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 that take you to the full reference for an article. Click on the full reference to return to your place in the text. 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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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.

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.

Whaingaroa (Raglan) estuary. Photo: Alastair Senior.

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

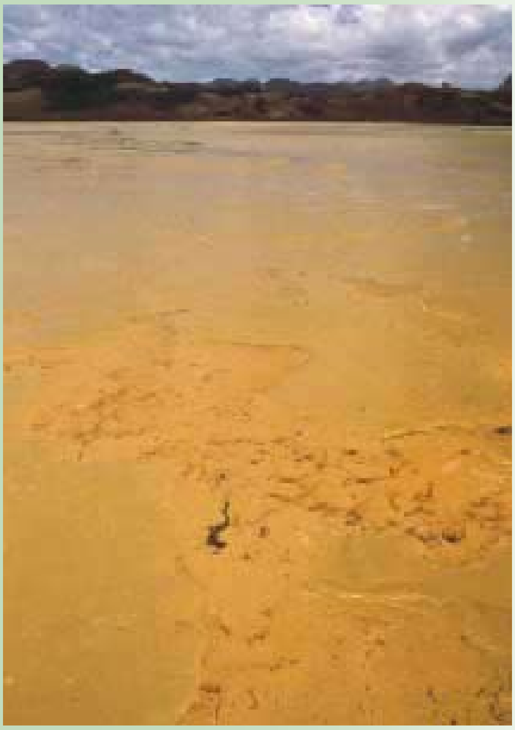


Photo: Don Morrisey.

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.

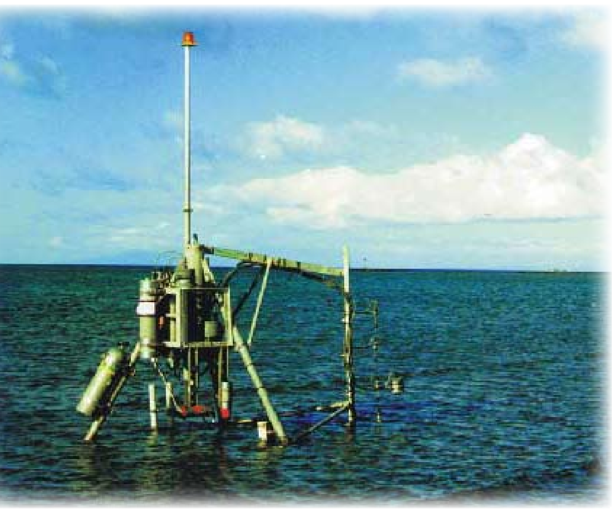
Models

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.

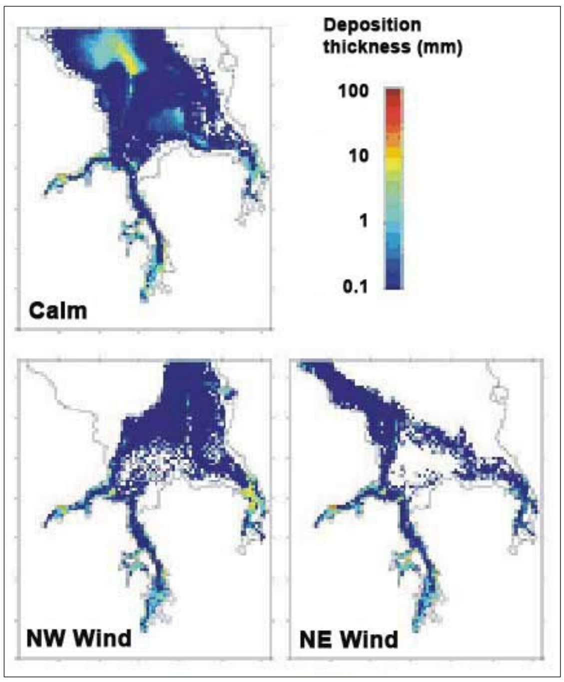
Wave gauge. Photo: Malcolm Green.



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

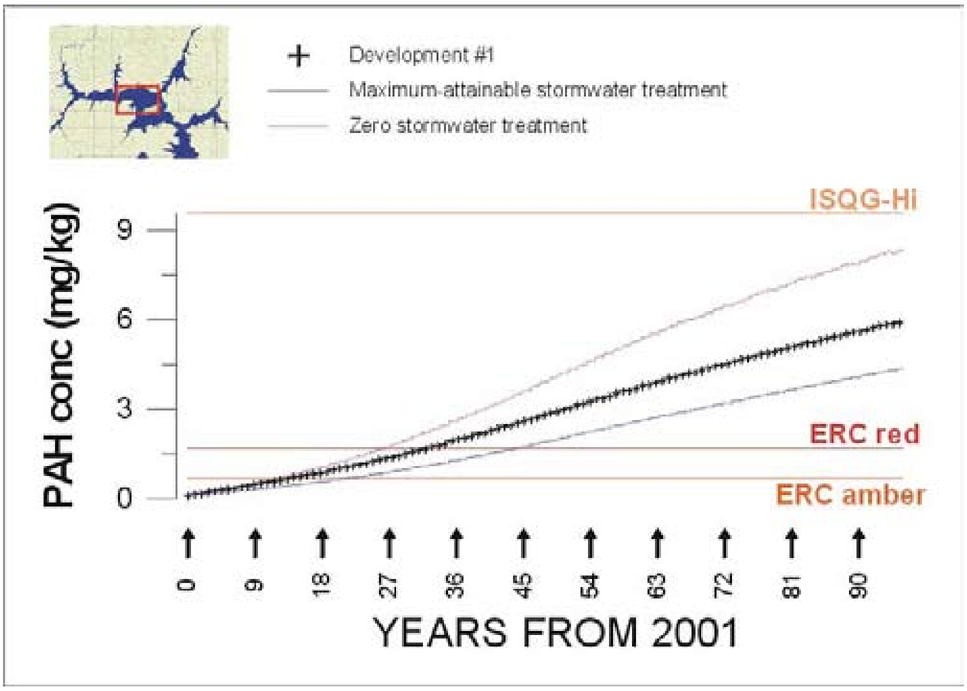
The USC-2 (Urban Stormwater Contaminant) model has been developed to make predictions of contaminant accumulation in estuaries over the next 50–100 years. Given a description of how the catchment is expected to develop, the model can predict where in the estuary and at what rate contaminants will accumulate.

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.



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