upper part of the estuary. However, at Waikopua Creek mangroves have also extended their distribution seaward, onto intertidal flats.

Sediment core from Waikopua Creek showing depth profile.

Analysis of core profiles at Waikopua indicates a decrease in particle size in denser mangrove stands or areas with low wave activity. This suggests that mangroves can provide sheltered settling areas for fine silts and clay by modifying water flow patterns. In addition, they may accelerate their own rates of spread by trapping mud, and subsequently providing a suitable habitat to colonise.

Mangroves and mud

Results from our plant monitoring in different sediments showed a number of correlations with sediment mud content. Mangrove tree height and growth decreased with distance down the estuary and taller mature trees and saplings grew faster in the upper, muddy parts of the estuary. This was expected since mangroves prefer lower salinity and wind-protected areas and they grow well in organic and nutrient-rich sediments. We found that significantly more young mangroves grew from propagules or seed in the upper more muddy reaches of Mangemangeroa. In addition, plants in this area contained more pneumatophores (breathing roots – an adaptation to ensure an adequate O_2 supply to tissues in the finer muds).

Teachers: this article can be used for Biology L7 A.O. 7.1a. See other curriculum connections at www.niwa.co.nz/pubs/wa/resources

Macrofauna

There were differences in invertebrate community composition between sites. In the spreading mangrove areas closer to the estuary mouth there was a greater abundance of pipi, cockles and polychaete worms, whereas in the upper estuary, highly sedimented mangrove habitats, there was a greater abundance of mud crabs and oligochaete worms. In general, for both estuaries we observed the greatest species diversity in the mangrove sites that were nearest to the mouth.

Implications and future research

Research to date suggests that further increases in rates of sedimentation into the Whitford estuary will result in increased spread of mangroves – as has already been observed in other Auckland estuaries. The rates of spread are likely to be limited by hydro-dynamic parameters such as the influence of wind-waves in remobilising sediments.

The encroachment of mangroves onto the sand flats at Waikopua could have important implications for the ecological functioning of this estuarine system. It will probably mean that the proportion of habitat types will change, resulting in a subsequent loss of other associated intertidal habitats.

All these results will contribute to our knowledge of the relationships between salt marsh/mangrove distributions and differing sediment regimes. Research continues to determine how changes in the distribution of fringe habitats affect animal communities. Findings will improve our understanding of the implications of changes in distribution of fringing habitats for the health and functioning of the estuarine ecosystem as a whole. ■

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This work has been funded by the FRST programmes "Ecological Effects of Sediment on Coastal Ecosystems" (C01825) and "Sustainability of Aquatic Ecosystems and Water Resources" (C01X0215).

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COASTAL ECOSYSTEMS

Nutrient enrichment in mangrove ecosystems: a growing concern

Pip Nicholls

Anne-Maree Schwarz

Nicole Hancock

Fertilisation experiments are showing that some mangroves grow well with a little nitrogen.

Teachers' resource for NCEA AS: Biology 1.7, 2.5, 2.9, 3.1; Science 2.2, 3.1; Horticultural Science 1.8 See www.niwa.co.nz/edu/resources

Pip Nicholls was formerly based at NIWA in Hamilton, where Anne-Maree Schwarz and Nicole Hancock are currently based.

Love them or loathe them, mangroves are an integral part of New Zealand's estuarine ecosystems. Like all large plants, they significantly influence many key processes, such as nutrient cycling. They also play a vital role in coastal sediment stabilisation. In the tropics, mangroves are highly valued as habitats for many fish and invertebrate species; however, many of these mangrove ecosystems are under threat. Accordingly, overseas, millions of dollars are spent every year on mangrove conservation and restoration.

In New Zealand, as in other parts of the world, pressure from increasing human population puts the health of coastal ecosystems under threat. Impacts are generally associated with land development, agriculture, and horticulture. For example, increased nutrient inputs to fresh waters ultimately end up at the coast. While we have an understanding that there are correlations between mangrove growth and sediment mud content in some New Zealand estuaries, little is known about how eutrophication (increased nutrient concentrations) of the coastal zone might also affect mangrove ecosystems.

Overseas studies have shown clearly that the nutrients nitrogen and phosphorus affect mangrove growth. When nutrient concentrations increase, mangroves may grow faster. Increased nutrients can also potentially influence certain life stages, for example propagule (seed) production.

Tagged branches on fringe mangrove trees.

New Zealand is one of the few places in the world where the area covered by mangroves is expanding seaward. While increasing nutrients may be involved in this spread, we don't know exactly how. This is one of the questions we hope to answer in a wide-scale experiment involving NIWA, the Smithsonian Environmental Research Center (USA), and the University of Queensland (Australia).

In this experiment we are investigating how changing nutrient levels affect physiology and growth rates of mangroves. The overall aim is to compare mangroves in tropical ecosystems (Belize and USA) and temperate ecosystems (Australia and New Zealand) and use the results to predict responses to environmental change.

Experimental work: New Zealand

In June 2001 NIWA set up the first field site in Waikopua Creek (Whitford, Auckland) where the substrate is fine sand/mud. In January 2003, a second site was established in the Whangapoua Estuary (Coromandel) where the substrate is relatively sandy.

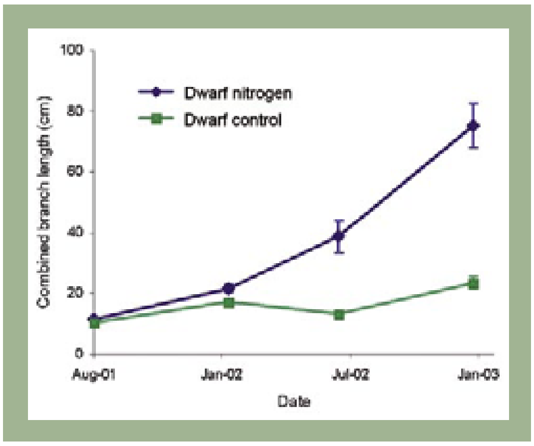
A general pattern in mangrove forests is that taller, more robust trees tend to grow along the edges of channels, while farther back from the channel the trees are much smaller. Previous studies in other tropical/temperate areas have shown that the channel-edge trees and dwarf trees react differently to nitrogen and phosphorus.

To investigate this we fertilised 18 mangrove trees alongside a major drainage channel and 18 smaller trees 25 m away. We added fertiliser near the base of the trunk of each tree, using individual slow-release bags containing either nitrogen or phosphorus or no fertiliser (control). To measure the mangrove trees' responses to fertiliser, we tagged and measured branches and measured tree height and diameter. Every six months fertiliser is re-applied and all the tagged branches are re-measured.

NIWA scientist measuring dwarf trees at Waikopu Creek. (Photos: Jane Halliday)

A response to nitrogen

In the first six months after the initial nutrient addition in Waikopua Creek there was no obvious difference in growth between treatments for any of the mangroves. However, over a longer period, the dwarf mangroves that were farther from the channel have started to show a marked response to additional nitrogen. Those trees are showing, on average, more branching and have longer branches than any of the other treatments, whether dwarf or fringe.



After three years we are still measuring more branch growth in the dwarf trees fertilised with nitrogen. These trees are distinguishable from the others, appearing very healthy because of their shiny robust leaves.

All the fringing mangrove trees on the channel edge showed steady but slow growth in comparison to the dwarf trees with nitrogen added. The patterns in growth were independent of treatment and do not indicate any effect on growth of the additional nitrogen or phosphorus.

The experiment at the sandier site in Whangapoua Estuary has been running for a shorter time. However, the pattern emerging is similar to that observed in Waikopua Creek.

What does this mean?

In Waikopua Creek, mangroves that are away from the channel, which tend to be smaller than those on the channel edge (fringe), are showing some evidence of being short of nitrogen under natural conditions because supplying extra nitrogen stimulated their growth.

Although these results are preliminary, there is evidence to suggest that some New Zealand mangrove forests, in areas prone to increased nitrogen inputs, may respond by growing faster and by increasing their potential to produce more reproductive propagules. If other physical conditions are suitable (that is, sediment, temperature, and salinity), this could have the potential to enhance rates of forest spread compared with areas with low nutrient inputs.

Altering one or more of the environmental conditions necessary for healthy mangroves will have positive or negative effects on mangrove growth and spread.

Long-term monitoring

We intend to continue fertilising and re-measuring mangrove trees in both experimental plots for the next two years. This will contribute to a clearer picture of the longer-term potential effects of eutrophication on New Zealand mangroves. Our results will be combined with those collected from the tropics (Belize, Florida, Panama) and other temperate areas (Australia) to help develop a global perspective on mangrove–nutrient relationships. ■

Mangroves in Whangapoua Estuary.

This research was funded as part of the FRST programme "Effects-based Protection and Management of Aquatic Ecosystems" (C01X0307).

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WEM
WAIKARAKA ESTUARY MANAGERS

nz landcare trust
ngā matapopore whenua

NIWA
Taihoro Nukurangi

For and against mangrove control

Malcolm Green, Joanne Ellis,
& Anne-Maree Schwarz (NIWA),
Nicki Green (NZ Landcare Trust),
Dave Lind & Brian Bluck
(Waikaraka Estuary Managers)

Coastal residents around the upper North Island are increasingly voicing concerns about the spread of mangroves in their local harbours. They perceive a decrease in amenity because of mangrove spread – reduced access, smelly mud, loss of water views, poorer fishing and shellfish gathering, decreased property values – and they want to know what to do about it. An earnest and urgent debate is developing at the local community level. On one side are residents who want to reclaim their waterways by cutting and removing mangroves; on the other are residents who want to let nature be. Occupying a middle ground are residents who want to draw a line in the sand and contain mangroves at present levels.

Residents need to decide among themselves what they most value about their waterways and then seek ways of achieving their goals. This will need to be done within the bounds of any applicable regional coastal plan, and possibly by recourse to the Resource Management Act. In the meantime, it is important that the debate be properly informed, and that is where science can contribute.

Facts about mangroves can be clarified, and in so doing, some apparent confusion can be resolved.

Consequences of proposed courses of action can be outlined.

The ***likelihood of achieving goals*** can be predicted.

We deal with all three issues in this leaflet, not in order to advocate for one side or the other, but to inform the parties engaged in the debate.

NIWA Information Series No. 31
2003
ISSN 1174-264X

What is the problem?

Waikaraka Estuary (Tauranga) 1976 ...

... and 1999.

The real problem is increased sediment runoff from the catchment (in the past and present); mangrove spreading is a symptom of that problem. Estuaries do naturally trap and fill with sediments, and mangroves do naturally spread in estuaries where climatic and other factors are favourable. However, what we are seeing today are the results of silt clogging waterways. This is caused by increased soil erosion on developing and deforested catchments, often coupled with inadequate sediment controls that could otherwise halt or limit the sediment onslaught. Under this deluge of silt, sandflat habitats become smothered and mangroves spread rapidly, expanding from the headwaters and sides of the estuary out into areas that were previously floored with clean sand. And here's the perverse part: mangrove spread and silt deposition are intimately bound together – mangroves help trap silt and silt provides the environment that helps mangroves to thrive. The problem here then is an *acceleration* of what are otherwise natural processes.

The true extent of the problem is not easy to determine, but there is evidence that sedimentation rates in some estuaries have increased by at least a factor of 10 since human occupation. What is clear is that getting rid of mangroves will not halt sediment erosion in disturbed catchments, and until this is controlled and abated, estuarine and coastal ecosystems will continue to degrade.

Frequently asked questions

Are mangroves a native species?

The New Zealand mangrove, Avicennia marina, or manawa, is native to New Zealand. We have only this one species of mangrove, and it is not regarded as threatened. It is believed to have arrived on our shores about 14 000 years ago. In northern New Zealand, mangroves grow as tall trees, but they become smaller and more shrub-like the farther south they grow. Avicennia marina is one of the most widespread mangrove species in the world. Its southernmost limits are in New Zealand, and in Victoria, southeastern Australia. In New Zealand, mangroves do not occur naturally south of about Ohiwa Harbour on the east coast and Kawhia on the west.

If we get rid of the mangroves, will the mud then disappear?

The situation will differ for every estuary. Mangroves do stabilise mud deposits by binding them with their roots and by helping to still waves and currents. By removing mangroves, mudbanks might be destabilised and the liberated mud might be dispersed. However, mud will still tend to accumulate in the quiet waters of the upper, sheltered margins of estuaries, whether there are mangroves there or not. It is fair to say that some mud will indeed disappear, to turn up in other parts of the estuary or to be carried out by tidal flows through the mouth of the estuary to the open coast.

Do fish use mangroves in New Zealand?

Overseas, mangroves are considered to be important nurseries for coastal and inshore fisheries, because they provide food (e.g., small worms) and shelter for numerous species of crustaceans and fish, especially juveniles. In some tropical mangrove forests (mangals), which can have up to 30 different species of mangrove, 90% of the fish present are obliged to spend part of their life cycle in the mangal. In New Zealand, there is less information available on how fish use mangroves, but research in progress is filling in some of the blanks. While it appears that fish species diversity is less than in some other estuarine habitats (e.g., seagrass beds), there are several species that do use mangrove channels, such as yellow-eyed mullet, grey mullet, smelt, and anchovies. The effect of estuarine water and habitat quality on fish usage of mangroves in New Zealand is not well understood yet – we have much more to learn about how fish "regard" mangroves in sediment-impacted estuaries before we can draw conclusions.

Are mangroves useful resources for people?

Mangroves are highly prized resources in other parts of the world, being used for timber, firewood, food, and coastal protection. This is not so in New Zealand.

Are New Zealand mangroves different from mangroves in warmer climates?

New Zealand mangrove forests are composed of a single species and individuals tend to be smaller than elsewhere. There is a strong trend in tree size from the north (where they are relatively big) to the south (where they are relatively small). These special features of our local scene mean that not all overseas research necessarily applies to New Zealand, and to assume that it does could be misleading.

Are mangrove spread and sediment runoff from the catchment related?

As in the rest of the world, there are many environmental factors that determine where and how fast mangroves grow in New Zealand. These include salinity, temperature, sea level, suitable substrate, and the supply and availability of nutrients. Although the relative importance of these factors varies from location to location, there is one common element: where there is an accelerated rate of mangrove spread in an estuary there will also have been an increased sediment runoff from the catchment that drains into that estuary.

Are mangroves weeds?

A weed is a plant in a place where it is not wanted, which is a value judgement made by humans. In the estimation of some people, mangroves are indeed weeds.

Are mangroves worthless?

Do not confuse being called a weed with being worthless. Mangroves serve physical and ecological functions, which may vary from place to place.

On the ***physical*** side, mangroves stabilise sediments that might otherwise cloud waters, settle in other parts of the estuary, or be flushed out to sea. Roots, trunks, and pneumatophores along with fallen leaves and twigs provide surfaces capable of trapping sediments. They also impede water movement, which further promotes sediment deposition. In these ways, mangroves help to maintain water clarity. Mangrove decline or eradication may, therefore, cause increased turbidity, and leave shellfish beds, seagrasses, and fish habitats elsewhere in the estuary more prone to smothering and siltation. On the other hand, by accumulating sediments and slowing water movement, mangroves help to reduce estuary flushing by tides. This might hasten the natural fate of the estuary, which is to fill with sediments and become a freshwater swamp or wetland.

On the ***ecological*** side, mangroves contribute to the species and habitat diversity of New Zealand estuarine ecosystems. Microscopic bacteria decompose leaves dropped by mangroves, thereby recycling nutrients in the estuary and making them available for other photosynthetic organisms (e.g., algae). These in turn are significant sources of food to animals that live in the sediment, such as crabs, snails, cockles, and worms. Mangrove trees also provide anchorage surfaces for filter-feeding organisms such as black mussels, small barnacles, rock oysters, and Pacific oysters. Carnivorous scavengers and predators, such as mudflat whelks and snapping shrimp, form another strand in the food web.

Whangapoua

What is the ecological issue here?

Mangroves do have intrinsic worth, but it is not easy to compare that with competing values. It is true that the number of species found in mangrove stands and associated sediments is lower than on adjacent intertidal sandflats, but the community composition (the types of animal that make up the community) is quite different. Sandflat communities have a higher proportion of shellfish than muddy areas, but relatively more worms live in mud. The only safe conclusion is that the ecological function of mangroves is different from the ecological function of sandflats. When mangroves spread, they do so at the expense of other habitats, and the value – ecological and human – of those habitats that are consumed is lost. The habitats that yield to the spread are the lower intertidal and subtidal zones, which people prize for kaimoana, recreational opportunities, and aesthetic reasons. On the other hand, mangroves are a natural, valuable part of the estuarine ecosystem, and spreading is a natural part of the way an estuary "ages". The problem here is that it is all happening too (unnaturally) quickly. Left alone and with unrestrained soil erosion in the catchment, mangroves will continue to spread. Eventually, the tide may turn against the mangroves, and the part of the estuary that they once inhabited may turn into swamp or land.

What would happen ... ?

Option 1. If we turn the clock back

Goals

- Remove all (or almost all) mangroves
- Restore sandy beds and clear water with corresponding animal life and improved human amenity (views, access, aesthetics, recreation, commerce)

Pros	Cons
Maximum improvement in human amenity	Probably not fully or easily achievable
Retain and restore sandy habitats (and their attendant ecological values) that are currently being consumed by mangroves. May lead to overall increase in estuary biodiversity	Physical functions of mangroves lost (mud presently bound up in mangroves may be released and dispersed, possibly to affect other habitats and the water column)
Possibly allow sediment that is presently building up in estuary to be flushed out to sea	Ecological functions of mangroves lost
Create opportunities to restore areas of saltmarsh	Trampling of adjacent habitats during initial and maintenance works if not properly organised and managed
Depending on level of participation, a sense of ownership and understanding of the ecosystem is fostered within the community	Maximum (and very likely unacceptable) cost

Are goals achievable?

Goals cannot even be approached without effective sediment controls (e.g., earthworks, riverside management, urban stormwater) in place in the catchment. Even with effective sediment controls, existing silt may tend to re-accumulate in sheltered, upper reaches of the harbour. The bed is, therefore, unlikely to turn sandy after mangrove removal. However, that may not be true in areas with natural physical processes that prevent mud buildup (e.g., exposed to predominant winds that generate waves that scour the seabed clean). Unless every single plant is removed, mangroves will try to recolonise, which will be aided by natural return of sediments to sheltered, upper reaches. Finally, water clarity may decline throughout the estuary as mud that was stabilised by mangroves is again reactivated and widely dispersed by waves and currents.

Time/effort/dollars

- Resource consent will be required
- Initial effort will be expensive (volunteer labour will reduce costs)
- Perpetual maintenance will be required

Option 2. If we draw a line in the sand

Goals

- Maintain status quo by preventing mangrove propagules from establishing

Pros	Cons
Possibly achievable, especially if effective controls on sediment erosion in the catchment can be put in place	Trampling of adjacent habitats during works if not properly organised and managed
Breathing room while catchment issues are addressed	Without erosion controls in the catchment, capacity of existing mangroves to “absorb” sediments may be exceeded in time, causing increased turbidity and increased smothering risk throughout rest of estuary
Physical functions of mangroves maintained	Human amenity only partially addressed
Loss of estuarine flushing capacity slowed	
Ecological functions of mangroves maintained	
Human amenity maintained in some areas	

Are goals achievable?

Possibly, with a commitment to ongoing maintenance.

Time/effort/dollars

- Resource consent ***might*** be required
- No large initial effort and expense required
- Regular maintenance will be required (may reduce over time)

Option 3. If we let nature be

Goals

- Allow estuary to age naturally

Pros	Cons
Achievable, but ...	... ageing may not be "natural", due to the disturbance of the catchment. Intervention may be appropriate to maintain ecological functioning and biodiversity of the estuary as a whole
Physical functions of mangroves maintained	Loss of other estuarine habitats and their attendant ecological and physical functions (shellfish beds, seagrass beds, flounder fishing areas, wading and diving, bird habitats)
Continued trapping of terrestrial sediments or contaminants	Loss of human amenity (access, kaimoana, aesthetics, recreation, commerce)
Reduced erosion of shorelines and stream banks	
Creation of coastal land for development	
Ecological functions of mangroves maintained	
Minimum cost	

Are goals achievable?

It is obviously easy to "let nature be", but "natural ageing" may not be the result in what are already sediment-impacted estuaries. Intervention may be appropriate and effective.

Time/effort/dollars

- None

The fourth way

There is another option: managed control (or "total estuary management"). For example, nature might be left alone to run its course in the estuary, but strong controls could be placed on sediment erosion on the land to retard the estuary ageing. Where mangroves are important for coastal protection, they can be left alone, but where overriding values relate to access or open-water views, an eradication or control scheme might be started. The fourth way may often be the smartest way, and it is becoming increasingly viable as we learn more about mangroves and the way estuaries work, and as we collect our experiences to date on attempts to control mangrove spread.

What is missing?

Usually, local knowledge. If every estuary or every part of an estuary were the same, then we could write the textbook on mangroves and that would be the end of the story. But that is not the case. Instead, we need to "tweak" our understanding and our expectations for each local setting. For instance, Option 1 may be viable in an embayment that is exposed to the region's dominant wind. This is because waves kicked up by the wind may readily scour the mudbanks that would remain behind after clearing of mangroves. An important early step in preparing any management plan is to develop an understanding of the local setting.

Where to from here?

Most importantly, mangroves cannot be adequately managed on an individual or uncoordinated basis; individuals need to band together to achieve a result.

The coastal marine area is Crown land, administered by the Department of Conservation and regulated by regional councils under regional coastal plans. Some district councils also regulate through by-laws down to mean low-water spring tide. Many estuaries have esplanade reserves or strips on the land bounding them, which are the responsibility of district councils. Numerous people might have interests in any given estuary, including those who live next to it, have a view to it, or use it for recreation. Maori have long used estuaries for food gathering and cultural resources. A successful estuary management plan will be based on the constructive involvement of all interested parties, rather than simply the opinions of one or two people. Long-term support will be required of the whole community. Acting individually or in isolated groups can lead to polarisation within the community, conflict, and even legal challenges.

What can you do if you are concerned about the state of your estuary? Here are some suggestions, based on the experiences of existing community groups.

1. Talk informally to neighbours and local marae representatives to find out their interests and concerns.
2. Find out what information the regional and district councils hold about the estuary, including regional and district plans and rules. Councils can often provide useful maps and aerial photos.
3. Call a public meeting to hear what others have to say, and build a shared vision for the future. What do you value about your estuary? The wildlife, boating opportunities, kaimoana, walking access, open-water views? How do you want your estuary to be, say, 10 years from now?
4. Focus on wider issues beyond mangroves; think about cause and effect, including changes required in the catchment to reduce silt loads. Identify potential ways of achieving your vision, and pick your first steps.
5. A community group can be formed to develop and implement a plan, and to maintain communication with agencies and the wider community. Group members should always seek to base decisions on sound information, discussion, and understanding of legal requirements.
6. An independent facilitator can be valuable in meetings to keep discussions on track and to ensure all parties are heard, particularly if views are diverse. A facilitator may also be able to help you find advice and resources, and to build relationships with agencies and other parties. In Tauranga Harbour, the NZ Landcare Trust is providing such support to Waikaraka Estuary Managers and other landcare groups. Similar support may be available in your area.

Concluding remarks

Sediment-clogged estuaries and coasts are symptoms of a problem that began on the land hundreds of years ago when New Zealand's forests were burned and cleared. True solutions, therefore, must include the catchment. Regional councils have at their disposal numerous statutes that can be brought to bear on the problem, and there are many devices and practices that can be used to control soil erosion. Statutes need to be enforced, and strengthened if inadequate. Erosion controls need to be used on land, and used properly. Discharges into estuaries must be controlled and managed. To truly effectively protect, restore, and enhance your local waterway requires you to become involved in the management of the catchment as well.

We thank André and Robin LaBonté for their contribution.
Research conducted by NIWA on sediment-affected estuaries and coasts is being funded by the Foundation for Research, Science and Technology.
For more information on NIWA's research programmes visit www.niwa.co.nz/rc/prog
For further information, contact Dr Malcolm Green
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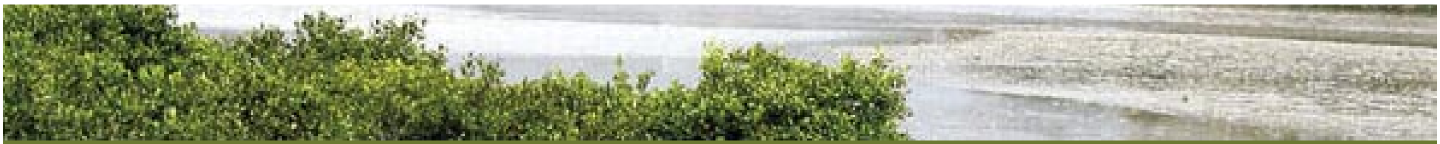
Estuary monitoring by communities

Mangrove habitats a case study

Anne-Maree Schwarz
NIWA

Sharon Parker, Michael Grose
Waikaraka Estuary Managers



Introduction

These guidelines outline a recommended minimum set of methods for a community group interested in following habitat changes in an estuary. They have been developed in relation to mangroves but the principles can be applied to a number of aspects of estuarine ecology in general. They are designed primarily to: *provide guidance in planning a simple monitoring programme enabling community groups to increase understanding of mangrove habitat in their local estuary*.

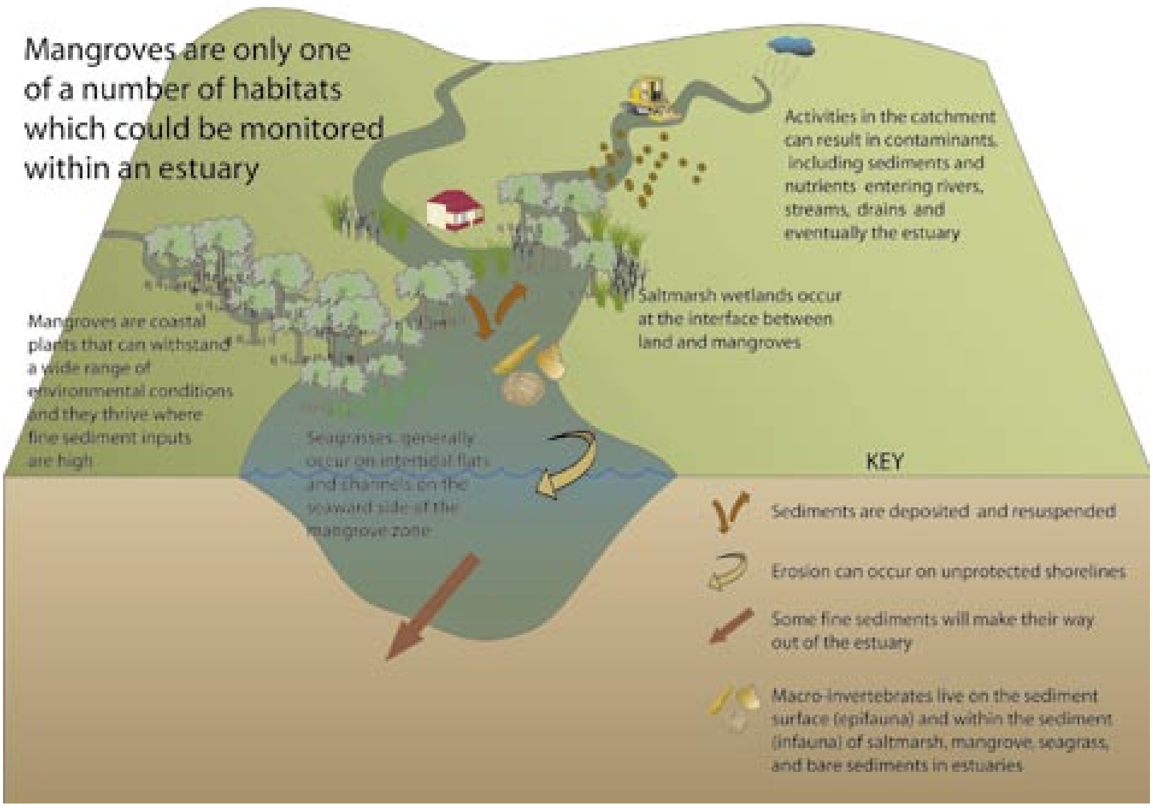
In this context 'monitoring' is used to mean taking a standard set of measurements at regular intervals and keeping a record of results so they can be compared over time.

These guidelines are based on the document "*Some options for community-focused ecological monitoring of mangrove habitats in estuaries"* compiled by the scientific working party of the Mangrove Steering Group (Environment Waikato). Interested parties are referred to that document for more detail regarding monitoring of consented activities.

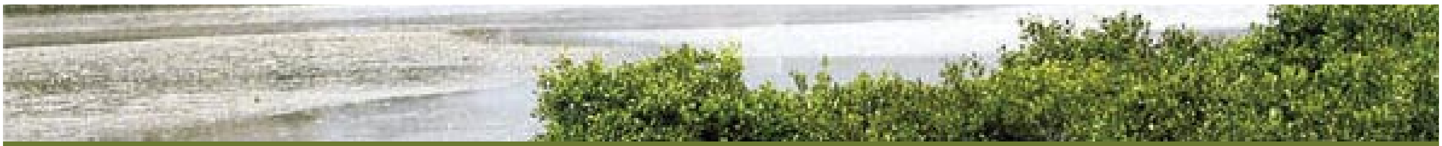
The methods have been developed in conjunction with a community group field trial (Waikaraka Estuary Managers). Further modifications may be required for your particular estuary, and there are a number of components that could be added. For example, subsequent to this trial the Waikaraka Estuary Managers have included birds in the monitoring programme. Methods were developed in discussion with Environment Bay of Plenty, Department of Conservation, and the Ornithological Society of New Zealand.

Follow the chart (www.niwa.co.nz/ncco/tools) using the methods and data sheet examples to see how Waikaraka community group are answering questions like:

- How do the characteristics of the mangroves change over time?
- What lives in the mangroves?
- What is the source of mud to the estuary, and where does it end up?



Symbols for diagrams courtesy of the Integration and Applicaton Network, University of Maryland Center for Environmental Science



Flow chart of actions

1 Decide to monitor

Community Group decides to initiate monitoring programme.

2 Plan a monitoring programme

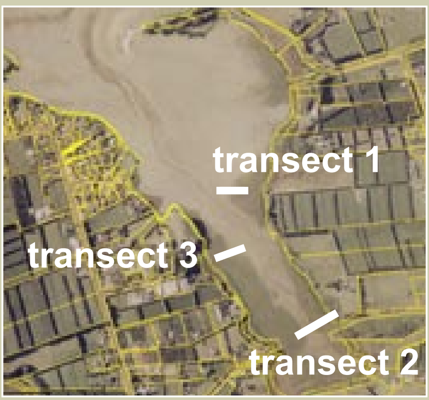
Discuss the use of the guidelines with a research provider or regional council.

3 Hold a briefing meeting

Organise a meeting of interested community group members. A minimum of four members in the monitoring team is recommended.

Agenda

- Agree on long-term vision and goals.
- Choose at least two sites within the estuary where there is a mangrove boundary that you are interested in.
- Choose any additional site where you would like to measure changes in sediment height.
- Choose sites where you are interested in water clarity.
- Mark all sites on an aerial photo or map (see example below).
- Allocate responsibility for equipment (Page 8), and data sheets (www.niwa.co.nz/ncco/tools) and assign someone to maintain the data record.
- Make up a timetable for one year of monitoring.
- Plan for one full low tide period to set up the monitoring site. Allow about 4 hours for four people.



Example timetable

Task	How often	When
Monitor mangrove boundary characteristics	Annually	December
Count epifauna	Annually	December
Sediment height, penetrometer	Every three months	September, December, March, June
Water clarity	Every three months	September, December, March, June

4 Hold a set up day, (methods are detailed on the following pages).

1. Establish permanent transects
2. Record mangrove boundary characteristics
3. Count epifauna
4. Take photographs
5. Install sediment height monitoring pegs and record height above sediment
6. Make penetrometer measurements
7. Measure water clarity

5 Monitor

Every 3 months repeat measurements for methods 5 to 7

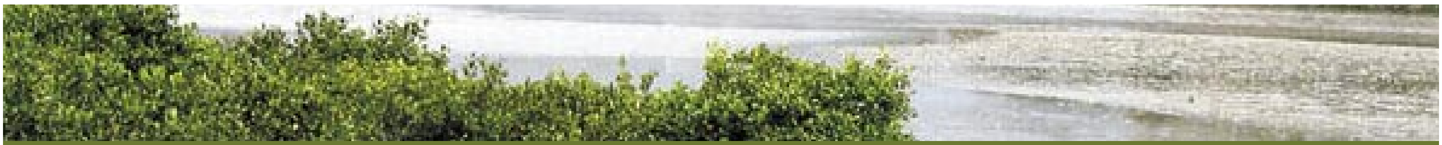
Every year repeat measurements for methods 1 to 4

Maintain records on paper, and if, possible in a computer spreadsheet

At least once a year, meet to assess progress, resources, findings, bottle necks, and make adjustments where necessary. Be prepared to make changes over the first year of your monitoring until you have a smooth repeatable system that can be carried out by a number of your group members. If possible, at this time it would also be prudent to involve a research provider or regional council representative to discuss your results.

Re-assess and allow for changes.

6 Arrange for summaries of your findings to be presented to your community group



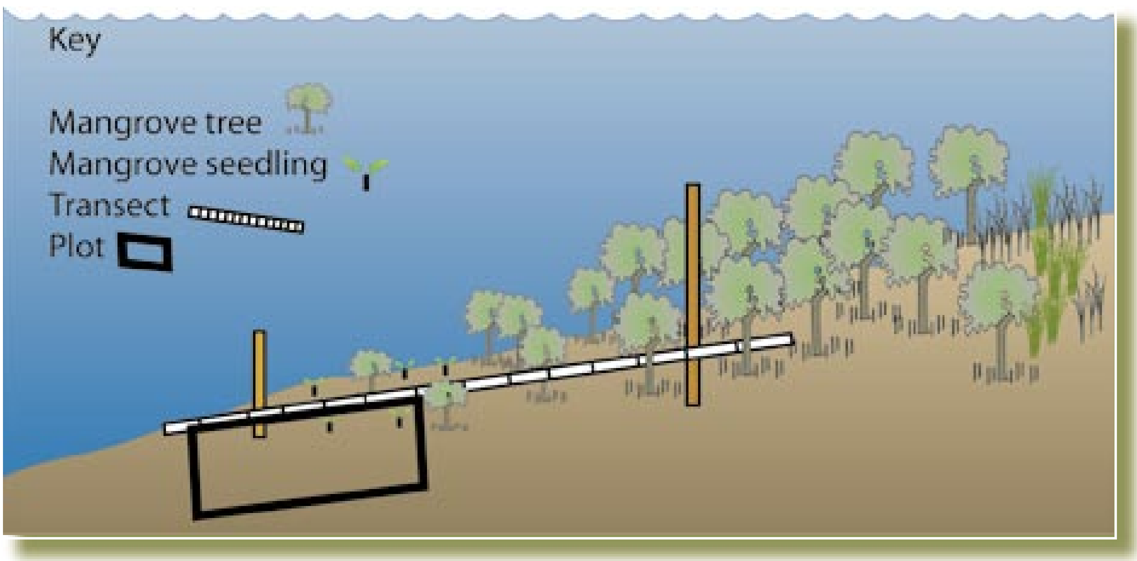
1. Establish permanent transects

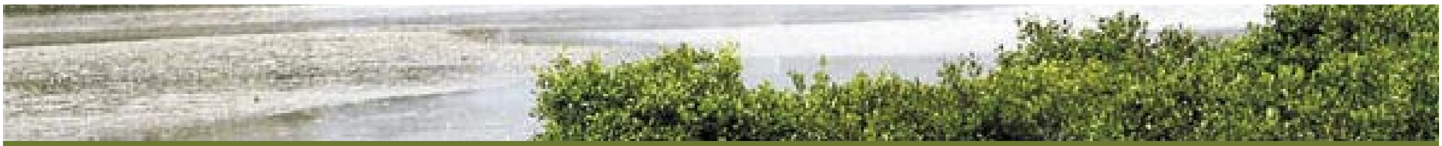
(Use data sheet 1 - NIWA website - www.niwa.co.nz/ncco/tools)

Goal: To establish permanent sites where measurements can be made to understand how the distribution and character of mangroves and adjacent habitats change over time.

It is likely that your main boundary of interest will be the seaward boundary between the mangroves and the tidal flats, and the wording in the methods reflects this. However, if relevant to your site, the same methods can be used across other boundaries, e.g., mangrove/saltmarsh.

At each site locate the start and end of your transects (two transects are recommended at each site). Mark each end of the transect by hammering in a wooden stake. Number the stakes to allow for future ease of identification. The length of the transect and the location relative to the mangrove boundary will depend on the characteristics of your site. The important thing is to ensure that the transect is long enough to cover the habitats of interest (e.g., mangrove boundary and mudflat, or mangrove boundary and saltmarsh). It is likely to be 20 to 50 m long. It is also important to place permanent markers so that the transect can be precisely relocated. It is recommended that a GPS reading is made where the stakes are placed in case the stakes are removed at any time.





2. Record mangrove boundary characteristics

(Use data sheet 2 - NIWA website - www.niwa.co.nz/ncco/tools)

Goal: To measure changes in the distribution and character of a mangrove forest boundary and adjacent habitats over time.

On the day chosen for regular annual monitoring, lay a marked rope or measuring tape between the stakes, noting which peg is zero. This is your transect. Walk along one side of the transect line only (to avoid trampling) and note the distance on the measuring tape where there is a distinct change in the plant community (e.g., seagrasses, mangrove seedlings, saplings, pneumatophores, and mangrove trees) or bare ground. Also note different types of sediment (e.g., sand, mud).

Temporarily mark a rectangular plot of a known area, adjacent to your transect line. The size of the area will depend on the characteristics of your site (e.g., 5 m x 10 m was appropriate for sparse shrub and seedling cover on a sandflat in Tauranga).

The important thing is that one edge of the plot runs along the transect and that you keep an accurate record of the location relative to the transect for future reference. A sketch can help. Use the space provided on data sheet 1. Ensure that the plot overlaps the existing boundary of mangrove trees and an area where you might expect to see mangroves expand into over time.

Within the plot count:

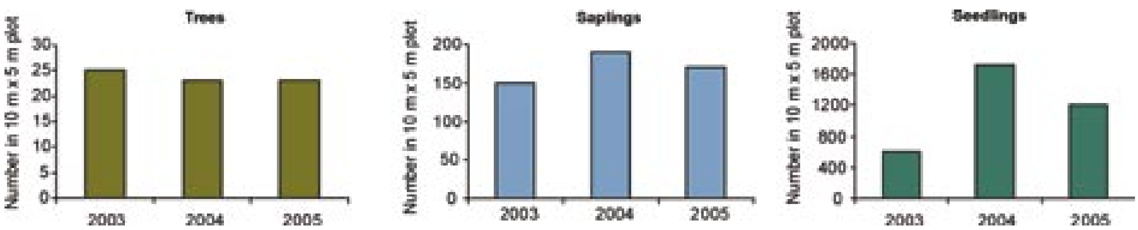
- the total number of trees and measure the height of ten
- the total number of saplings
- the total number of seedlings

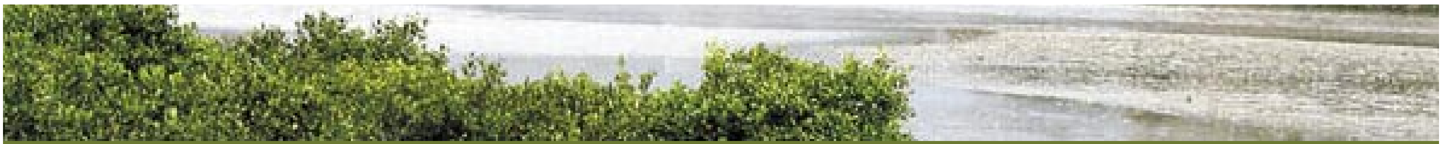
If the number of seedlings is too large to count, then count all individuals in a smaller area of known size, e.g., 1 x 1 m. Replicate if possible three times.

It is important to keep a record of exactly which methods were used each time you visit, including the size of the plots you used.

Example of how counts from the plot can be recorded in an Excel spreadsheet and then graphed to show changes over time.

	A	B	C	D	E	F	G
1	TRANSECT 1						
2		2003		2004		2005	
3	Number of Trees in 10 x 5 m plot		25		23		23
4	Number of saplings in 10 x 5 m plot		150		189		170
5	1x 1m replicate for seedlings	13		62		20	
6	1x 1m replicate for seedlings	11		28		43	
7	1 x 1m replicate for seedlings	13		13		9	
8	Average	12.0		34.3		24.0	
9	Number of seedlings in 10 x 5 m plot		600		1717		1200





3. Count epifauna (animals living on the sediment surface)

(Use data sheet 3 - NIWA website - www.niwa.co.nz/ncco/tools)

Goal: To characterise the animals that use different habitats within and adjacent to a mangrove stand.

Place a 25 x 25 cm quadrat at five haphazard locations, no further than 10 m from your transect line, within each of your main habitat types, e.g., mudflat, seedlings, mangrove trees.

Record the number of different animals seen on the sediment surface within each quadrat. A general field guide to marine invertebrates of N.Z. will be useful to help in identifications and you may like to make up a a guide specific to the animals you commonly find in your estuary.

It is important to include all of the animals that you see within the quadrats each time you visit the site. If there are very large numbers, you may need to count the animals in only one quarter of the quadrat and multiply the count by four.

	A	B	C	D	E
1	Date Dec 2003		quadrat number	titiko	mud whelk
2	Transect 1				
3	within trees		1	0	25
4			2	1	22
5			3	1	21
6			4	4	25
7			5	3	16
8		average		1.8	22
9	within saplings		1	2	13
10			2	1	12
11			3	3	13
12			4	1	11
13			5	0	9
14		average		1.4	12
15	on the sandflat		1	0	4
16			2	0	6
17			3	1	4
18			4	0	5
19			5	0	7
20		average		0.2	5.2

Example of how data can be recorded in an Excel spreadsheet. ▲

4. Take photographs

(Use data sheet 4 - NIWA website - www.niwa.co.nz/ncco/tools)

Goal: To maintain a photographic record of each of the transects.

At each annual sampling, take a photograph from the same perspective at each of the transect markers. Any other photographs (e.g., of sediment height marker pegs) will provide a useful record for later comparison.

5. Install sediment height monitoring pegs

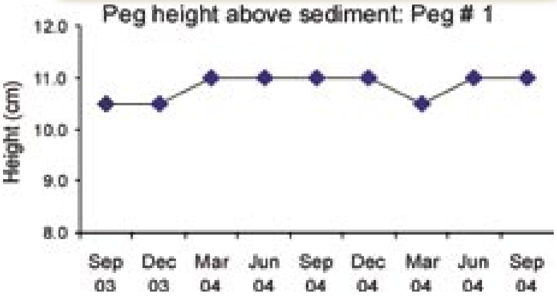
(Use data sheet 5 - NIWA website - www.niwa.co.nz/ncco/tools)

Goal: To measure rates of sediment accumulation or loss.

Hammer a series of wooden stakes*, firmly into the sediment (leaving up to 20 cm exposed). Number each peg for future identification. Place the stakes haphazardly along the transect line and at various distances away from the transect (alternatively choose a range of locations throughout the estuary that are within your areas of interest). Pay particular attention to having sufficient replication (5 stakes) both within the mangrove stand and around the boundaries of the mangrove forest. Lay a ruler on the ground next to the stake to account for any erosion close to the stake. Measure the distance from the top of the stake to the level of the ruler.

** Wooden stakes are susceptible to erosion at the base but are inexpensive and less likely to be tampered with than some alternatives. For further discussion of alternative techniques, see the "Mangrove Guidelines" (contact Environment Waikato) document.*

Example of how measurements from one peg can be presented to show change over time.



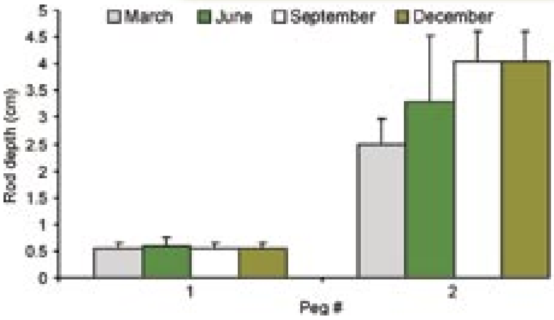
6. Make penetrometer measurements

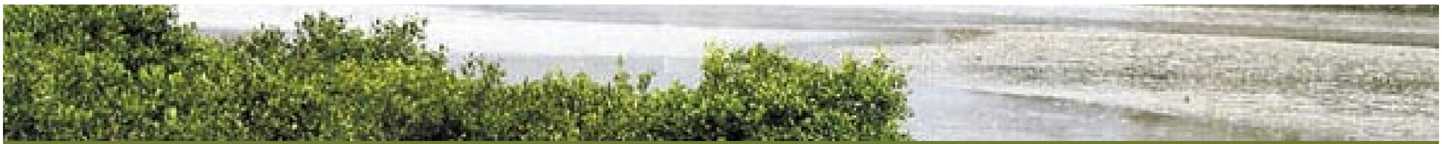
(Use data sheet 6 - NIWA website - www.niwa.co.nz/ncco/tools)

Goal: To measure the degree of sediment compaction at sites where sediment height monitoring rods are installed.

Sediment compaction is an important factor determining sediment re-mobilisation. A penetrometer measures the force required to penetrate the sediment to a given depth. Drop the penetrometer from a standard height of 1 m. Note the depth to which the steel rod penetrates and repeat this process 10 times around each sediment height monitoring rod. Use a ruler to measure the height of the penetrometer above the sediment surface. The penetrometer should be measured only when it is roughly vertical. Calculate the average of the 10 measurements. Repeat every three months.

Example of how data from two pegs measured four times in a year can be plotted to show changes over time.

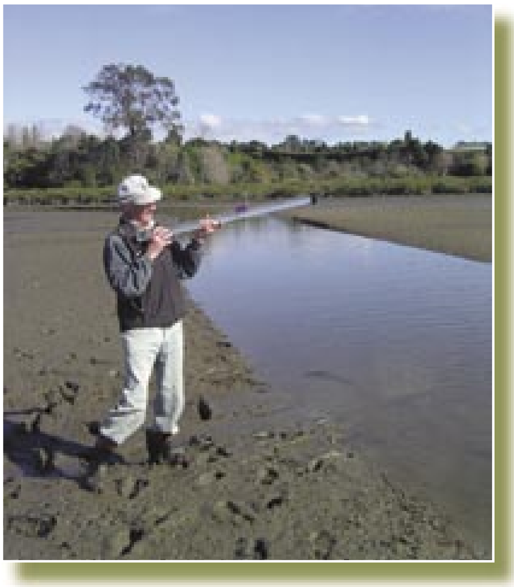




7. Measure water clarity

(Use data sheet 7 - NIWA website - www.niwa.co.nz/ncco/tools)

Goal: To compare tributaries and how water clarity changes as a result of sediment remobilisation at different places within the estuary.

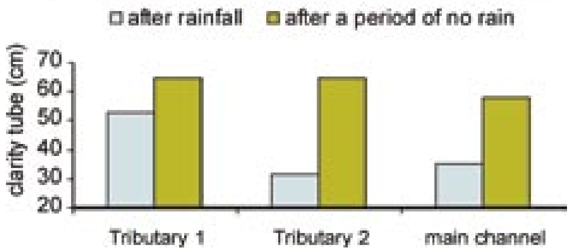


Use a NIWA clarity tube to measure water clarity at selected sites at three monthly intervals. Fill the tube with water at the site and move the black magnetic indicator until it just disappears from view. Record the average value of up to three members of the team. Note the time at which measurements were made.

It is important to thoroughly rinse the tube with fresh water after use.

In addition to your regular monitoring, extra measurements are recommended immediately following storm events or heavy rainfall.

Example of how water clarity data can be presented. After rainfall, tributary 2 was notably more turbid, and this affected clarity further down the estuary. ▶



Useful terms as they are used in this document

Mangrove seedlings:	Plants less than 25 cm tall.
Mangrove saplings:	Bigger than a seedling (> 25 cm tall) but have not branched.
Mangrove trees:	Mangrove plants larger than a sapling and branched.
Mangrove boundary:	Limit of trees where only saplings and seedlings are found.
Pneumatophores:	Aerial roots for gas exchange.
Epifauna:	Animals living on the surface of the substrate.
Infauna:	Aquatic animals living within the sediment.
Habitat:	The place where environmental conditions are suitable for the survival of a particular organism (e.g., mangroves).
Site:	General area of interest within an estuary, likely to be at the scale of a bay or inlet.
Transect:	A line on the ground along which sample plots or points are established for collecting data.
Quadrat:	A square with sides of equal size, e.g., (25 x 25 cm) within which counts can be made of organisms in a known area.
Replicate:	More than one sample unit to account for natural variability.

Equipment List

Setup day only

- Four numbered wooden stakes (about 100 x 5 x 5 cm)
- Sledgehammer
- Ten numbered wooden stakes, 100 x 2 x 2 cm
- GPS

Regular monitoring

- Backpack
- Camera
- Data sheets and pencil
- Camera
- 50 m measuring tape
- Ruler
- Penetrometer sharpened steel rod (40 cm long, 0.7 cm diameter)
- Water clarity tube
- Watch
- ID sheets
- 25 x 25 cm quadrat
- Aerial photo/map showing location of sites
- Temporary corner pegs and string for marking plot

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ESTUARINE AND COASTAL ECOSYSTEMS

Effect of increased suspended sediment on suspension-feeding shellfish

Judi Hewitt

Research is underway to pin down the effects of increasing sediment inputs to coastal waters on some of New Zealand's important shellfish species.

Teachers: this article can be used for Biology L7 A.O. 7.1a. See other curriculum connections at www.niwa.co.nz/pubs/wa/resources

Judi Hewitt is based at NIWA in Hamilton.

In New Zealand, changes in land use (such as deforestation and urbanisation), and modification of coastlines have increased sediment build-up in coastal environments. Suspended sediment concentrations in estuaries and along the coasts can increase by orders of magnitude for hours to several days following erosion during storms. In big storms, a large proportion of the annual sediment load may be delivered in a matter of hours. Because of processes that cause sediment to go back into suspension – like waves, currents, animals digging in the sediment – suspended sediment levels are often highest in bottom waters.

In estuaries and coastal embayments, most shellfish consumed by people (oysters, mussels, cockles and pipis) are suspension feeders. They often make up a large proportion of the animals that live in and on the seabed in these places and affect exchanges between the water column and the seabed (such as nutrients and sediment). As these animals feed by removing particles from the water, they are likely to be directly impacted by changes to suspended sediment. It is important to be able to predict any negative effects on suspension feeders caused by such changes.

Effects of extra sediment

Effects of elevated suspended sediment depend primarily on two factors: the size range of the sediment particles, and the food content of the suspended sediment.

If the changes to sediment involve particles above the maximum size used by most suspension feeders (about 20 mm diameter) then effects will probably be minimal.

If the food content in sediment increases, animals may be able to get more nutrition for time spent feeding. If the food content decreases, animals will have to work harder for their food. The more energy they have to spend to gain the same amount/quality of food, the less energy they have for growth and reproduction. As the energy used on feeding increases, the animal loses condition and, finally, dies.


Cockles


Pipi


Horse mussels

Scientists have investigated feeding rates of suspension-feeding bivalves for many years. Most of the species studied are those that are commercially and recreationally important overseas. Water temperature, velocity, particle size and suspended sediment concentrations, and food quality have all been found to affect feeding rates. Similar factors are likely to be important for New Zealand species, though differences in feeding morphologies, behaviour, feeding methods, energy uptake rates and metabolic costs mean that we cannot transfer the results directly.

Study species

NIWA scientists are investigating the relationship between increased suspended sediment concentrations and the ingestion, growth rates and condition of a number of suspension-feeding shellfish. So far work has concentrated on the horse mussel (*Atrina zelandica*), the cockle (*Austrovenus stutchburyi*), and the pipi (*Paphies australis*).

Horse mussels are large (up to 30 cm long) and live in many coastal areas of New Zealand in depths ranging from shallow subtidal to about 50 metres. Cockles are the most common intertidal bivalves found in New Zealand, and frequently occur in very dense beds. Adult pipis are generally found in low intertidal areas, near channels with fast flows, and are generally 6–10 cm long.

The answers so far

Although our studies are still in progress, we have found adverse effects of increased suspended sediment concentrations on each of these species. For example, consistently negative effects were found on the growth and condition of horse mussels, the growth of cockles, and the condition and reproductive output of pipis. Feeding rates of all species initially increased, but as suspended sediment continued to increase, feeding rates decreased. Condition of cockles showed a similar result, with peak condition occurring at suspended-sediment levels around 400 mg/litre. Some of our research also suggests that the response to increases will depend on the reproductive state of the animal and whether they live in areas with frequent high suspended-sediment concentrations.

We will continue to investigate effects on suspension-feeding shellfish, broadening the number of species investigated. However, other types of animals may also be affected by increased suspended-sediment concentrations. The increased flux of sediment settling on the seabed is likely to affect animals that feed on deposited sediment. Lower water clarity may affect the quantity, type and depth to which bottom-living microscopic algae and seaweeds can grow, thus affecting feeding and distributions of grazers (such as paua). Lower water clarity may also affect feeding abilities of visual predators (such as snapper). New studies will investigate the effects for these types of animals. ■

This work is being carried out in the FRST programme "Effects of sediment on estuarine and coastal ecosystems" (contract C01X0028)

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COASTAL ECOSYSTEMS

Modelling the effects of muddy waters on shellfish

Nicole Hancock

Judi Hewitt

Statistical models can assist in predicting the effects of different levels of sediment in the water for maintaining the health of coastal ecosystems.

Teachers' resource for NCEA AS: Biology 1.4, 2.4, 2.5, 2.6, 3.1; Science 1.1, 2.2, 3.1; Geography 3.1. See www.niwa.co.nz/edu/resources

Nicole Hancock and Judi Hewitt are based at NIWA in Hamilton.

You may have noticed that after heavy rain and strong winds the sea along our coasts becomes brown and dirty. Some of this dirt (sediment) is from fine marine sediments being resuspended from the sea floor by wave and current action (see *Water & Atmosphere 11(2)*: 20–21). But rain also washes sediment from the land into the sea, particularly during heavy rain or floods. This occurs especially where the soil is exposed, such as in housing developments, farms and forestry areas (*Water & Atmosphere 11(1)*: 1–13). Streams and rivers carry the terrestrial sediment into estuaries and coastal ecosystems, where it mixes with the sea. Changes in land use over the past 150 years have led to increased sediment runoff into some New Zealand estuaries (*Water & Atmosphere 11(1)*: 14–15).

Why should this matter?

One reason is that shellfish like cockles, pipis and horse mussels all get their food by filtering water through their gills and catching the food particles. During the search for food the shellfish also take in non-food particles suspended in the water (such as sediment). These particles are either bound up in mucus and rejected, or ingested along with the food. Either way, non-food particles require the shellfish to use more energy during feeding, leaving less energy for maintaining healthy weight, growth or reproduction.

Some shellfish species can be very important ecologically (*Water & Atmosphere 10(2)*: 22–23) and many species are also culturally important. Thus there are good reasons for

Cockle
(Photo: Michael Ahrens)

investigating potential threats to shellfish populations.

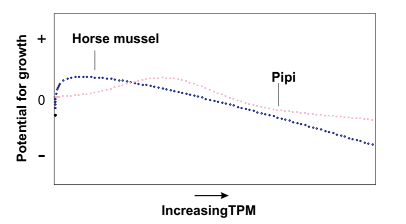
Measuring sediment and modelling shellfish

Scientists at NIWA have been studying and modelling the effects of sediment particles in the water on the health of some common species of shellfish (cockles, pipis, horse mussels). The amount of sediment carried in the water is described as **total particulate matter** (TPM). TPM comprises all suspended particles in the water including sediment (silt and clay) and organic material (such as algae). For the modelling part of the work we use a so-called scope-for-growth (SFG) model (see panel opposite).

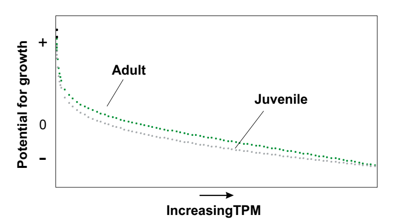
Because species vary in the way they handle and process food, each species needs a separate model. For example in the left-hand graph (top of opposite page) you can see that the horse mussel shows highest potential for growth at very low levels of TPM. Potential for growth then steadily declines as TPM increases. The

Sediment plume from the Waimakariri River, Canterbury. (Photo: Rob Bell)

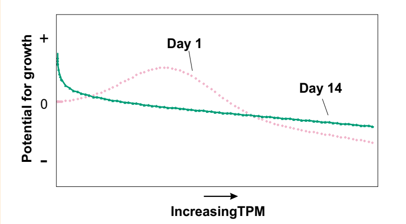
Scope-for-growth model graphs



Response to TPM is species-specific. The modelling showed different responses from horse mussels and pipis.



Juvenile shellfish are more adversely affected by TPM than adults of the same species.



Exposure time to TPM affects shellfish response. Longer exposure causes lower potential for growth in pipis.

pipi's highest potential for growth occurs at slightly higher TPM levels and then once again potential for growth steadily decreases as TPM increases.

Two factors that the models highlighted as important in shellfish response to TPM were shellfish age and length of exposure to high TPM levels.

Shellfish age Although both adult and juvenile pipis showed decreasing potential for growth as TPM increased (see centre graph), juvenile pipis were less tolerant of TPM than adult pipis. In the same way that children are more susceptible to some diseases than adults, juvenile shellfish are less resistant to stress than adults.

Length of exposure The right-hand graph shows that pipis exposed to various levels of TPM had a best potential for growth on the first day of exposure at intermediate TPM levels, seen on the graph as a peak on the "Day 1" line. As TPM increased, potential for growth decreased, with lowest potential for growth on day 1 at very high TPM levels. This is because the pipis stopped feeding altogether as they waited for conditions to improve (as they would in the sea when a storm passes). As high TPM conditions continued over the following days, these pipis eventually had to start feeding. The other line on the graph represents predicted potential for growth after 14 days of exposure to a range of TPM levels. By this time, pipi potential for growth was highest at very low TPM and then decreased with increasing TPM, no longer showing the same optimum feeding level behaviour at intermediate TPM levels.

A limitation with all models is that they include assumptions, so the results must be used as guidelines rather than definite outcomes. It is important to remember when using models that they are extrapolations from collected data and they are limited by what information can reasonably be included in the model. Even complex ecophysiological models (see panel) do not deal well with changes to TPM caused by events such as storms. Nor can they accurately take into account site differences in algal composition, or animal health and behaviour.

Conclusions

Our modelling confirmed that shellfish are sensitive to changes in TPM. Thus they can reasonably be used to reflect aspects of the health of ecosystems. Models can help scientists determine effects of TPM on shellfish, by allowing easy visualisation and manipulation of data, and prediction of shellfish response to increased levels of TPM. The information can be used to advise planners and resource managers about the effects of different levels of sediment runoff for monitoring and maintaining the health of coastal ecosystems, taking into account existing marine resuspended sediment levels. Informed managers can then take steps during the planning stages of land development – or estuary restoration – to minimise the effects of sediment runoff on coastal marine ecology. ■

A choice of models

Models can be used to predict the effects of total particulate matter (TPM) – a measure of sediment suspended in the water – on suspension feeders. We base the models on data collected during experiments. There are several approaches to modelling.

- **Statistical models** describe trends in the experimental data.
- **Scope-for-growth (SFG) models** describe shellfish production (potential for growth) in terms of energy in (absorption of food) minus energy out (respiration plus excretion). The SFG model gives us a simple way of visualising the interaction between variables that combine to give the shellfish's physiological response to TPM.
- More complex **ecophysiological models** take into account changes in physiological responses to seasonal variations in temperature and food quality, together with population aspects of the shellfish such as size, reproduction and the number of shellfish in one area. NIWA scientists have produced some of these models, which require large amounts of information.

Of these examples, simple SFG models can be quickly assembled and can still give good predictions to responses to TPM.

Horse mussel bed. (Photo: Pip Nicholls)

ESTUARIES

Winds, waves, and recovery from sedimentation in estuaries

Carolyn Lundquist
Sara Hatton

Can estuaries recover from sedimentation? Models and field experiments are starting to provide some answers.

Teachers: this article can be used for NCEA Achievement Standards in Science (2.2), Geography (3.1). See other curriculum connections at www.niwa.co.nz/pubs/wa/resources

Carolyn Lundquist is based at NIWA in Hamilton; Sara Hatton was formerly with NIWA, Hamilton.

There is little doubt that New Zealand's estuaries are getting muddier (see article on pages 19–21 in this issue). Several research projects have examined the direct effects of fine sediment on the animals that live in estuaries (for example, see *Water & Atmosphere 10(2)*: 22–23). But other questions remain: Do estuaries recover from events that cause sedimentation? How might this happen? Is it possible to make predictions to identify which areas or habitats are most, or least, likely to recover?

When an area of estuary has been affected by a disturbance such as a sediment dump, recovery depends on many factors. Are enough animals nearby to recolonise the area? How far can waves, tides and storms carry animals of various sizes? How long is the area under water?

Models and measurements

We have developed simple models to predict the transport of colonising animals into disturbed parts of an estuary. For example, exposed estuarine sandflats are predicted to receive more colonisers than high intertidal areas such as mudflats and tidal creeks; and strong tidal currents lead to higher transport rates than neap tides and calm conditions.

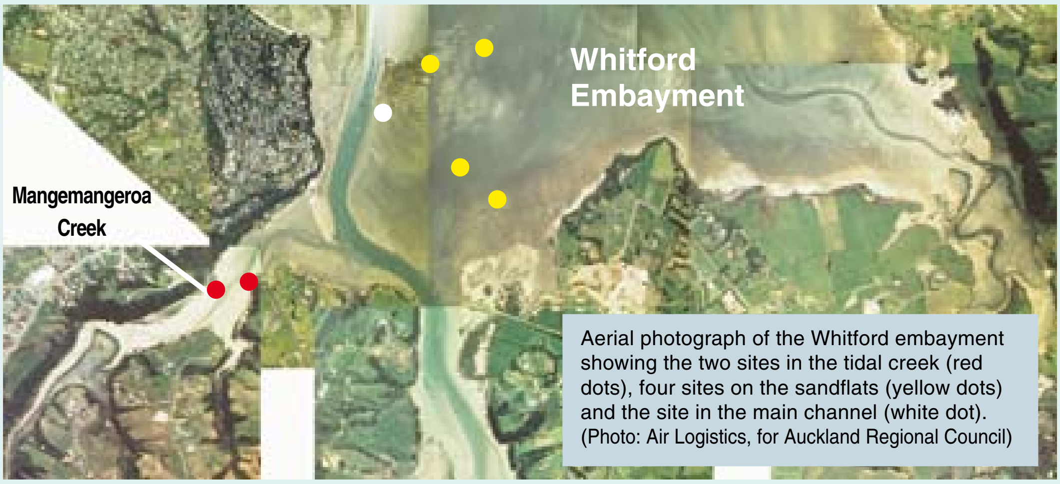
With the predictions of the model in mind, we designed a field experiment to explore the potential for recolonisation in different habitats in an estuary. We looked at two factors:

1. differences among sites in the numbers of animals brought into the area;
2. the effects of physical conditions like tidal currents and waves.

We made measurements and observations at 7 sites in the Whitford embayment, Auckland, in December 2001 and February 2002. Five sites were in the estuary itself: four sandflat sites (upper and lower areas) and one next to the main channel, so that each site had a different time under water. There were also two intertidal sites (called the mud and mangrove sites) in Mangemangeroa Creek, upstream of the estuary.

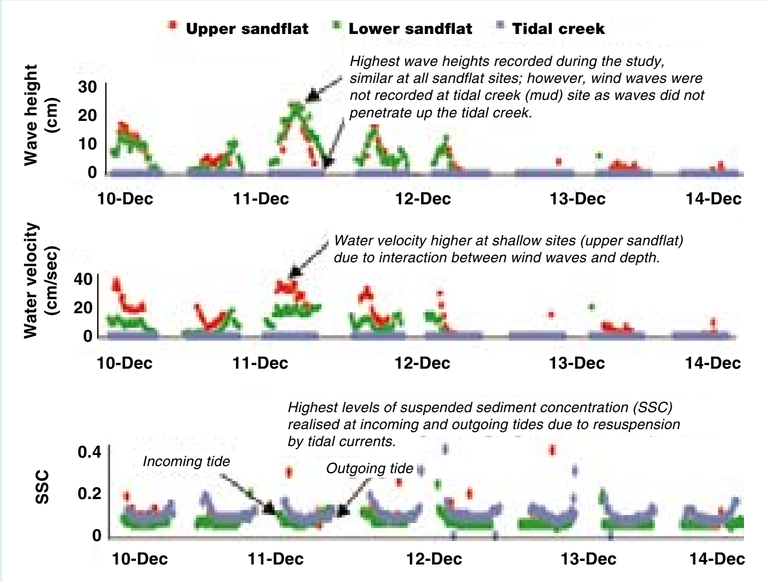
At each site we installed sediment traps to collect animals transported along the sediment surface and animals floating in the water. Wave gauges (DOBIEs) and other instruments gave information on water depth, wave height, water flow at the sediment surface, the amount of sediment in the water, and currents caused by tides or wind at each site.

Here we discuss the results from our first set of measurements on 10–14 December 2001. During this time there were spring tides, and both calm weather and a storm. We show differences in physical conditions using data from 3 of the sites. Differences in colonising animals are illustrated for all 7 sites.

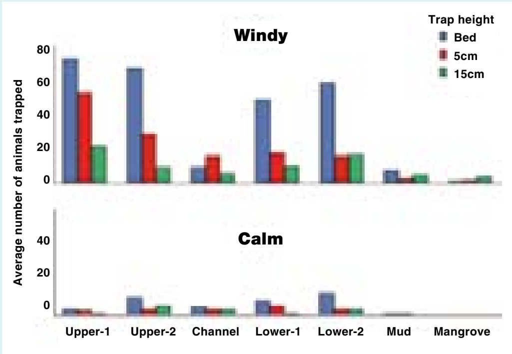


Aerial photograph of the Whitford embayment showing the two sites in the tidal creek (red dots), four sites on the sandflats (yellow dots) and the site in the main channel (white dot). (Photo: Air Logistics, for Auckland Regional Council)

A DOBIE at one of the sandflat sites. DOBIE wave gauges measure water pressure, and from this calculate wave height, wave period and water depth. Some DOBIEs also measure the suspended sediment concentration of the water using an optical back-scatter sensor (see *Water & Atmosphere 11(1)*: 11–13). (Photo: C. Lundquist)



above:
Wave height, water velocity and suspended sediment concentration (SSC) measured by DOBIEs at three of the sites during the December experiments. The storm was on 10–12 December. There are gaps in the data at low tides when the sites were not underwater.



above left:
Number of animals (e.g., polychaetes, bivalves, amphipods) collected at the seven sites over 24 hours on a windy day and a calm day. Each bar is the average of collections from three traps for each of three trap heights (at the sediment surface, and 5 cm and 15 cm above the sediment).

Differences highlighted

As the graph (right, above) shows, larger waves during the storm on 10–12 December caused more water movement at the sediment surface at the upper sandflat site than at the lower sandflat site, because of shallower water at the upper site. But in the tidal creek (mud site), there were no waves at all, even in the storm.

During the storm, at all sites we measured more suspended sediment on incoming and outgoing tides than during the periods between tides. During the calm period, this pattern occurred only in the tidal creek.

The information collected by the wave gauges and other instruments gave us a picture of how animals might be transported by tidal currents only (measurements made in calm conditions), and how they might be transported by tides plus storm-generated waves.

The number of animals collected in traps clearly showed the role of waves in transporting organisms. During the windy period, 10–20 times more animals were collected in the traps at all the sandflat sites than in the calm period (see graph). The traps at the site in the channel and the two tidal creek sites collected consistently lower numbers of animals than those at all four sandflat sites, though there was still an increase during windy conditions.

Collecting animals at different heights showed that more organisms were transported just above the sediment surface (along with the sediment itself) than up in the water column. Since we expect sediment on the seabed to move shorter distances than sediment carried higher up in the water, the result suggests that most of the animals are moved only short distances by waves. This implies that large disturbed areas may take much longer to recover than smaller, more localised disturbances, because colonist animals are much farther away.

The importance of waves

Our results suggest that small waves generated within harbours or estuaries are important in recolonisation of disturbed intertidal soft-sediment areas. We also showed that the rate of colonisation varies among different locations within an estuary.

We are using the results from these modelling and field studies to develop general models of estuarine recovery after disturbance. The general models can then be applied to other estuaries to predict areas or habitats that are most sensitive to, and are least likely to recover from, increasing sedimentation. ■

This research was carried out as part of NIWA's FRST-funded programme "Effects of Sediments on Estuarine and Coastal Ecosystems" (C01X0024).

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RESOURCE MANAGEMENT

Sediment dumps in estuaries: filling in the gaps with a risk map

Pip Nicholls

Help is available to assess the threat posed by sediment inputs to estuaries.

Pip Nicholls is based at NIWA in Hamilton

Estuaries are important sites for many biological and physical processes, yet they are often taken for granted. They act as "service centres" for nutrient cycling, they are a source of fish and shellfish for human consumption, and they provide nurseries for juvenile fish and birds. These ecosystems can also act as "sinks" for land-based sediments and contaminants.

Many of us live beside estuaries because they are less exposed and offer a protective buffer from the sea, but most of the time we fail to recognise the impact that humans have on these sensitive ecosystems.

New Zealand's increasing population, migration to coastal urban centres, and changing land use from rural to residential and urban, have meant that estuaries and their fringing habitats are under increasing threat. For example, housing developments, construction of roads, and the removal of forests and bush can increase the vulnerability of soils to erosion, which results in more sediment entering estuaries. Steep slopes, loose volcanic soils and high, sporadic rainfall are typical of much of New Zealand, and increase the likelihood and potential size of slips and landslides.

Occasionally these factors combine to produce catastrophic events in which large volumes of sediment enter the estuary as a blanket or "dump". Sediment dumps can cloud the water, thereby increasing turbidity and decreasing algal and phyto-plankton production.

Sediment dumps can also smother and kill estuarine plants and animals within hours. If the sediment persists, recovery can be extremely slow.

Because rehabilitation of a sediment-impacted estuary is difficult, prevention of damage in the first place remains the best option. The first step in preventing damage is identifying risk, so that limited resources can be properly targeted. Scientists at NIWA have developed a guide to help managers produce a "risk map" of an estuary.

How does too much sediment affect estuaries?

Field experiments have shown that:

- Sediment dumps as little as 2–3 cm thick kill most resident animals.
- Only large burrowing crustaceans, such as crabs, seem able to cope.
- Clay dumps can remain in place for a long time (years) and recovery of animal communities is slow because the clay does not provide a good substrate for colonising animals.
- Depending on location in the estuary, clay is either blown off by storms, covered by sand ripples, or mixed and transported by crabs and other large crustaceans.
- Large or repeated dumps degrade estuarine biodiversity and the habitat at the community, species and generic levels.

Guide to producing a risk map

The first step is to identify **values** associated with the estuary. These might relate to specific physical, ecological, cultural, economic and aesthetic features that are worth protecting and monitoring. These might include habitats of endangered species, areas used for recreational harvesting and popular swimming beaches.

Next, assess whether an estuary has already been affected by sediment dumps, by looking for **key dump signs** such as patches of gravel over fine mud, or sandflats covered by yellow/brown mud. Once the extent of damage has been assessed, more resources might be channelled into protecting and reducing the risk of a dump in those estuaries that have been relatively unaffected so far. Alternatively, resources might be targeted at rehabilitation of badly affected but otherwise valuable estuaries or habitats within estuaries.

To help assess future threats, identify any **threat indicators**. These are the physical characteristics of the estuary catchment, such as topography,

left:
Risk map guide, pages 1 and 2.

catchment land use and local climate, all of which affect an estuary's predisposition to a sediment dump. The severity of a sediment dump depends largely on the length of time that the sediment persists in the estuary. Factors that can affect the rate and extent of recovery of the ecosystem include estuary shape, wave exposure, the presence of artificial structures (such as wharves and causeways), and the presence of animals such as crabs – called bioturbators – that rework and break up the dumped sediment. These factors can also be built into the threat indicators.

Look for **ecological changes** to help identify those areas or processes that are affected by sediment dumps. These include changes to mangroves, salt marsh and sea grass beds, or changes in the diversity, abundance and size of resident animals.

Finally, seek ways to reduce the chance of sediment dumps. These include:

- managing soil erosion on the land
- maintaining and planting riparian vegetation
- managing structures within the estuary that affect tidal flows and wave climate
- controlling sediment erosion associated with high-risk activities, such as building roads, constructing houses, and clearing forests.

■

The guide to formulating an estuary sediment risk map (pictured above) is available on request from NIWA, Hamilton.

For further information, contact: Pip Nicholls, NIWA, PO Box 11 115, Hamilton
(ph 07 856 7026, fax 07 856 0151, p.nicholls@niwa.co.nz)

Some key dump signs

Brown clay covering coarse sand and shell.

Abrupt changes from sand to mud.

Threat indicators

Removal of vast areas of vegetation.

The mud crab *Helice crassa* is an excellent bioturbator.

Managing soil erosion

A sediment screen around a culvert adjacent to road works.

ESTUARIES / RESOURCE MANAGEMENT

Assessing human impacts on estuaries: it's a risky business

Alastair Senior
Malcolm Green

A team of modellers at NIWA Hamilton has developed a way to help environmental managers assess "risk" in sediment-impacted estuaries.

Alastair Senior and Malcolm Green are based at NIWA in Hamilton.

Estuaries are often muddy – ask any *Helice crassa* (mud crab). The reason is that clay, mud and silt are continuously being eroded from the land and then delivered to the estuary by streams and rivers. Most sediment arrives during and after heavy rainfall. Some moves straight through to the coastal ocean, but the rest settles in the estuary, usually on intertidal flats or in "fringe habitats" such as mangroves or marshes.

Is this a problem, and what is the risk here?

Too much mud can smother and kill shellfish, cause siltation of navigation channels, turn clear water brown, and encourage the spread of fringe habitats, including mangroves. In short, sediments are irreversibly changing our estuaries. Some changes are natural, but others are definitely not. Tree-felling, building and river/stream bank disturbances can all create soil erosion. Construction of marinas, bridges and navigation channels can alter the water circulation in an estuary that might otherwise help it to "digest" its sediment diet.

"Risk", then, relates to the prospect that human activities might result in damage to the estuary and its ecosystem.

Soil eroded during heavy rainfall has deposited a thick layer of mud on an intertidal flat in this estuary, smothering and killing any shellfish beneath it.

Risk = damage x probability

We define risk as the combination of damage and the probability that this damage will occur. As well as ecological damage (for example, decline in shellfish productivity) there can be social damage (such as loss of aesthetic appeal, restricted access for boats).

Defining damage and its probability of occurrence can be difficult. For example, damage caused by a given sediment input may be harmful in an estuary that is already under pressure, but hardly noticed in a pristine estuary. There might be a threshold of damage: for example, no harmful effects on the ecosystem until turbidity reaches a certain level. Some damage is reversible and some is not. On top of all this, there is still a lot to learn about the way estuarine ecosystems function. All these factors need to be taken into account in any risk assessment.

To help untangle these complexities, we can devise a "risk index". This is done by multiplying the extent of the damage by the probability that damage will occur. The range of levels of risk can then be debated – usually involving regulatory authorities and the general public – and decisions taken on what risks are acceptable or unacceptable.

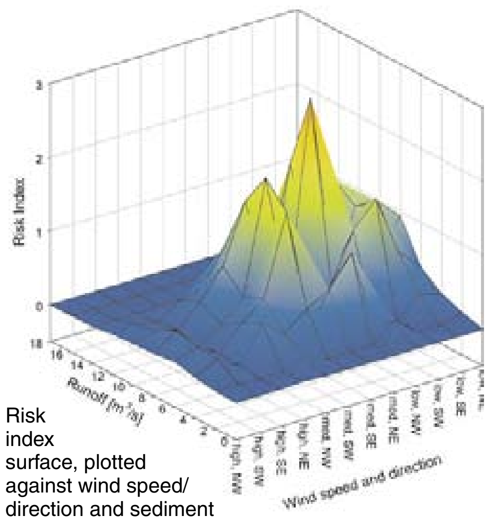
One of the big unknowns in devising a risk index is that it is not easy to predict what will happen to sediment once it reaches the estuary, even though we can predict quite accurately how much extra sediment will be produced on land. A host of factors – winds, waves, tidal currents, freshwater discharge, etc. – influence sediment distribution within an estuary. Fortunately we have a computer model that can help with such predictions (see panel on facing page).

The matrix simulation method

We have developed the so-called "matrix simulation method" for estimating the risk index. The method can be used to investigate a range of issues.

Imagine a shellfish bed that has high productivity and cultural values. Development in the catchment is going to cause increased sediment inputs into the estuary. The volume of sediment runoff from the land and the wind speed/ direction are the major factors controlling sedimentation at the shellfish site.

Using the computer model, we can predict the amount of sediment likely to be deposited on the shellfish bed for every realistic combination of sediment runoff and wind speed/direction. For each combination, the damage to the estuary is the expected decline in shellfish production (based on what we know about



Risk index surface, plotted against wind speed/ direction and sediment runoff from the land. The highest risk is associated with medium sediment runoff and a medium-strength north-east wind.

how shellfish respond to sediment deposition). We can then use weather records to estimate the probability of each wind speed/direction occurring. We can also relate sediment runoff from the land to rainfall and then estimate probability of rainfall. Multiplying those probabilities by the damage produces the risk index. This can be illustrated as a 3-D plot of risk against sediment runoff and wind speed/ direction to create a "risk index surface".

The figure (above) shows that in this example the highest risk is associated with medium sediment runoff combined with a medium-strength north-east wind. The risk associated with smaller sediment runoff is lower, simply because less sediment is available for deposition on the shellfish bed. The risk associated with larger sediment runoff and stronger winds is less, because this combination is less likely to occur.

The debate on choosing an acceptable level of risk can now focus on the analysis of risk presented in the graph. Suppose there are options available for controlling soil erosion on the land: is it worth the cost to implement those controls? We could build another risk index surface based on the lower sediment runoffs that would occur if these controls were in place, and compare the two surfaces to see if the reduction in risk is worth the cost of the controls.

The matrix simulation method can be extended to any level of complexity. Each time we add a new variable into the analysis – perhaps waves or tides, for example – we add another dimension to the simulation matrix. Combining this matrix with a "probability matrix" of the same dimension will generate a risk index matrix, again of the same dimension. Research continues on ways to improve the method, including the development of a decision-support scheme based on the procedure.

The matrix simulation method, which is based on sophisticated computer models of how estuaries function, is a transparent and repeatable way of estimating risk that can provide environmental managers with better information that will improve decision-making.

Planning for the future may not be such a risky business after all! ■

A computer model of an estuary

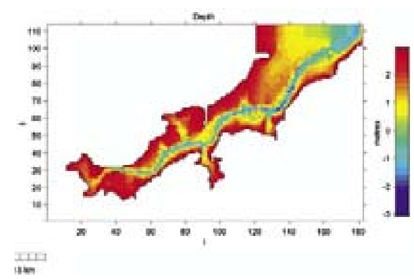
A computer model can predict sediment movement and deposition in an estuary. We use mathematical equations to describe the physical processes that control sediment movement and deposition (tidal currents, waves, etc.) and then write them into a computer code.

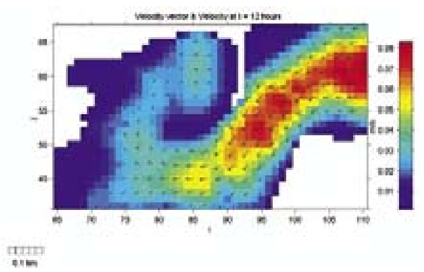
To apply the computer model to a particular estuary, the bathymetry (the shape of the estuary bed) is input first. The model is then controlled by boundary conditions, which specify, for instance, how the tide rises and falls at the seaward entrance of the estuary, how much fresh water and sediment is discharged into the estuary from streams, and the strength and direction of the wind.

For example, one scenario may represent a moderate flood by applying a freshwater discharge of 20 m^3/s and a strong onshore wind continuously over the period of the simulation (typically between four days and one month). A second scenario may investigate the effect of an offshore, rather than an onshore, wind.

From the model, we can obtain results such as the speed and direction of water currents, the tide height, and the amount of sediment (both in suspension and deposited on the bed) at any location within the estuary, and at any time within the simulated period.

Research continues on the physical processes driving sediment transport in estuaries. New knowledge is being incorporated into computer models, which improves their accuracy and increases the range of situations that can be simulated.





above:
Bathymetry of Okura estuary, as input to a computer model.

left:
Output from a computer model, showing currents flowing round a sand ridge during an incoming tide. Sediment deposition is more likely to occur where the water currents are low (smaller arrows).

ESTUARIES

How will habitat change affect intertidal animals in estuaries?

Jane Halliday

Simon Thrush

Judi Hewitt

Greig Funnell

Climate change has been predicted to make our estuaries muddier. How will this affect the species living within the sediment?

Increasing inputs of mud are probably one of the most serious threats to our estuaries. A range of research projects has looked at the effects of excess fine sediment on individual estuarine animals and animal communities. Until recently, however, little information has been available to help managers and ecologists forecast how these animals might respond to *long-term* changes in sediment type.

We have now developed several statistical models that will allow us to forecast changes in the distribution and abundance of several important intertidal species as sediment mud content changes.

Building a dataset

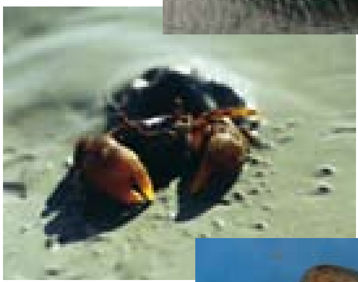
To look for relationships between estuarine communities and the environment – especially sediment type – we needed information from many estuaries. Since few data exist already, the first step was to design survey methods to gather data rapidly and cost effectively.

Our survey included 19 sites in 18 North Island estuaries, harbours and embayments (see map). At each site we collected samples from areas ranging from deep, soft mud to firm sand, all in the intertidal zone. By limiting the sampling to a small area within each estuary we tried to minimise the effect of other factors such as salinity and elevation on relationships between animals and sediment muddiness. We identified the species present in each sample, and determined their abundance. For each sample we also assessed the content of sand and mud.

Of the 92 invertebrate species identified in the survey, we chose 13 common species for modelling. These species represented different phyla (e.g., worms or snails), different feeding methods (e.g., grazers or predators) and different life histories (short-lived or long-lived species). Some of the species selected for modelling were a mud crab, an anemone, several species of worms and three shellfish.

Estuarine animals

Cockle, *Austrovenus stutchburyi*



Mud crab, *Helice crassa*

Nut shell, *Nucula hartvigiana*

Polychaete worms, *Boccardia* spp.

(Photos: mud crab, David Roper; others, Greig Funnell)

Teachers: this article can be used for NCEA Achievement Standards in Biology (2.5, 2.9, 3.1, 3.2), Science (2.2, 2.3), Geography (3.1). See other curriculum connections at www.niwa.co.nz/pubs/wa/resources

Jane Halliday, Simon Thrush, Judi Hewitt and Greig Funnell are all based at NIWA in Hamilton.

Collecting samples in Kawhia estuary. (Photo: Jo Ellis)

Two kinds of model

Using the data for the 13 common species we developed two types of simple model. Both are relevant to the naturally patchy distribution of estuarine animals.

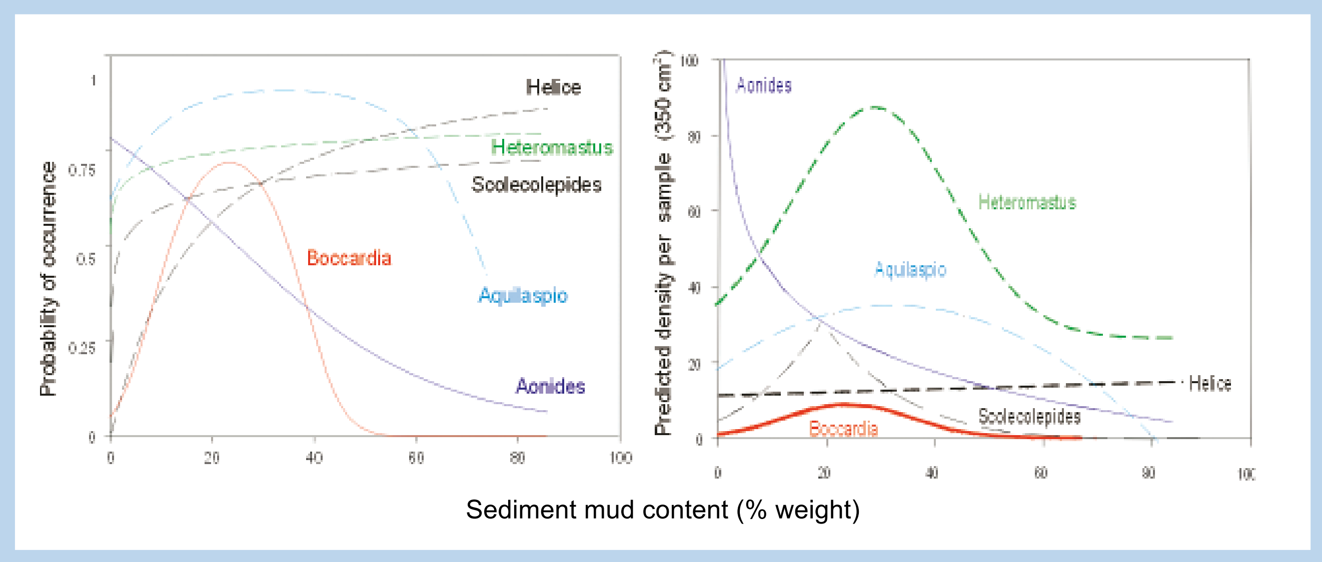
The first was an **occurrence model**. This forecasts the probability of a species occurring at a given mud content (0–100% chance). The second model forecasts the **maximum density** that a species could achieve in a given mud content. The maximum density of a species is more ecologically meaningful than its occurrence because the way in which animals interact with their ecosystem – predation, resuspending sediments – is often most significant when there are many animals present. Modelling changes to maximum density therefore helps to provide an insight into the threat that increased sediment mud content may pose for both biodiversity and the ecosystem.

The occurrence models explained 60–81% of the variation in species distribution found in the survey. Forecasted occurrences of some species plotted against sediment mud content are shown in the graph (opposite). The models show a variety of shapes indicating that each species reacts differently to sediment mud content. For example, the mud crab *Helice crassa* is more likely to occur in areas with high mud content. In contrast, you are more likely to find cockles at sites with little mud. The polychaete worm *Boccardia syrtis* is most likely to occur at sites with an intermediate percentage of mud.

To derive the maximum density models, we plotted the chance of a species occurring at maximum density against sediment mud content for each species. Examples are shown in the graph (opposite). From our dataset, most models explained at least 60% of the variability in the distribution of maximum density. An exception was the mud crab *Helice*, where maximum density did not seem to be related to sediment mud content at all. In this case we

Our estuaries are changing

There is good evidence that sediment loading to New Zealand's estuaries and coasts has increased along with human population growth and the development of coastal margins. This has been highlighted in several recent articles in *Water & Atmosphere* (for example, see *11(1)*: 11–15). Most sediment is washed into estuaries during floods. Therefore, estuaries with steep catchments, heavy sporadic rainfall, and land-use development are at high risk of inundation by fine sediment. Climate projections for many parts of the planet, including New Zealand, indicate that sea level will rise, rainfall will be more intense and the frequency of storms will increase. This climate-change scenario points to even muddier estuaries in the future.



Occurrence models (left) and maximum density models (right) derived from the survey data for six species.

think another environmental variable (such as food supply or water chemistry) must have been controlling their abundance.

As the graphs show, maximum density models varied from simple line relationships (mud crab *Helice*), to curved (polychaete worm *Aonides*), and humped relationships (polychaete worm *Aquilaspio*) to bell-shaped response curves (polychaete worm *Heteromastus*).

In general, the two models showed similar responses to mud content for individual species. For example, both models indicated that the polychaete *Aonides* preferred sand, and was unlikely to occur, or be at maximum density, in mud.

Interestingly, for a few species the two models gave quite different responses to mud content. For example, in the maximum density model the polychaete *Heteromastus* preferred 20–40% mud, whereas in the occurrence model there was no preference. The maximum density models generally predicted a smaller habitat preference range than the occurrence models. This makes sense ecologically because some species may be found at very low densities across a variety of habitats; yet their preferred habitat – where they occur at high density – may only span a short range of mud content.

Habitat preferences

Estuarine species are thought to be very tolerant of a wide range of environmental conditions. If this is true, the relationship between mud content and occurrence or maximum density should be a flat line. However, both models show that most of the 13 species have habitat preferences either for sand, mud or mixed sediment.

An interesting example is for the four spionid polychaete worms, *Aonides*, *Aquilapsio*, *Boccardia* and *Scolecolepides*. These are closely related, they have similar general natural history characteristics, and all are surface deposit feeders. However, our models for each species are quite different. For example, *Aonides* appeared to be the most sensitive to increased muddiness, while *Aquilaspio* appeared to prefer 20–50% mud. This highlights the pitfalls of making predictions from ecological data based on broad taxonomic groups or by feeding method.

Future work

Models such as these can be used to forecast the effects of habitat change on the ecology of estuaries. For example, our data suggest that if climate change and catchment development continue to cause estuaries to get muddier, mud-sensitive species, such as the polychaete *Aonides* and bivalves, will decrease in abundance.

The next step in developing these models is to test them on data collected from different locations. Eventually it should be possible to combine them with other models, such as **risk assessment models** (see *Water & Atmosphere 10(2)*: 18–19; *10(4)*: 22–23), in order to get a long-term assessment of the possible impacts of environmental changes on estuaries and the flow-on effects to sediment-dwelling animals. ■

Further reading

Thrush, S.F. et al. (2003). Habitat change in estuaries: predicting broad-scale responses of intertidal macrofauna to sediment mud content. *Marine Ecology Progress Series 263*: 101–112.

This research was carried out in the FRST-funded programme "Effects of Sediments on Estuarine and Coastal Ecosystems" (C01X0024).

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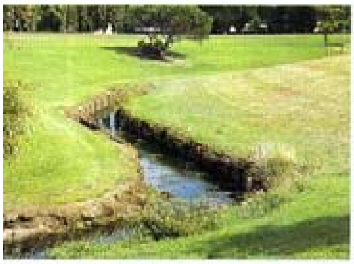
STREAM RESTORATION

SWAT's Up, Doc?

The effects of StormWater And Transport on urban streams and estuaries

Mike Timperley and Gerda Kuschel

Every time it rains in the city, dirt and grime are washed off streets and buildings into the stormwater system and then into urban streams and estuaries. New research aims to find ways to help urban aquatic ecosystems recover from this contamination.



MOST STREAMS in our towns and cities have been piped and covered over to make way for buildings and roads, but the open stream sections that still exist are being increasingly regarded as valuable ecosystems in our urban environment. The problem is that many such sections have been structurally modified to improve their effectiveness as drains for stormwater. Even where these open channels look attractive and natural, the chances are that they contain only a fraction of the many and diverse plants and animals that normally inhabit natural streams.

NIWA's SWAT (StormWater And Transport) research on urban streams and estuaries came about because of escalating interest in restoring these ecosystems to something like their original forms.

It is usually fairly straightforward to identify what needs to be done to restore even the most severely modified stream to something at least *visually* similar to its natural state. For example, it might involve removing concrete channelling. However, the changes required to restore the stream to something *ecologically* similar to its natural state, with self-sustaining natural communities of animals and plants, are much more subtle and complex.

above:
Urban streams come in many forms including straightened "natural" channels and concrete-lined drains with grass or sealed riparian margins. (Photos: M. Timperley)

What's changed in urban streams?

The changes that have altered urban streams from their natural state can be broadly grouped into three types: physical, hydrological and chemical.

Physical changes include such things as removing shade (over-hanging vegetation), which causes the streamwater temperatures to increase above normal levels, and replacing the natural stream banks and beds with timber or concrete.

Hydrological (water flow) changes arise because urban catchments contain high proportions of impervious surfaces such as roads, car parks and roofs. This increases the rate at which rainwater runs off into the stormwater system and eventually into streams, causing flooding and high water velocities. It also reduces the amount of rainwater that can infiltrate the soil to keep streams flowing between rainfall events, and therefore streams dry up more often and for longer. These extremes make life very difficult for aquatic plants and animals.

Chemical changes are caused by the way we use our urban environment. When it rains, chemicals produced from transport, industrial, commercial and residential activities are washed from the atmosphere and the roads through the stormwater systems into the streams. Where urban development occurs around estuaries, most of these chemicals eventually end up in the estuarine sediments, where they can accumulate to concentrations high enough to damage the animals living there.

SWAT research

"Mitigating Contaminant Effects in Aquatic Habitats" is the formal name of NIWA's PGSF research programme on stormwater and transport (SWAT). The programme, which began in July 1998, focuses on the hydrological

and chemical problems in urban streams and estuaries and looks at the importance of transport activities as a source of chemical contaminants. The physical problems are addressed in other research programmes (e.g., see *Water & Atmosphere* 6(4) for an article on the effects of riparian changes on aquatic insects).

Over the next five years we aim to:

- determine the impact of contaminants from motor vehicles on urban aquatic ecosystems;
- find ways to reduce the harm contaminants do to aquatic life in urban streams;
- investigate options for managing high and low water flows to reduce the damage these cause to stream aquatic life;
- predict how chemicals from stormwaters affect life in urban estuaries.

What effect does transport have on urban streams?

Motor vehicles contaminate waterways through emissions to the air and deposits onto roads. Particles emitted into the air eventually settle out onto the ground. On roads they are joined by oil from engine leaks, material from brake linings, and rubber particles from tyre wear. When it rains, all of this material is washed through the stormwater system into urban streams and estuaries.

In the first year of SWAT research we developed and tested a system for collecting the information needed to compare the quantities of chemicals originating from vehicles with the quantities picked up in road runoff.

Our "test site" was near Avondale in Auckland. Here, all the stormwater from a known area of road surface drains through a single stormwater system.

A weir, flow recorder and an automatic water sampler were installed in the stormwater manhole. A mobile trailer parked on the roadside contained instruments to monitor rainfall, wind speed and direction, carbon monoxide and polycyclic aromatic hydrocarbon (PAH) concentrations, and to collect samples of fine particulate matter for later analysis. PAHs are produced from the combustion of fossil fuels, such as diesel and petrol in motor vehicles, and are also present in automotive oils and lubricants. We also installed traffic counters along with collectors to trap particles deposited from the atmosphere.

Most of this equipment was operated for seven weeks and an example of some of the data collected is shown in the figure on the right.

Our next task is to relate the quantities of contaminants leaving the road environment through the atmosphere and in the stormwater to vehicle numbers, type and speed and to various meteorological conditions. Eventually this will be incorporated into a user-friendly model that will be able to predict contaminant amounts reaching streams from any road system in New Zealand.

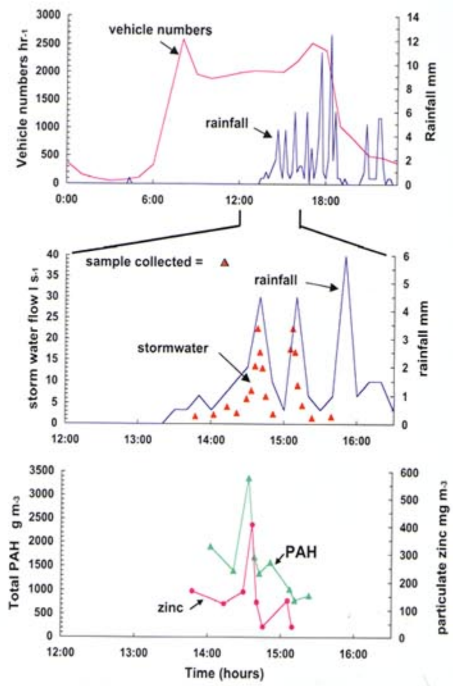
How can we reduce the effects of contamination in urban streams?

As well as the contaminants produced by traffic, stormwater contains metals – particularly zinc – washed from our house roofs. Oil and grease, metals, detergents and other cleaning chemicals, inks and industrial chemicals are washed from workplace floors and yards into the stormwater system. Small amounts of the pesticides and herbicides we use in our gardens also find their way into streams.

Over the past year, we have measured the range of concentrations of three key contaminants – copper, zinc and PAHs – in urban stream waters. Copper and zinc come from roofing, spouting and downpipes. Copper also comes from vehicle brake linings, and zinc is present in vehicle tyres.

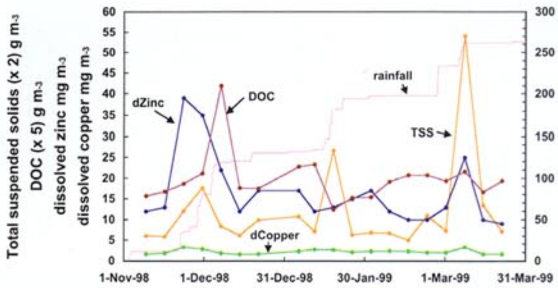
Urban stormwaters usually contain chemicals at high concentrations but stream life is exposed to these only briefly, for short periods immediately following rain. For the rest of the time, stream life is still exposed to chemicals but at lower "baseline" concentrations.

In the first year of the project we measured baseline concentrations in a range of different urban streams as a first step towards evaluating the extent of the contamination problem. Some of our sampling coincided with rainfall events so we also obtained an indication of the range of high stormwater concentrations.



Some of the data collected on one day (6 April 1999) during the transport study at Avondale in Auckland. (A) rainfall and the number of vehicles passing along the road during the day. (B) the first three rainfall peaks and the resulting flow of stormwater off the study section of road. The red points on the stormwater flow line indicate when samples of stormwater were collected. (C) concentrations of total PAHs and zinc attached to sediment in the stormwater samples.

left:
Transport activities contribute chemical contaminants to our urban environment. (Photo: G. Kuschel)



Some of the results for Botany Creek in Manukau City collected during the 20-week stream survey. Higher concentrations of the substances measured occurred following rainfall, but between rainfall events the baseline concentrations did not change much.

Water samples were collected each week for 20 weeks from each of 20 sites in 10 urban catchments in Auckland, Hamilton and Christchurch. The catchments ranged from relatively untouched native forest, to rural pasture, to purely residential, to a mix of residential with commercial and minor light industrial activities.

The graph above shows some of the results obtained for Botany Creek, which drains a residential development in Manukau City. The peaks in concentration generally correspond to rainfall events. For each of the 20 sites we took the median concentration as the best indicator of baseline concentrations.

For dissolved zinc, the lowest median concentration (5 mg/m^3) was recorded in the water draining the native forest catchment and the highest value (61 mg/m^3) was found in the stormwater from the most industrialised urban catchment. Total PAH concentrations followed a similar pattern.

The baseline concentrations of copper (range of median values: 0.5 to 2.5 mg/m^3) are close to the minimum values that have been found to cause adverse effects on aquatic life in studies worldwide. The concentrations of zinc are slightly above these minimum values.

Although our study was not designed specifically to detect the maximum concentrations that occur in stormwater, the results indicate that dissolved copper reaches at least 10 mg/m^3 whereas the peak dissolved zinc concentrations can be in excess of 300 mg/m^3. The effects of short-term exposure of stream life to these high concentrations are not well known at present.

We also looked at the production of dissolved organic matter (DOM) from the decomposition of different types of plants typically found in urban stream riparian margins. DOM – measured as dissolved organic carbon (DOC) – plays a major role in reducing the toxicity of dissolved metals and organic contaminants (e.g., PAHs) to aquatic life.

In future years, we aim to develop ways to manipulate natural instream and riparian zone processes involving DOM and other substances so that they minimise the harm done to aquatic life by chemical contaminants.

Managing stormwater flows

Although stormwater systems help to keep our feet dry and prevent flooding, their effects on urban streams result in poor habitats for stream insects, plants and fish. Faster flood flows destroy the nooks and crannies that aquatic animals inhabit and also wash away the animals and plants themselves. Channel modifications required to cope with flooding, such as lining channels with concrete, reduce habitat diversity and quality. Reduced streamwater flows between rainfall events can cause high water temperatures and low dissolved oxygen concentrations – conditions that are unsuitable for most aquatic animals.

Our aim is to produce a landuse–hydraulic interaction (LHI) model that can be used to determine the most effective way of reducing peak stormwater flows into urban streams and of increasing the amount of water entering the streams from the soil during dry periods. The model will be developed and tested using water flow data from three sites:

- Manukau Experimental Basin, Somerville. This site was first monitored 30 years ago but measurements stopped 16 years later when the catchment was built up. We will resume the monitoring to obtain an after-development record of the effects.
- Alexandra Stream, North Shore. This site already has a before- and after-development record.
- Okeover Stream, Ilam, Christchurch. This site contains a mixture of residential, park, and light commercial land use.

What happens to contaminants in estuaries?

All urban stormwater eventually finds its way to the sea. When the sea happens to be a sheltered estuary adjacent to the urban area, the chemical contaminants in stormwater tend to accumulate (see *Water & Atmosphere* 5(1): 8–10). In Auckland estuaries, for example, there has been a gradual increase of zinc, lead, copper and PAH concentrations in surface sediments as the surrounding catchments have become

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Estuaries accumulate many of the chemicals washed from coastal urban areas. (Photo: B. Williamson)

more and more built-up. Biological surveys in two of these estuaries indicate that present effects on ecosystems are slight. However, in 20–50 years, the predicted concentrations of zinc are likely to cause widespread biological effects unless steps are taken to minimise contaminant inputs to these estuaries.

The standard method for testing sediment toxicity involves exposing animals to artificially contaminated sediments. In the past, however, many of these tests failed because the animals responded to artefacts introduced by the physical and chemical modifications used to produce the contaminated sediments.

Our research involves developing procedures for producing contaminated sediments that don't have these artefacts and yet still retain their natural physical and other chemical characteristics. When we have achieved this, we will then be able to realistically predict the future effects of contaminated sediments on New Zealand estuarine animals.

As our SWAT research progresses we will gradually build up a full picture of how contamination from transport and other activities affects aquatic ecosystems in urban areas and how we can go about reducing these effects. The models and methods we develop will help in the quest for "natural" stream and estuarine habitats in our towns and cities. ■

Mike Timperley and Gerda Kuschel are based at NIWA in Auckland.

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MARINE BIOSECURITY

New alien mudworm now becoming a pest in longline mussels

Geoff Read
Sean Handley

An invasive worm makes for trouble, not pearls, inside a prized shellfish.

Teachers' resource for NCEA AS: Biology 2.6, 2.9; Science 2.2. See www.niwa.co.nz/edu/resources

New Zealand mussels were thought to have few harmful animal parasites, so it came as an unwelcome surprise when worm-inhabited blisters were found inside the shells of farmed green-lipped mussels in mid-2003. Green-lipped mussels (*Perna canaliculus*) can be colonised by some native shell-borer worms, but until last year no outbreaks of severe shell defects induced by these worms were known. It had seemed that the hard mussel shell with its shiny protective covering (or periostracum) was rather difficult for most worm species to attack, and in any case not an ideal home for them because it is comparatively thin.

When NIWA scientists investigated the problem blisters in mussels from marine farms in the Firth of Thames along the Coromandel Peninsula, they found that the polychaete mudworm *Polydora haswelli* was triggering the shell malformations. *P. haswelli* is a blister-inducing shell-borer worm, first described from Australia, and a new invasive alien polychaete for New Zealand. It was recently discovered in the northern North Island in scallops and oysters. At least some of its previous occurrences were overlooked because of its morphological similarity to *Polydora websteri*, another pest mudworm which also occurs in New Zealand, mostly inhabiting Pacific oysters. Live specimens of *P. haswelli* can be readily distinguished from *P. websteri* by its distinctive anterior dorsal pattern of black pigmentation and the black bands on its feeding tentacles; both features are lacking in the better-known *P. websteri*.

Head region of a live *Polydora haswelli*.
(Photo: Geoff Read)

How the damage is done

Normally, members of this group of worms tunnel fairly harmlessly lengthways inside shells. In contrast, the *P. haswelli* were drilling perpendicularly straight through the green-lipped mussels, and intruding into the space between the shell lining and the living mussel. In response the mussels sealed off the worms under a thin overlay of organic material with a further calcareous shell layer on top. The fragile internal chambers thus formed were either long, low blisters extending into the shell peak (umbo) or less-extensive, but more projecting, nodule-like blisters.

A large broken blister inside an infested mussel shell.
(Photo: Geoff Read)

The affected mussels were of harvestable size at about 80 mm long, and had blisters up to 60 mm long. Some of the blister cavities were up to 7 mm deep, but most were not much over 1 mm deep. Within this cavity, a *P. haswelli* worm occupied a U-shaped track surrounded by a firm brown "mudpack" of fine debris. A figure-eight or B-shaped pair of adjoining holes usually indicated the worm entrance. The contents of cavities abandoned by worms could be blackened and anaerobic.

A feature of this particular event was that the *P. haswelli* strongly favoured settlement on the mussels' more severe growth-check lines. These are low ridges or steps that can form in the shell when mussel growth is disturbed by transferring them to new ropes on the farm longlines. Viewed

Geoff Read is based at NIWA in Wellington and Sean Handley is at NIWA in Nelson.

A feeding *P. haswelli* projects its palps from one of its pair of burrow-entrance tubes bored at a growth-check step. (Photo: Geoff Read)

P. haswelli revealed inside a blister; palps in this individual are regenerating. (Photo: Geoff Read)

close-up, the growth checks range from small overlapped gaps in the periostracum to distinct steps in the shell profile. They appear to provide a crevice or ledge on which larval worms can settle more readily than on the normal very smooth shell surface. While some worms were settling away from growth checks on the mussels, it seems probable that minimising growth checks would reduce infestations.

Why are shell blisters in mussels of concern? If the worm is soon sealed-off how can it affect the health of the mussel? Unfortunately this is not the issue. While it is probable the energy cost to the mussel of walling off this little worm intruder is not very important, the end result is an obviously flawed shell. This is going to be repellent to an end consumer, and in any case contamination of mussel flesh from the muddy or unpleasant anaerobic contents of broken blisters is not acceptable. Badly blistered mussels are not suitable for processing.

Help stop the spread

Polydora haswelli has probably not been in New Zealand very long. It was first recorded in oysters in Mahurangi Harbour in 1996 and first noticed in abundance in the Firth of Thames by scallop harvesters in 1999. How did it breach our biosecurity? Perhaps planktonic larvae were discharged into the Hauraki Gulf in ship ballast water. Now it is well established and we must learn more about it in order to reduce the damage it could do in shellfish farms. We know the worm occurs at least as far north as Whangarei Harbour; so far it seems it has not yet reached the major aquaculture areas in the Nelson/Marlborough districts. Therefore, we advise against transferring northern mussels and oysters to the south for on-growing or as broodstock if the shells are large enough to have *P. haswelli* borings. Any suspected occurrences of *P. haswelli* outside its known distribution should be reported to NIWA. ■

A line of healthy green-lipped mussels in culture.

The authors would like to hear from anyone who finds *Polydora haswelli* south of the Coromandel.

You can contact Geoff at 04 386 0300 (g.read@niwa.co.nz) or Sean at 03 548 1715 (s.handley@niwa.co.nz).

Learn more about polychaetes in the Guide to New Zealand Shell Polychaetes at **www.niwa.co.nz/ncabb/tools/**

WATER QUALITY

Flood flushing of bugs in agricultural streams

Rob Davies-Colley
John Nagels
Andrea Donnison
Richard Muirhead

Floods can make farm streams very dirty indeed: they stir up not only the sediment on the bottom, but trillions of bacteria as well.

Pastoral agricultural streams in NZ are chronically contaminated by livestock faeces – washed in during rainstorms or else deposited directly when animals get into the channel. Most of this faecal contamination is usually found not in the stream water, but in the sediments. This means that when the muddy bottoms of farm streams are disturbed, the resulting turbid plumes can be heavily contaminated with faecal indicator bacteria, or "bugs" – up to a billion of them in every cubic metre.

Faecal contamination of an agricultural stream

We reached these conclusions following a study of faecal contamination of a pastoral agricultural stream that drains a catchment in dairy and dry stock (sheep/beef) farming. In our study stream – the Topehaehae, near Morrinsville in the Waikato Region – during normal flows there are typically about 100 faecal indicator bacteria per 100 ml.

During a natural flood in September 1999 in the Topehaehae Stream we measured very much higher concentrations of bugs in the water, peaking at around 40,000 per 100 ml. In fact, the number of bacteria washed out over about three days by this one flood event was more than that washed out in a full year at normal flows; and the maximum number of bacteria passing per second was about the same as that typically flowing in the Waikato River, which is 100 times larger than the Topehaehae.

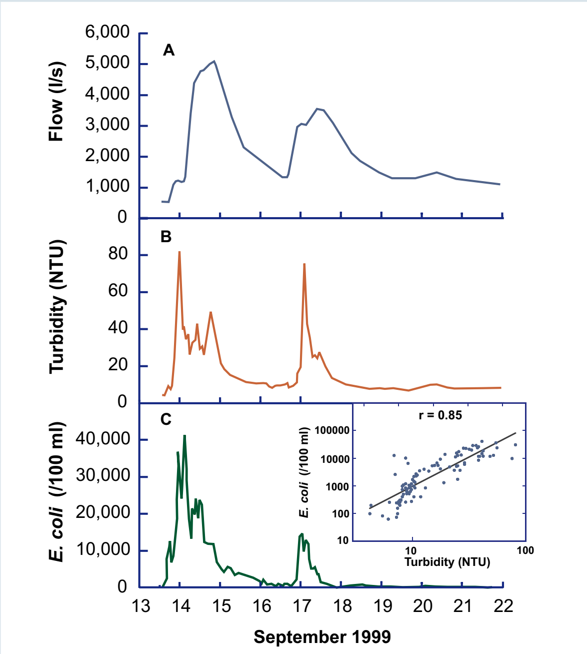
During this flood the bacteria concentrations correlated much more closely with turbidity than with flow, apparently because bacteria behave rather like fine sediment. (Turbidity is a convenient index of fine suspended matter in the water.)

The graphs opposite (above) show that both bacterial concentrations and turbidity peaked before the flood peak. The relationship between turbidity and bacterial concentrations is shown in the inset graph.

Teachers' resource for NCEA AS: Biology 1.8, 2.9, 3.2; Science 2.2, Agricultural & Horticultural Science 1.5. See www.niwa.co.nz/edu/resources

John Nagels demonstrating the muddiness of bed sediment in the Topehaehae Stream. Such turbid plumes have very high levels of faecal indicator bacteria. (Photo: Rob Davies-Colley)

Rob Davies-Colley and John Nagels are based at NIWA in Hamilton; Andrea Donnison is at AgResearch, Hamilton, and Richard Muirhead at AgResearch, Mosgiel.



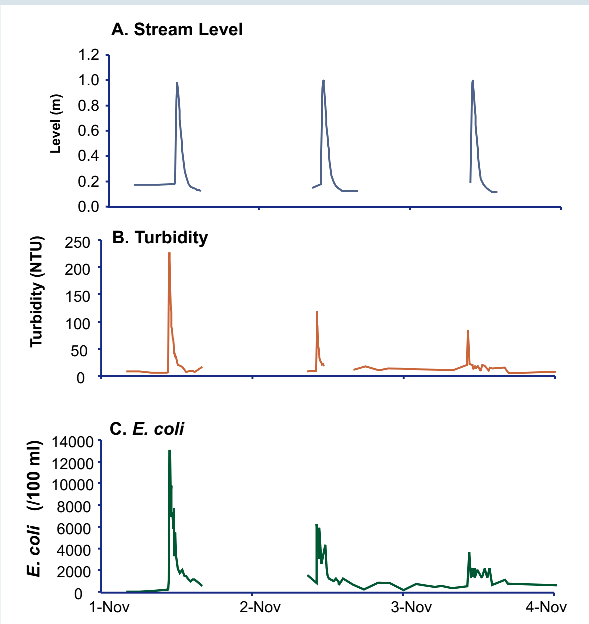
above: Natural flood event, Topehaehae Stream, 15 September 1999. (Photo: Rob Davies-Colley)

left: Flow (A), turbidity (B) and faecal indicator bacteria concentrations (*E. coli*) (C) measured in the Topehaehae Stream near Morrinsville during the natural flood event pictured above. The inset graph shows the relationship between faecal indicator bacteria and turbidity (an index of light scattering by fine suspended sediment) during the period of measurement.

In a flood, the bacteria could have come from the stream sediments, or from faecal deposits on pasture washed into the stream. To study the sediment source of bacteria separately from pasture wash-in, we created short artificial floods in the stream by releasing water from a water reservoir (supplying Morrinsville) located on the upper reaches of the Topehaehae Stream. The experiments were carried out during fine weather when the stream channel was the only possible source of bacteria.

The graph below shows the results of an experiment in which a series of three identical flood events were produced on three successive days. Just as with the natural flood, the bacteria peaked well ahead of the flow peaks, and there was a good correlation between faecal bacteria and turbidity caused by fine sediment entrained by the flood flows. This shows that much of the faecal contamination mobilised by floods comes from the sediments of the stream.

The faecal contamination produced by the first event peaked at 13,000 bacteria per 100 ml, and the bacteria peaks were lower on subsequent events due to progressive wash-out of the sediment store of bacteria. By assuming that an infinite number of identical floods would



left: Response to a series of three artificial flood events created by releasing water from a supply reservoir down the Topehaehae Stream, showing water level (A), turbidity (B), faecal indicator bacteria concentrations (C).

below: The front of one of the artificial flood events on the Topehaehae Stream. Richard Muirhead is about to take a sample for bacterial analysis. (Photo: Rob Davies-Colley)

wash out every last bacterium in the stream, we calculated the size of the sediment store: 100 million bacteria per square metre of streambed.

From our measurements, we concluded that most of the time the water in this agricultural stream contains only a tiny fraction (about 1/1000) of the total faecal contamination in the stream. The rest is in the streambed, from where it can be released by floods, but also by livestock walking in the channel or, more ominously, by children wading in the stream.

The flushing out of bacteria by floods is not so much a problem in the stream itself as in waters well downstream, including lakes and estuaries. Faecal contamination by floodwaters from pastoral agricultural land is a threat to shellfish gathering and shellfish aquaculture in estuaries and coastal waters.

Sediment sampling for bugs

We are currently trying to devise ways to directly measure the faecal bacteria in stream sediments. In sandy areas of streambed, this is not too difficult, but sampling of rocky streambeds is not straightforward. We know that the bacteria are not present on the accessible rocks of the streambed surface, probably because sunlight, which is highly bactericidal, kills exposed cells. It is more likely that the bacteria lie deeper in the stream sediment, under the shade of surface rocks. We are also testing continuously measured turbidity as a surrogate for bacterial analysis in several ongoing studies of faecal pollution.

We expect this research will contribute to a better understanding of faecal pollution of streams by livestock in this country. Our findings will contribute to the development of systems for improving water quality and reducing downstream impacts, notably on shellfish aquaculture. ■

Indicator bacteria

Faecal indicator bacteria such as *Escherichia coli* are not themselves dangerous to humans (apart from some rare exceptions). These bacteria (and others such as faecal streptococci) are used to *indicate* faecal contamination – and therefore health risk – because they are always present in faeces of warm-blooded animals, including livestock, wild animals, and people. In contrast, the pathogens (disease-causing micro-organisms) are only present sporadically in faecally contaminated waters and are not suitable for routine monitoring.

The concentration of faecal indicator bacteria is expressed, traditionally, per 100 ml water. One reason for retaining this (non-standard) volume unit is that it approximates a small cupful – the amount of water a person may consume during swimming. More importantly, people who work in water quality and related fields are used to thinking in terms of bacteria concentrations per 100 ml.

Human pathogens

In New Zealand, faecal contamination of waters by our approximately 10 million cattle and 45 million sheep, and increasing numbers of other livestock (notably 2.6 million deer), greatly outweighs the contribution of our 4 million people. But is animal faecal contamination really a problem?

People are often more concerned about contamination by human sewage than by animal faeces. However, animals can carry many diseases of humans (caused primarily by bacterial or protozoan pathogens). An example is campylobacteriosis – a very high-incidence disease in New Zealand (400 cases per 100,000 people per year). Recent research suggests that campylobacteriosis may be amplified by livestock faecal contamination of waters.

Guidelines for water quality are usually expressed in terms of concentrations of indicator bacteria like *E. coli* with the (reasonable) assumption that, where these bacteria are present, pathogenic organisms like *Campylobacter* and *Cryptosporidiim* could be too.

Cattle ramp as a source of faecal pollution on the Topehaehae Stream. Note faecal deposits and lack of grass on the trampled, compacted ramp surface. Such features may be an important source of faecal contamination of unfenced streams by livestock. (Photo: Rob Davies-Colley).

Further reading

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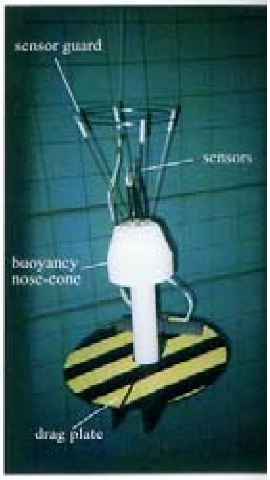
INSTRUMENTS / OCEANOGRAPHY

SCAMP: measuring turbulence in estuaries, lakes and coastal waters



Craig Stevens

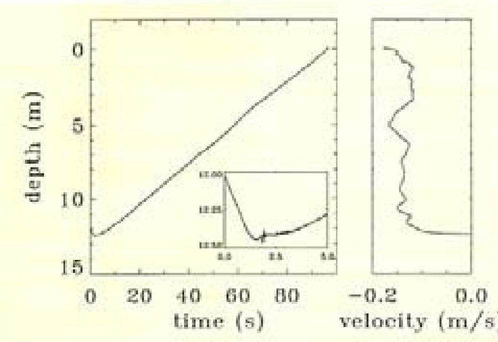
Murray Smith

Alex Ross

Measuring turbulence in large water bodies requires an approach different from that used in rivers. A new instrument seems to fit the bill.

TURBULENCE refers to the irregular variations over time in the movement (both speed and direction) of fluids. Turbulent mixing is very important in controlling how materials are transported in almost all fluid environments. It is also very difficult to measure. In water, "acoustic doppler velocimeters" can provide useful measurements at single points (e.g., in rivers, see *Water & Atmosphere* 5(3): 22–24). However, in big water bodies such as estuaries, lakes and coastal waters, "vertical density stratification" – the formation of water layers as a result of density differences caused by temperature and salinity variations – is known to cause turbulence to vary dramatically. Thus, point measurements recorded even a small distance apart can return very different answers. So, in these situations, how can we obtain an accurate picture of turbulence that will allow us to learn more about the mixing process?

One way is to use profiling methods that can capture minute temperature variations over equally tiny distances. The resulting profiles can be used to calculate turbulence through the water column.



SCAMP's depth vs. time trajectory on a profile in Akaroa Harbour. The inset shows the initial turnaround when the profiler stops sinking and starts its ascent. The right-hand panel shows the calculated rise velocity.

above right: *The SCAMP underwater in a dive pool. The sensors are hidden within the sensor guard. The yellow and black disk is a drag plate and the white collar is a buoyancy element.*

A new profiler for ocean research

NIWA has recently purchased a SCAMP – Self Contained Autonomous MicroProfiler – for temperature and conductivity measurements. This is a "free fall/rise" profiler that can be deployed from small boats. Its speed of descent or ascent is controlled only by drag and buoyancy, using a drag-plate in combination with floats and ballast. The photograph (above) shows the SCAMP rising to the surface in a 5-m-deep dive pool.

Originally developed by the Centre for Water Research (www.cwr.uwa.edu.au) at the University of Western Australia, SCAMP is now manufactured by a Californian company, Precision Measurement Electronics (www.pme.com). The profiler is essentially a high-precision conductivity–temperature–depth (CTD) device. The data it generates complement those from more traditional devices used aboard NIWA's research vessel *Tangaroa*, such as the SeaBird CTD, which is more stable in its absolute calibration. The SCAMP records data every millimetre whereas a SeaBird has a spatial resolution of perhaps hundreds of millimetres.

The very small-scale measurements of the SCAMP make it possible to estimate very precisely how stable a vertical water column is, as well as the amount of mixing and energy dissipation occurring in various regions of the profile. A drawback of the technique is that the profilers are very delicate with sensor tips that are viewable only under a microscope. This delicacy leads to elevated activity in the equipment operator's nervous system when playful dolphins come around to see their new toy!

Near-surface measurements

Mixing and energy dissipation within the water column are often driven by wind and waves at the surface. Therefore it is best to make measurements as close to the surface as possible. This is difficult with the traditional CTD because of the arrangement of the sensors. But with the SCAMP we can place the sensors at the top of the profiler and use the instrument in a rising motion so that it slowly approaches the surface from below.

The operator launches the probe with only a thin kevlar tether. The probe then sinks to a pre-programmed depth where it releases an expendable ballast weight and starts to rise at a speed of around 10 cm/s. Data can be returned to the operator via a cable or stored in the profiler for later downloading.

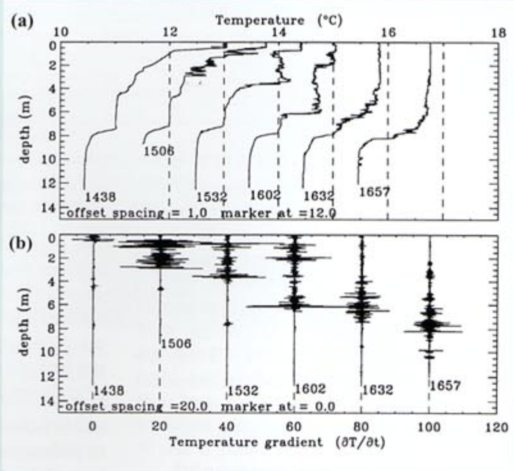
The figure left shows the depth time-series from a profile in Akaroa Harbour. The profiler released its ballast at a depth of 12 m and simultaneously started to measure. The measurements captured the final phase of the sinking and the subsequent acceleration period as the instrument started to rise. The profile is broken up into many sections for analysis and, while a constant velocity is desirable for good results, the SCAMP needs to hold this velocity only over the duration of each of these segments. Thus the many bumps and wiggles in the velocity profile shown in the figure are not detrimental to the observations.

Ocean–Atmosphere Interactions

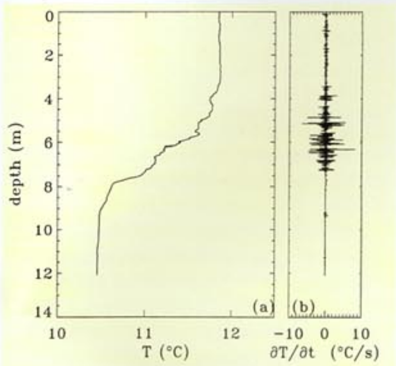
THE "OCEAN–ATMOSPHERE INTERACTIONS" programme, funded by the Public Good Science Fund (PGSF), includes experiments designed to determine the link between wind conditions and air–sea gas and heat exchange. A vital component of this is the mixing of surface waters caused by surface waves. This energy is significantly enhanced by the presence of deep-water wave breaking. This type of wave breaking occurs naturally in oceans, lakes and estuaries and is not related to the shallowing of a beach but to unstable growth of the waves – they simply get too steep and break. The overturning plume of water rushing down the face of the wave injects bubbles and energy into the near surface region of the water column.

The sequence of SCAMP profiles shows how the temperature and temperature-gradient profiles develop. The temperature profiles show how the sharp thin surface layer caused by the warm morning sun in the absence of any significant breeze is gradually eroded until it is mixed down to the pre-existing thermocline (at a depth of about 8 m). The temperature-gradient profiles give a direct picture of temperature variations and show where light and heavy fluids are mixing. Once this is adjusted to take background stratification into account, turbulent energy dissipation can be determined from segmented versions of these profiles.

The initial strong surface stratification is especially important to the Ocean–Atmosphere programme. Temperature variations such as this affect the solubility of gases at the water surface. These types of detailed near-surface observations need to be recorded to reduce the present uncertainty in our understanding of air–sea gas exchange. The Ocean–Atmosphere programme seeks to link the changes in near-surface turbulent levels with changes in the waves and wind and from this improve our understanding of mass and momentum exchange between the atmosphere and the oceans.



A sequence of microstructure profiles. The panels show (a) temperature and (b) temperature gradient profiles recorded at one location in Akaroa Harbour at about half-hour intervals as the wind increased from around 5 to nearly 20 knots. The warm fluid in the near-surface layer gradually mixes down over this time. An interesting point is that the turbulent mixing identified by two-sided gradient data is not confined to above the shallowest region of thermal stratification. In other words, the present situation is not determined solely by top-down mixing. Some internal process, possibly shear-related, may be introducing turbulence at depth, many metres away from the surface where the wind and waves are acting. However this shear is most likely wind-driven.



left: *Vertical profiles of (a) temperature and (b) the "temporal gradient" of temperature.*

The figure above shows a SCAMP temperature profile. The key difference between this profile and one recorded at the same time with a traditional CTD are that the SCAMP data are much higher resolution and the profile goes right to the surface. Another difference is the SCAMP's ability to record a plot of temperature changes over time vs. water depth. This can be translated into the distribution of different-sized turbulent fluctuations and used to generate an estimate of turbulent energy dissipation. Application of this technique provides many opportunities for scientific development. For example we have recently trialled the NIWA SCAMP in a cross-comparison with colleagues from the Southampton Oceanography Centre (SOC), UK.

At the time of writing there are only 13 SCAMPs worldwide and they have successfully been deployed in many estuaries, coastal regions and lakes. Locations include Lake Kinneret (Israel), Mono Lake (California), Lake Biwa (Japan), Maracibo estuary (Venezuela), Venice Lagoon (Italy), and recently in New Zealand, at Akaroa (deployed by NIWA) and the Hauraki Gulf (deployed by SOC).

The first job for the NIWA SCAMP will be to look at surface mixed-layer energetics as part of the Ocean–Atmosphere programme. This PGSF programme seeks to link variations in near-surface mixing (see panel) to breaking-wave occurrence determined by microwave radar (*Water & Atmosphere* 6(2), 26–27). The SCAMP will also play a support role in another PGSF programme aimed at describing the mixing habitats of coastal embayments such as Pelorus Sound and Akaroa Harbour. ■

Craig Stevens and Murray Smith are based at NIWA in Wellington; Alex Ross is at NIWA in Christchurch.

Acknowledgements

Philip Boyd, Edward Abraham and Murray Poulter are thanked for their efforts in making this work possible. The SCAMP was funded through NIWA's CAPEX programme.

Further reading

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