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Coastal Sedimentation: What We Know and the Information Gaps

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Glossary

Accelerated erosion	Erosion caused or advanced by human activity.
Benthic invertebrates	Animals with no backbone (invertebrates) such as worms or shellfish that live on or within the sea bed (benthic).
Catchment	A catchment is an area of land that provides water to a stream, river, lake or estuary.
Erosion	Erosion of the land or soil produces sediment. It is the wearing away of land or soil by the action of wind, water or ice, by down slope movement in response to gravity. Erosion is usually measured in tonnes/unit area, for example, t/km^2.
Estuary	An estuary is a semi-enclosed coastal body of water with one or more rivers or streams flowing into it and with a free connection to the open sea.
Harbour	A natural harbor is a landform where a part of a body of water is protected and deep enough to allow safe anchorage. Some estuaries are also harbours.
Deposition/sedimentation	Deposition, also known as sedimentation, is the geological process whereby material is added to a landform (in the context of this report an estuary).
Infilling	Infilling is the process of sediment accumulation in estuaries. The sediment is carried to the estuary in rivers and streams. Infilling is a natural process but can be accelerated by catchment changes such as vegetation clearance, urbanisation and farming.[1]
Landslide	A landslide is the mass movement of soil and/or rock caused primarily by gravity acting on a steep slope (but there are other factors involved affecting slope stability).
Mud	Mud is the fine sediment (silts and clays) that are of a particle size less than 63 µm.
Scalping (or soil scraping)	Scalping is the dragging of logs along the ground, during harvesting, and the associated deep soil disturbance.
Sediment delivery ratio	The sediment delivery ratio is the quantity of sediment exported out of a catchment in relation to the total amount of sediment mobilised within that catchment.
Sediment yield	The sediment yield is the quantity of sediment exported out of a catchment over a given time. Sediment yield is usually measured in tonnes/year.[2] *Specific sediment yield* is the mean annual yield per unit catchment area (for example, $tonnes/km^2/year$).[3]
Streambank erosion	Streambank erosion is the removal of material from the bank of a stream by the action of flowing water, usually seen as the undercutting of the bank and subsequent collapse of material above.[4]
Tidal prism	The tidal prism is the volume of water that moves into and out of an estuary or harbour, over a tidal cycle.

[1] Mead and Moores. 2004.
[2] Auckland Regional Council Technical Publication, No. 69. March 1996.
[3] Hicks and Griffiths. 1992.
[4] Wild and Hicks. 2005.

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Executive summary

This report aims to bring together available information on coastal sedimentation, summarising what is known and identifying what is not known about the sources and the effects of coastal sedimentation.

Sedimentation in estuaries is a natural process that can be accelerated by changes in land use or land management within the catchment, or by development of structures within the estuary. Estuaries are under increasing pressure from coastal development or catchment activities and development, such as farming, subdivision and vegetation clearance. Estuaries on the east coast of the Coromandel Peninsula are at high risk of infilling because of the erosive nature of their catchments (steep topography and frequent high intensity rainfall events) and the physical nature of the estuaries (sandbars or barriers narrow the harbour entrances). In addition, major land use changes have occurred on the Coromandel Peninsula following European settlement. Large scale deforestation in the late 19th century was followed by conversion to pasture (early to mid 20th century) and then exotic production forestry became established from the 1950s until present.

Some studies have provided information that is applicable to all east coast Coromandel estuaries.

The effects of sedimentation on the biological communities of an estuary

- High levels of suspended sediment within the water column increase the turbidity and decrease the light available to plants, such as seagrass and phytoplankton. This decreases the food available to benthic animals and may also clog their gills and feeding structures.
- Deposition of sediments can smother seagrass beds, encourage mangrove growth and bury benthic animals, including kai moana species. There has been a period of rapid mangrove expansion over the last 25 years or so in the majority of the estuaries on the Coromandel Peninsula. Mangrove expansion is thought to result from increasing sedimentation, which raises the intertidal flat level and allows mangroves to become established in areas that were once too frequently inundated by the tide. The mangroves trap fine sediment, further increasing sedimentation and increasing suitable habitat for mangrove growth.
- A change in the plant and animal communities can reduce feeding grounds and habitat for bird and fish species.

Sediment sources and delivery

- It is likely that shallow landslides are the biggest source of sediment to estuaries. These occur on all land use types and are caused by intense rainfall events. Landsliding most commonly occurs on slopes greater than 25°.
- On the steep Coromandel slopes, exposed to frequent high-intensity rainfall events, pasture would generate much more sediment than an equivalent catchment under forest. For the protection of soil and water, permanent native forest is the ideal land use because plantation forest is harvested every 25-30 years, exposing the steep slopes to further the risk of shallow landsliding.
- Sediment is generated during and following harvesting of plantation forest. The canopy of a mature forest intercepts a large amount of rainfall; the loss of the canopy exposes the ground to that water. Harvested trees' roots begin to fail one to two years following harvesting and no longer bind the soil, increasing the risk of erosion. The roots of new trees do not get big enough to bind the soil for several years. It is very likely that for the six to eight years following harvesting there is a risk that accelerated erosion (most importantly, landsliding), can occur.
- Riparian vegetation reduces streambank erosion.
- Sediment cores comparing pre and post-European sediment yields indicate increased sediment accumulation with the advent of European settlement. In

Whangapoua Harbour the sedimentation rate increased from 0.03 to 0.08 mm/year to 0.89 to 1.5 mm/year post-European settlement. In Whangamata Harbour the sedimentation rate increased from 0.10 to 0.18 mm/year pre-European settlement to 5 mm/year from the 1940s until mid-1990s. In Wharekawa Harbour the sedimentation rate increased from 0.1 mm/year pre-European settlement to between 5 and 8 mm/year from 1945 to the 1990s. Sedimentation rates also increased in Whitianga Harbour post-settlement, with high rates of around 20–30 mm/yr that correspond roughly to the 1960s and before. More recent sedimentation rates in the arms of the estuary range from 5–9 mm/yr.

- Post-European levels of sediment yield and sediment deposition in five east coast Coromandel estuaries have been estimated using several methodologies giving a range of values.
  - The range for Whangapoua Harbour is 58.8 tonnes/km^2/year (Hicks and Shankar model) to 140 tonnes/km^2/year (SedRate extrapolation from measurements taken in Opitonui River).
  - The range for Whangamata Harbour is 98 tonnes/km^2/year (Hicks and Shankar model) to 664 tonnes/km^2/year (NIWA sediment core study).
  - The range for Wharekawa Harbour is 60 tonnes/km^2/year (SedRate extrapolation from measurements taken in Wharekawa River) to 183-252 tonnes/km^2/year (NIWA sediment core study).
  - The range for Whitianga Harbour is 36 tonnes/km^2/year (SedRate extrapolation from measurements taken in Waiwawa River) to 69.3 tonnes/km^2/year (Hicks and Shankar model).
- The range for Tairua Harbour is 80.7 tonnes/km^2/year (estimated from the NIWA sediment model by Hicks and Shankar), to 150 tonnes/km^2/year (SedRate extrapolation from hydrological and suspended sediment data collected in Tairua River).
- The measurements and estimates for sediment deposition (that is, the amount of sediment deposited in the estuaries) are substantially greater than those for sediment yield (that is, the amount of sediment travelling in suspension in streams). It is likely that the sediment yield model is limited by the fact that it is not expected to identify the effects of land use. Also, both sediment yield estimates (SedRate and the Hicks and Shankar model) are for suspended sediment yield. They do not attempt to measure bed-load, which is thought to be 3-10 per cent of total sediment load. It is possible that bed-load contributes more to total sediment load than is currently thought.
- Information is also lacking on the storage times of sediments in streams, and bed-load and gully erosion contribution to sediment yield for east coast Coromandel estuaries.

Estuaries vary in their susceptibility to infilling, erosion rate and sediment delivery system, so that no one estuary can be described as typical of the Coromandel Peninsula or the Waikato region. In this report five estuaries – Whangapoua, Whitianga, Tairua, Wharekawa and Whangamata Harbours – were used as case studies and the available information on each was reviewed.

Tairua Harbour

- Tairua Harbour provides habitat for a wide variety of plant and animal species. The small estuary area (6 km^2) compared with large catchment area (282 km^2) and small tidal prism (5 million m^3) are likely to predispose this estuary to infilling.
- Almost half the catchment is currently in native forest, 21.2 per cent in scrub, 15.2 per cent in plantation forest and 14.7 per cent in pasture.
- The increase in mangrove coverage from 12 ha in 1983 to 31 ha in 1995 suggests sedimentation may have had an effect on the estuary. A figure for current mangrove coverage is expected to be available in 2007/08.
- A marker bed study has estimated the sedimentation rate in the lower estuary, between 1933 and 1984, to have ranged between 2 and 22 mm/year and to have averaged 6 mm/year, much greater than pre-European settlement sedimentation rates.

- The estimates for sediment yield (SedRate and the Hicks and Shankar model) are 150 and 80.7 tonnes/km^2/year, respectively.
- There has been little monitoring of biological communities in the estuary over time, although it has been reported that shellfish beds have declined in size.

Whangapoua Harbour

- Whangapoua Harbour has been the focus of many studies. The estuary has a large tidal prism and so will most likely flush out some sediment, especially fine mud. However, even transitory deposition of sediment can impact on the benthic communities.
- Current land use in the Whangapoua catchment is predominantly exotic forest (54 per cent). Native forest and pasture account for 20 per cent and 17 per cent respectively.
- Sediment cores have been used to estimate pre-human settlement sedimentation rates at 0.03 to 0.08 mm/year and post-European settlement sedimentation rates at 0.89 to 1.5 mm/year. This represents a 10 to 30 fold increase. However, this study was conducted in 1992 and more recent sedimentation rates have not been assessed.
- The estimates for sediment yield (SedRate and the Hicks and Shankar model) are 140 and 58.8 tonnes/km^2/year.
- There is evidence that sedimentation is having an adverse effect on benthic plant and animal communities and the potential effects on predator species is of concern but is largely unknown. The decline in benthic communities in different parts of the estuary correlates with the amount of clearfelling over previous years in the catchment feeding into those parts of the estuary.
- Mangrove cover in the estuary has more than doubled, and seagrass cover more than halved, over the past 50 years.
- A harbour sediment study (by NIWA) provided evidence that exotic pine plantations and pastoral land have both contributed large amounts of sediment to certain areas of the estuary and noted the presence of coarse, catchment derived sediment in the estuary. Further information on the relative importance of sediment sources may be provided by sediment fingerprinting research (by Brendan Roddy, University of Waikato) in the next few years.

Whangamata Harbour

- Whangamata Harbour catchment contains 43 per cent plantation forest, 30 per cent native forest and 11 per cent pasture.
- The most recent estuary sediment core study estimated that pre-European settlement sedimentation rates were between 0.10 and 0.18 mm/year in Whangamata Harbour. From the 1940s until the 1990s the average sedimentation rate was estimated at 5 mm/year but may have been as high as 15 mm/year in some areas of the estuary, such as near the Moanaanuanu Causeway.
- A rapid expansion of mangroves and a decrease in seagrass has been observed around the same time as the rise in sedimentation rates. Mangrove coverage has tripled and seagrass almost halved over the last 50 years.
- The estimate for sediment yield from the Hicks and Shankar model (5048 tonnes/year – for the entire 52km^2 catchment) is much lower than the estimate for sediment deposition (14,622 tonnes/year – for just a 22km^2 sub-catchment). The sediment deposited in the estuary has been identified as catchment derived.

Wharekawa Harbour

- Current land use in the catchment is 50 per cent exotic forest, 32 per cent native forest and 12 per cent pasture.
- Wharekawa Harbour is very shallow (90 per cent is intertidal). Sediment core studies show that the sedimentation rate has increased from 0.1 mm/year pre-European settlement to between 5 and 8 mm/year from 1945 to the 1990s. Given the characteristics of the estuary, it is most likely that almost all sediment input has been from the catchment.

- Seabed level monitoring carried out over the last decade indicates present day sedimentation rates to be approximately 4.1 mm/year, which suggests that sedimentation has decreased slightly in recent years (when compared with rates of 5 to 8 mm/year for the period 1945 to 1995, calculated from sediment core studies). However, this measure of current sedimentation rates is still forty times that of pre-European sedimentation rates.
- Rapid mangrove expansion has occurred in Wharekawa Harbour. Mangrove cover was assessed in 1983 (20 ha) and in 1995 (49 ha).
- The estimates for sediment yield (SedRate and Hicks and Shankar model – 60 and 96.9 tonnes/km^2/year, respectively) are much lower than sediment deposition measurements (sediment cores - 183 to 252 tonnes/km^2/year).
- Results from a sediment source study indicate that silt (flood material) contributed high proportions (29-95 per cent) to the estuary sediments.

Whitianga Harbour

- Whitianga Harbour catchment contains only a small amount of plantation forest (7 per cent), and 44 per cent of the catchment is currently in native forest, 22 per cent in pasture and 26 per cent in native scrub.
- Based on available data, mangrove expansion has been only moderate in Whitianga. The specific sediment yield estimates (from SedRate and Hicks and Shankar model) are the lowest (36 tonnes/km^2/year) and second lowest (69.3 tonnes/km^2/year) values of the five estuaries we have studied in this report. Although the sediment estimates should be treated with caution, it suggests that there is relatively less sediment generated in the Whitianga catchment than in the other four estuaries.
- Sediment core dating was undertaken in 2007, with results suggesting considerable variability in sedimentation over time. Sedimentation rates of up to 30 mm/year were reported for the period around and prior to the 1960s, compared to rates of between 5 and 9 mm/year for the last few decades.

In summary, the steep slopes of the landscape of the Coromandel Peninsula are very prone to erosion and therefore the estuaries of the Coromandel are prone to sedimentation. This sedimentation has very likely been accelerated by land-use change. Initial catchment deforestation (shortly after European settlement) and subsequent pastoral farming likely initiated large scale erosion, but land management practices have improved in recent years.

Estimates of sediment yield (from SedRate and the Hicks and Shankar model) are much lower than estimates of sediment deposition (from sediment core studies). In particular, it is difficult to assess the contribution of sediment from different land uses to current sedimentation in estuaries. However, a rapid rise in recent sedimentation rates, (observed in sediment core studies) coincides with the establishment of exotic forestry on large areas of estuary catchments. It is important to note that the discrepancy between the sediment yields and sediment deposition rates may be due to the complexity of the systems involved. The movement of sediment around, into and out of estuaries is highly dynamic and can affect the sediment core studies. The movement of the sediment through catchments is influenced by bed-load, sediment remobilisation and storage in streams; all of which are complex, likely to vary between catchments and therefore uncertain.

All five estuaries studied in this report are Areas of Significant Conservation Value (ASCVs). All are productive ecosystems supporting high biodiversity. Any decline or degradation of habitat will affect these communities, potentially decreasing biodiversity and productivity. A decline in species abundance and habitat degradation has already been observed in some estuaries, and has been linked with sedimentation. Therefore, despite the uncertainty over the contribution of various land uses to sedimentation, a strategy should be developed to minimise future erosion and associated impacts.

Recommendations

- Sedimentation is placing stress on ecological communities already strained by other pressures. The steep, highly erodible soils in the catchments are better protected under forest than under pasture but there is evidence that harvesting of exotic forest is associated with a decline in the estuary species sensitive to sedimentation. Although it is difficult to assess the current contribution of areas under differing land use to current sedimentation rates, the evidence gathered to date warrants further research into the effects of exotic forest harvesting on estuarine communities. As a minimum, estuary monitoring programmes should be continued, as long-term data has the potential to detect adverse changes in benthic communities.

- Newer, more accurate techniques are now available for sediment core studies. Previous core studies have estimated sediment deposition rates over time periods of approximately 50 years, limiting their use in evaluating current (that is, after land management practice improvements have been made) sedimentation rates. Newer techniques might be able to assign sedimentation rates on finer time scales. However, uncertainty over the storage time of sediment in streams may limit this study to some extent as sediment eroded many years ago may be remobilised during large events and progressively moved down the river system, arriving in the estuary many years after the erosion took place.

- The reasons for the difference between the estimates for sediment deposition and those for sediment yield could be investigated. Both sediment yield estimates (SedRate and the Hicks and Shankar model) are for suspended sediment yield. They do not attempt to measure bed-load, which is thought to be 3-10 per cent of total sediment load, but it may be that bed-load contributes more to total sediment load than is currently thought. Information is also lacking on the storage times of sediments in streams, and gully erosion contribution to sediment yield for east coast Coromandel estuaries. It may be possible to expand knowledge in these areas but due to the complexity of the systems involved it would likely require years of monitoring and further research, at great cost.

- Rather than wait to see if further research and monitoring conclusively provides a culpable land use for sedimentation in estuaries, it would be better to adopt a soil conservation strategy now that could identify critical erosion areas throughout the catchment. Measures could then be put in place to control erosion and sediment entering the river system.

- As the relative sources of sedimentation (in terms of land use), and relevant soil conservation strategies, are likely to differ between estuaries/catchments, it is recommended that local harbour and catchment management plans be progressed for individual localities. These should assess whether sedimentation is a problem in the estuary, and if it is, address what can be done to reduce the sedimentation.

This report is not intended to be the final word on coastal sedimentation. It is expected that conclusions and recommendations will be expanded in line with the results of further research and monitoring.

Introduction

The issue

Estuaries are transition zones between the land and the coast. They are dynamic and complex systems, subject to change. Because estuaries are the receiving environments for run-off from land, activities in the surrounding catchment can result in changes to estuarine systems and ecology.

Sedimentation in an estuary is a natural process. In the absence of sea level rise, over time all estuaries will infill. The rate of sedimentation is controlled by the availability of sediment, the processes that deliver the sediment to the estuary, and the ability of the estuary to flush or retain sediment. This rate can be altered by changes in land use or land management within the catchment or by development of structures within the estuary (for example, causeways).

Estuaries in the Waikato region are under increasing pressure from coastal development (such as marine farms and marinas) and catchment activities and development (such as farming, subdivision and vegetation clearance). Estuaries are highly productive ecosystems which provide habitat for a wide variety of species. Potential ecological changes associated with increased sedimentation include mangrove expansion, loss of seagrass beds, loss of shellfish beds and a reduction in the diversity of animals that live on the seabed, as well as fish and birds.

Several studies have investigated past sedimentation rates in selected estuaries, using pollen or radiocarbon dating of sediment cores. Results indicate that pre-European sedimentation rates in estuaries on the Coromandel Peninsula were approximately 0.1 to 0.2 mm per year. Typically, increased sedimentation rates, to between 1 and 8 mm per year, were observed following settlement by Europeans.

Coastal communities are concerned about sedimentation, sometimes linked to habitat change such as mangrove expansion. Some also perceive a link between production forestry and sedimentation in estuaries. Accumulation of sediment in the Waikato region's estuaries is a key resource management issue for the coastal marine area.[5]

This report focuses on east coast Coromandel Peninsula estuaries. Estuaries on the Coromandel Peninsula are highly valued for cultural, recreational and economic reasons. Catchments on the Coromandel Peninsula are typically of very steep topography and covered by soils that are highly susceptible to erosion. High intensity, localised rainfall events occur relatively frequently, mobilising exposed soil and triggering landslides. In addition to the high risk of erosion, estuaries on the Coromandel Peninsula east coast are susceptible to infilling by sediments because they often have sandbars or barriers (forming barrier-enclosed lagoons) that narrow the harbour entrance. These estuaries have high ecological value, are highly valued for recreation, and are under increasing pressure from development.

Major land use changes have occurred on the Coromandel Peninsula following European settlement. Polynesian settlement was most likely concentrated close to the coast, with only small scale land clearance, although large accidental fires also occurred. Sediment cores taken from Whangapoua, Wharekawa and Whangamata estuaries show a small increase in sedimentation following Polynesian settlement and a much larger increase following European settlement.[6]

[5] Turner and Riddle, 2001.
[6] Hume and Dahm, 1992.

Large scale land cover changes began in the mid 19th century. Major deforestation and soil erosion occurred as a result of gold mining, gum digging and kauri logging. In the 20th century pastoral farming became the major land use. Large scale planting began during the 1930s and exotic production forestry became established from the 1950s to the present day.[7]

The scope and structure of this report

This report aims to bring together available information on coastal sedimentation, summarising what we know about the sources and effects. The report also aims to identify information gaps. A number of studies have investigated the rate and the effects of sedimentation in various Waikato estuaries. In this report, case studies on five estuaries and their catchments, namely Whangamata, Wharekawa, Whangapoua, Tairua and Whitianga harbours are used to discuss the state of knowledge on sources, delivery and effects of sedimentation.

No one estuary can be described as typical. The five estuaries assessed in this report cover a range of infilling susceptibility, erosion rate and sediment delivery systems.

This report is not intended to be a technical document; rather it provides a summary of our current understanding, presented in lay language.

The life of an estuary

Coromandel estuaries formed when sea-level rise inundated the land, which then stabilised about its current level 6500 years ago. The estuaries that originally formed were very different from those that we see today. Since that time they have filled with sediment. Estuaries have a life; they are born, they age and then they die. Examples of the last stage in the aging process are seen at Hotwater Beach or at Waikawau estuary (see Figure 1), where the upper reaches of the estuaries are farmland and the lower reaches so choked with marine sands that the sea only enters at high tide.

Figure 1: **Waikawau estuary** *(Digital photographic imagery sourced from Terralink International Limited, 2002. COPYRIGHT RESERVED).*

The geomorphology of today's estuaries depends on the topography of that prehistoric landscape, and on how the estuaries were modified by subsequent sediment infilling.[8]

[7] Turner and Riddle, 2001.
[8] Hume and Swales, 2003.

The shape and size of the flooded basin determines the accommodation space available in which sediment can accumulate. Also, the pattern of infilling is controlled by the interaction of stream and river processes, tidal exchange and waves, and can receive sediment from both the land and the sea.

The variety of landscapes flooded by sea level rise, and the many forms that estuary aging can take, provides the variety of estuaries that we have. For example, deeply incised landscapes where significant soil erosion can occur will result in rapidly infilling estuaries. Many of the Coromandel east coast estuaries fall into this category, for example, Wharekawa and Tairua.

In these estuaries sediment can accumulate rapidly in shallow basins to develop low gradient intertidal flats. Tidal creeks in the middle to upper estuary are in-filled with many metres of mud which spill out into estuaries via mud-dominated deltas. In addition, tides and sediment delivery from the sea can play a major role in the aging of shallow lagoons such as Wharekawa, in particular where river inflows are relatively small compared to tidal flows. Marine sand, driven along the coast, can accumulate in low-energy sheltered positions behind rocky headlands, where estuaries discharge into the sea. The sand accumulation at the entrance is sculpted by tide and wave-driven currents to create both flood- and ebb-tidal deltas. These deltas are usually in some form of equilibrium, but where freshwater inflows are relatively low, tidal inflows can begin to dominate, resulting in marine sand accumulation in the lower estuary. However, in wave-dominated estuaries, sedimentation can slow late in the infilling process. The limited accommodation space and consequential increase in sediment mobilisation by wind generated waves causes fine sediment to be carried out of the estuary on ebb flows.[9]

The infilling process can be accelerated. Colonisation of intertidal areas by fringing vegetation such as mangroves occurs where a combination of suitable substrate and protection from wave action allows. The vegetation then slows current speeds on the intertidal flats, resulting in deposition of more sediment, which is further enhanced by increased sediment entering the estuary as a result of catchment deforestation, agriculture and urban development. An extreme example can be seen in the Firth of Thames where sediment accumulation resulting from land use changes has been followed by rapid mangrove expansion of approximately 1 km seawards in 50 years.[10]

The process of sedimentation in estuaries

Rivers and streams carry sediment to estuaries suspended in the water column. Deposition of these suspended sediments will occur when the water slows down.

Flocculation

The finer (and lighter) the sediment particles are, the slower the water will need to be moving for deposition to occur. Very fine sediment, such as clays, will only be deposited at very low water speeds. However, where freshwater meets saline water another process (flocculation) acts on the suspended sediments. The salinity induces the fine clay particles to join together, effectively creating heavier sediment particles which are then deposited.

This is most likely to occur in areas where tidal flow is weakest, such as the upper reaches of an estuary. However, it is possible that during heavy rain events a layer of less dense, sediment laden freshwater can form over the lower reaches of an estuary resulting in deposition of fine sediment. The rate and pattern of deposition within an

[9] Swales and Hume, 1995.
[10] Swales *et al*., DRAFT.

estuary will affect the sea bed level and the location and size of channels and tidal flats.

Susceptibility to infilling

Some estuaries have a higher susceptibility to infilling than others. Those enclosed by a barrier retain sediment more readily than estuaries with little or no barrier. East coast Coromandel estuaries are generally wave-dominated, barrier-enclosed estuaries, while those located on the west coast (for example, Manaia, Coromandel and Te Kouma) have formed principally as drowned valleys, embayments or rias.[11]

The west coast estuaries generally have wide, unconstricted entrances and are 'seawater' dominated. In contrast, east coast estuaries can vary from being well-mixed to salinity-stratified because significant volumes of freshwater input can occur at times as river inflow. In a well-mixed estuary, deposition of sediment will generally be restricted to areas close to stream and river inflow. If the water column is more stratified, then sediment deposition may occur further away from areas of freshwater input.

The volume of water passing through an estuary inlet due to tidal influence (known as the 'tidal prism') will also affect its ability to retain sediment. If a large amount of water needs to pass through a small inlet, high current speeds will help to flush sediment out of the estuary. Tairua Harbour has a small tidal prism of 5 million m^3. In comparison, Coromandel Harbour has a large tidal prism of 47.8 million m^3.[12] Estuaries with relatively small tidal prisms and large catchments are potentially more vulnerable to sediment infilling because of the restricted accommodation space available within the estuary relative to potential sediment sources.

The ratio of tidal prism to catchment area may be considered as a *simple* vulnerability index. Applying this to east coast Coromandel estuaries indicates Tairua Harbour at most risk of infilling, followed by Whitianga and Wharekawa and then Whangamata and Whangapoua. Tauranga and Katikati harbours have been included for comparison. Both have relatively large tidal prisms in comparison to catchment area and on the basis of this assessment would be less vulnerable to infilling than the other estuaries.

Table 1: Ratio of tidal prism to catchment area for east coast Coromandel estuaries. (Data source: Hume and Herdendorf, 1992).

	P	A	Ratio
Estuary	**Spring tidal prism (x10^6 m^3)**	**Catchment area (x10^6 m^2)**	**P : A**
Wharekawa	3.1	92	0.034
Whangamata	3.93	52	0.076
Tairua	5.02	271	0.019
Whangapoua	8.54	109	0.078
Whitianga	12.56	431	0.029
Tauranga	95.82	851	0.113
Katikati	130.8	368	0.355

However other significant factors, such as orientation and the shape of the estuary also play an important role in determining the potential of an estuary to infill. Estuaries orientated to the prevailing winds will tend to be better 'mixed' through the effects of wind waves acting to re-suspend fine sediment and generate currents on the intertidal flats and within the central basin. Application of estuarine shape factors and orientation could be used to refine this vulnerability index further. It is also important to note that catchment land use, slope and rainfall intensity will largely determine the amount of

[11] Carter and Woodroffe, 1994; Hume and Herdendorf, 1992.
[12] Mead and Moores, 2004.

sediment generated and therefore the amount of sediment available to be deposited in the estuary.

All of the above processes will affect the way in which deposition of sediment will occur in an estuary. The rate of estuary infilling will depend on a number of characteristics in addition to the amount of sediment delivered to the estuary. The deposition of sediment can have an effect on the flora and fauna that live within the estuary, such as encouraging mangrove growth. In turn, mangroves slow current speed which increases the rate of sediment deposition.

Summary

The life of an estuary and the process of sedimentation in estuaries

Conclusions

- From the time that estuaries are created, they begin to infill with sediment.
- The pattern of infilling is controlled by the interaction of stream and river processes, tidal exchange and waves, and can result in infilling from both the land and the sea.
- The aging process can be accelerated by catchment deforestation, agriculture and urban development; all are activities that can increase the amount of sediment reaching an estuary.
- Rivers and streams carry sediment to estuaries suspended in the water column.
- Deposition of suspended sediments will occur when the water slows down and meets saline water, causing the sediment particles to stick together (flocculation).
- Some estuaries have a higher susceptibility to infilling than others. Those enclosed by a barrier retain sediment more readily than estuaries with little or no barrier. East coast Coromandel estuaries are generally wave-dominated, barrier-enclosed estuaries.
- Estuaries with relatively small estuary areas and large catchments are potentially more vulnerable to sediment infilling because of the restricted accommodation space available within the estuary relative to potential sediment sources.
- The ratio of tidal prism to catchment area may be considered as a *simple* vulnerability index. Applying this to east coast Coromandel estuaries indicates Tairua Harbour at most risk of infilling, followed by Wharekawa and Whitianga, and then Whangamata and Whangapoua harbours. Note – this does not take into account other risk factors, such as land use or estuary area.

Further research

- In a current study for Auckland Regional Council (ARC), ASR Ltd quantified ‘sedimentation potential' along the ARC coastline. The project determined whether a given estuary was ebb- or flood-dominated, and modelled average near-bed current velocity. Ebb-dominated estuaries were deemed not to be vulnerable to sedimentation, and areas where average bottom current velocities were relatively high, were deemed not depositional.

  This is an approach that could be applied to east coast Coromandel estuaries.

The effects of sedimentation on estuaries

This section of the report deals with the effects of sedimentation on estuarine life and on humans. Sediment is usually carried to an estuary in suspension and then deposited within it when water speed slows. Both suspended sediment and deposition of sediment can have a direct effect on plant and animal life and indirect impacts further along the food chain. The infilling of an estuary can affect aesthetic and recreational values.

Sediments mostly enter the estuary in suspension, within the freshwater input from rivers and streams. Storm events can cause greatly increased levels of suspended sediments in the water column. Once sediment is deposited it can be resuspended by wave action and tidal flows and transported to different areas of the estuary.

Deposition of sediments can cause broad scale changes in the estuarine environment, such as channel infilling and a general shallowing of the estuary. This can cause vegetation changes, such as rapid expansion of mangroves, as well as specific effects on the plants and animals within the ecosystem.

Accelerated sedimentation rates may not adversely affect coastal plants and animals in areas where other pressures are low, but can pose a serious threat in areas where other pressures, for example, fishing pressure and invasive species, are high.

The effects of sediment on specific biological communities are discussed below.

Effects on plants

High levels of suspended sediment within the water column increase the turbidity and decrease the light available to plants. Seagrass (Figure 2) is especially vulnerable to greater suspended sediment concentrations because it has relatively high light requirements.[13] Deposition of sediment can smother seagrass beds, reducing the plants' ability to photosynthesise and thereby reducing growth and survival.

Microalgae growth (in the water and on the seabed) can also be slowed by increased suspended sediment levels.[14] These algae are a major food source for benthic animals, such as marine worms (Figure 3), snails and bivalves such as the wedge shell (Figure 4).

Increased sedimentation can result in expansion of mangroves, as sediments increase the intertidal area available for mangroves to colonise. Mangrove roots trap fine sediments, further increasing seabed level, and therefore, habitat suitable for mangroves. Mangrove expansion can occur at the expense of other types of estuarine habitat, such as seagrass beds and unvegetated intertidal flats.

A comparison of aerial photographs of Coromandel estuaries taken in the 1970/80s and 1995/1997 shows that in a number of estuaries monitored there was a marked increase in the spatial extent of mangroves. The smallest increase (10 per cent) was in Whitianga Harbour, the largest increase (465 per cent) occurred in Otahu Estuary.[15]

[13] Turner and Riddle, 2001.
[14] Vant, 1991 and Williamson *et al*., 2003.
[15] Turner and Riddle, 2001.

Figure 2: **Seagrass beds and open mud flats in Coromandel Harbour.** *(From Graeme and Dahm, 2007).*

Effects on benthic animals

High levels of suspended sediments can adversely affect benthic (sea-bed dwelling) animals in a number of ways. As described above, algae they feed on may become depleted due to decreased light levels, the feeding structures of filter feeders (such as the cockle) may be damaged or clogged, the nutritional value of the particles on which they feed may be changed, and their gills can be damaged.[16] [17] There is some evidence that bivalves (such as the cockle and the pipi) may be particularly sensitive to repeated exposure to high levels of suspended sediments. [18]

Estuarine animals are generally adapted to changeable conditions, and tolerate some sedimentation. However, research has shown that deposition of sediment as thin as 3 mm can change the benthic community structure, and deposition of 2 cm of sediment can kill all benthic animals present.[19] [20]

Sedimentation can change the particle size structure of the sea bed, most often resulting in an increase in mud content. This can then cause changes to plant and animal communities that live within or on the sea bed. An increase in mud content can lead to a decrease in the number of burrowing animals, such as marine worms. These animals break down organic matter and bring fresh oxygen into the sediment. A decrease in their abundance can alter sediment chemistry and decrease the productivity of the entire estuary.

Contaminants attached to sediment affect benthic animal behaviour, mortality and community structure. Such contaminants are often associated with fine sediments. Other, more subtle changes in community structure related to sedimentation can occur. [21] For example, changes in water depth may change exposure to ultra-violet (UV) radiation.

[16] Hewitt *et al.*, 2001
[17] Nicholls, *et al.*, 2003
[18] Norkko *et al.*, 2006
[19] Lohrer *et al.*, 2004
[20] Thrush *et al.*, 2004
[21] Nipper *et al*., 1998

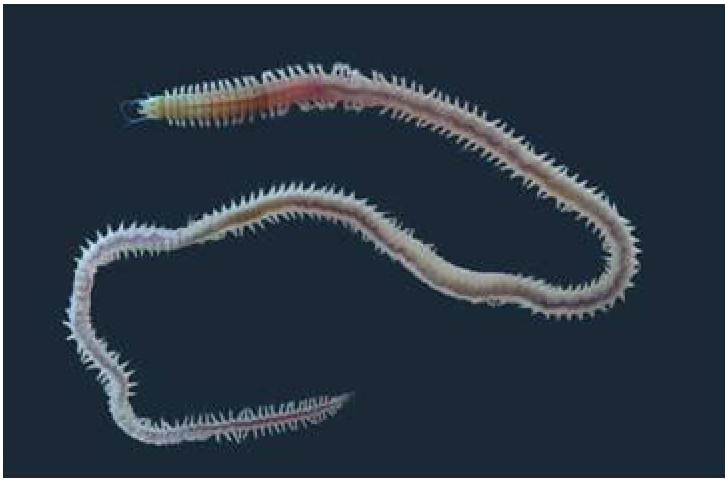

Figure 3: **Marine worm** *Photo: Dr Barry O'Brian (University of Waikato).*

Figure 4: **Wedge shell (*Macomona liliana*)** *Photo: Dr Barry O'Brian (University of Waikato).*

Wider effects

At the interface between land and sea, estuaries are dynamic. Estuarine sedimentation is a natural process, however, accelerated sedimentation may cause adverse effects on the resources used by birds and fish, and through impacting these and plant resources, on humans.

The visual effects of increased sedimentation can alter the aesthetics of an estuary. This often causes concern to coastal communities, who see their local estuaries becoming muddier and infilling. Infilling of estuaries can also impede navigation, necessitating expensive maintenance dredging.[22]

A decline in benthic animal species or changes in community composition is a concern for a number of reasons.

- Changes in community structure may be irreversible and knock-on effects on predators may affect the region's biodiversity.
- Benthic species make up an essential part of the ecosystem as prey for larger animals, such as shorebirds and fish.

[22] Auckland Regional Council Technical Publication, No. 69, March 1996.

- Different benthic species are prey for different bird species, so maintaining species diversity is important. A major increase in mangroves decreases intertidal mud or sand flat area, potentially reducing wading birds' feeding habitat.
- Recent studies indicate that seagrass beds are an important habitat for snapper.[23] However, most seagrass within Waikato region estuaries is intertidal, and any fish species will only be able to use it as habitat at high tide.
- People collect benthic animals from the estuary. Kai moana species, such as pipi and cockles, have cultural and recreational significance and these species can be adversely affected by sedimentation.
- Plants and benthic animals also have important roles in maintaining water quality, by cycling nutrients and stabilising the sediments.

Summary

The effects of sedimentation on estuaries

Conclusions

- High levels of suspended sediment within the water column increase the turbidity and decrease the light available to plants, such as seagrass and plankton. This can decrease the food available to benthic animals and clog their feeding structures.
- Deposition of sediments can smother seagrass beds, encourage mangrove growth and bury benthic animals.
- Contaminants attached to sediment affect benthic behaviour, mortality and community structure.
- Changes in the plant and animal communities can reduce feeding ground and habitat for bird and fish species and can impact on kai moana species.
- Cumulative effects on plants and animals from low levels of sedimentation may be detrimental.
- Sedimentation is not the only pressure on coastal plant and animal communities, and the impacts of sedimentation should be considered in conjunction with other pressures.

Information gaps

- How serious are the current effects (and potential future effects) of sedimentation?

Further research

- Continue monitoring estuarine communities. Long-term monitoring is essential to determine the magnitude of impacts.
- Evaluate the severity of the impacts of sedimentation on estuarine ecological values.

Sources and delivery of sediment

Sediment yield is influenced by many factors, including run-off, geology, soil type, vegetation, land use, topography and rainfall. Sediment yields are higher from short-duration, high-intensity rainfall events (especially on steep, already saturated slopes) than from prolonged low-intensity rainfall events.

Studies indicate that in some areas a native forest catchment yields less sediment than pasture and exotic forest catchments. Pasture catchments generally yield more sediment than exotic forests. Changes in land use, such as urbanisation and forest harvesting can induce major, but often temporary, changes in sediment yield.[24]

[23] Morrison and Francis, 2002.
[24] Hicks and Griffiths, 1992.

This section of the report will describe processes governing sediment generation and yield, and identify what we know about these processes in the Coromandel and some of the major information gaps.

Sediment generation

Steep slopes, weathered volcanic soils and frequent storms predispose slopes on the Coromandel Peninsula to erosion.

There are three main erosion processes responsible for sediment generation:

- slopewash
- streambank erosion
- landsliding.

Each of the above processes occurs naturally, but can also be accelerated by human activity.

Landsliding

Figure 5: Landslide, Mokau *(Image from www.ew.govt.nz).*

A slope experiences two sets of stresses. One stress acts to hold the slope together (shear strength) and the other acts to move material down the slope (shear stress). When shear strength becomes less than shear stress, the slope fails and a landslide occurs. Slopes can be gradually weakened by a range of processes, including deforestation, weathering, erosion, undercutting by a stream and construction activities. The trigger can be an earthquake or volcanic activity but is more often prolonged or intense rainfall.[25] On the Coromandel Peninsula landslides usually occur when unstable rock and soil on steep slopes are saturated by heavy rain. Landslides occur in all land use types, including native forest, mature pine forest, harvested pine forest and pasture.

Slopewash (surface erosion)

During and after rainfall, sediment can be eroded from bare non-vegetated areas and carried down the slope. This can be exacerbated by gullying, which is the process of erosion by ephemeral streams, (streams formed during and immediately after rain fall).

[25] Saunders and Glassey, 2007

Streambank erosion

Figure 6: Streambank erosion *(Image from www.ew.govt.nz).*

Streambank erosion is the erosion and/or remobilisation of sediment from the banks of streams.

Extreme rainfall is well documented in the Coromandel Peninsula and can trigger and/or worsen all three processes of erosion described above.

Human activity can contribute to the magnitude and/or frequency of these three erosion processes in several ways, such as:

Scalping	(S*oil scraping*) Deep soil disturbance caused by trees dragging along the ground during logging has been found to be a significant contributor of sediment to streams.[26]
Roading	Historically, construction of roading has been regarded as a persistent and widespread source of surface erosion.[27] Current forestry practices are believed to minimise the amount of sediment generated from forestry roads to an acceptable level. However, there have been few studies carried out on the effects of roads on sediment generation and those were in situations different from what is generally practised in modern forestry.[28]
Other earthworks	Clearance of vegetation for development (for example, subdivision) can leave bare ground exposed to erosion for extended periods of time.
Pastoral farming	Removal of vegetation to produce grassland for pastoral farming on steep slopes increases erosion. This is caused by the lack of a canopy intercepting rainfall and the fact that root systems of grasses are less effective at binding the soil than the roots of trees.
Agriculture/horticulture	These activities can also expose bare soil, especially if the land is ploughed.

Question
No recent studies have been carried out on forest roads. Is further research important?

[26] Fransen *et al*, 2001.
[27] Fahey and Coker, 1992.
[28] Phillips, 2005 (Environment court evidence).

Sediment yield

Sediment yield is the quantity of sediment exported out of a catchment over a given time period.

Determining detailed effects of land use on sediment yield is problematic because rates of erosion also depend on other factors, such as topography, soil type and the intensity and frequency of rainfall. However, it is clear that vegetated areas will generate much less sediment than non-vegetated areas. Forested catchments (native or exotic) typically yield a half to a fifth of the sediment of an equivalent basin under pasture.[29]

A number of studies have attempted to measure sediment yields in areas under differing land use and this data can provide an indication of the range in sediment yield for these areas. For example, information collected in the Auckland region by NIWA is summarised in the table below. Note that data were collected over different periods in the late 1980s and early 1990s and provide an indication only of sediment.

Table 2: Average sediment yields for five areas under various land uses in the Auckland region (Hicks, 1994).

Area	Sediment yield (tonnes/km^2/year)
Alexandra (urbanising)	970
Wairau (mature urban)	107
Pakuranga (mature urban)	24
Manukau (pasture)	49
Whangapouri (market gardening)	49

Another report, also by NIWA, compared sediment loads from urban areas with erosion rates for other land uses in New Zealand. It suggested order of magnitude of sediment yields for the various land uses included in the table below.

Table 3: A comparison of sediment yields for various different land uses. (After Williamson, 1993).

Land use	Approximate sediment yield (tonnes/km^2/year)
Low hill country native catchment	10
Low hill country pasture catchment	100
Mountainous regions	1000
Mature urban catchments	100
Catchments with a significant proportion of construction	1000

Forest harvesting can increase water yields, (mainly because vegetative cover that would intercept rainfall is lost), which can in turn generate more sediment. The increase in water yields increases surface run-off and associated erosion, and where there are bare slopes the likelihood of landsliding increases. Data collected in areas of exotic forestry (at different stages of rotation) and pasture catchments are contained in the table below.[30]

[29] Hicks *et al*, 2004
[30] Fahey *et al*, 2004

Table 4: Sediment yield for different phases of forest rotation and pasture catchments in Maimai and coastal Hawke's Bay. (From Fahey *et al.*, 2004).

Location	Land use	Sediment yield (tonnes/km^2/year)
West coast South Island (Maimai), near Reefton	At harvesting (skidder)	139
	Adjacent pasture catchment	17
	At harvesting (hauler)	25
	Adjacent pasture catchment	17
East coast North Island, near Napier	Mature exotic forest (1995-1997)	30
	Adjacent pasture catchment	67
	At harvesting (1998-1999)	89
	Adjacent pasture catchment	41
	Post-harvesting (2000-2001)	150
	Adjacent pasture catchment	102

A comparison between the exotic forest and pasture shows that sediment yield from the mature forest is roughly half that of the pasture. At harvesting, however, sediment yield from the forest is more than double that of the pasture. Post harvesting (2 to 3 years following harvest) sediment yield in the forest is still 50 per cent greater than that of the adjacent pasture. Note that sediment yield is highly variable. In the pasture catchment, over the three different periods (1995–1997, 1998–1999 and 2000–2001) sediment yield ranged from 41 to 102 tonnes/km^2/year.

There appears to be a lack of directly comparable data on sediment yields from land under native and exotic forestry. This is likely related to the long-term monitoring (an entire exotic forest rotation, approximately 30 years) that would be required to gather data to cover the variability of sediment yield during planting, mature forest, harvesting and post-harvesting phases. Also, native forest in the Coromandel is often confined to the very steep slopes (with the highest erosion risk) above exotic forest. There is therefore a lack of similar catchments of exclusively native and exotic forest.

Connectivity

Not all sediment generated in a catchment will contribute to the sediment yield. Some eroded soil will stay close to its source, some will be deposited in stream channels (where it may be stored for some time), and some will be carried in rivers and streams to the estuary.[31] The amount of eroded soil that passes through the channel system to the estuary is the sediment yield.

Question

- What influences connectivity? Can it be predicted from an overview of stream networks and an assessment of slopes prone to landsliding?

Sediment yield from catchments studied

Significant storm events generate large amounts of sediment that dominate deposits in estuaries, making it important to measure sediment yield over a period long enough to include the larger, relatively infrequent storms. Methods are available that allow us to estimate the total amount of sediment delivered to an estuary from its catchment (the

[31] Marden *et al*, 2006

sediment yield). There are also methods available to estimate rates of sediment deposition in an estuary.

The three methods outlined below have been used to estimate sediment yields for catchments and estuaries on the east coast of the Coromandel.

SedRate (Environment Waikato)[32]

Environment Waikato monitors river flow and suspended sediment concentrations at a number of sites in the region. Four of these sites are located in the catchments of estuaries on the east coast of the Coromandel Peninsula. The hydrological data and suspended sediment data collected at peak flows can be used to calculate the long-term average sediment load carried by the rivers, using the SedRate software (NIWA Christchurch). Based on the assumption that the conditions in the sub-catchments for which we have data are similar to conditions in the whole catchment, then the annual sediment load can be estimated. The table below contains the estimated sediment load to four case-study estuaries considered in this report. It is important to note that sediment load values for Tairua and Whitianga (in italics) were calculated using a much smaller data set than those for Whangapoua and Wharekawa. They therefore should be treated as approximate. It should also be noted that for each estuary data was collected from only one river.

Table 5: Sediment loads carried by four Coromandel rivers and the *pro-rata* estimated loads carried to the corresponding estuaries.

River	**Tairua River**	**Opitonui River**	**Wharekawa River**	**Waiwawa River**
Monitoring site	Broken Hills	Opitonui	Adams Farm	Waiwawa
Period of sediment sampling	1986–2001	1991–2006	1991–2003	1991–2001
Number of sediment samples	46	1157	478	31
Sediment load (tonnes/year)	*17,600*	4,000	2,800	*4,300*
Standard error (%)	33%	4%	5%	29%
Specific sediment yield (tonnes/km^2/year)	*150*	140	60	*36*
Estuary	**Tairua Harbour**	**Whangapoua Harbour**	**Wharekawa Harbour**	**Whitianga Harbour**
Estimated sediment load for estuary (tonnes/year)	*42,000*	15,000	5,000	*15,000*

The advantage of the SedRate estimates is that they are based on *in situ* measurements of suspended sediment. Bed-load is not measured, however, so the sediment yields may be underestimates. It is unlikely that conditions (such as slope and land cover) measured in the sub-catchments are similar to those of the whole catchment, and so the extrapolation may be invalid. Also to date, large data sets are only available for Whangapoua and Wharekawa.

Hicks and Shankar (NIWA) sediment model

Using the Hicks and Shankar (2003) NIWA model, we were able to obtain an estimate of sediment yield for five Coromandel estuaries. This model estimates suspended sediment yield based on mean annual rainfall and an "erosion terrain" classification. The "erosion terrain" is based on data on slope, rock-type, soils and erosion processes, along with expert knowledge. A grid of suspended sediment yields of 100 m x 100 m was used in GIS to estimate the annual sediment load for each estuary's catchment.[33]

[32] Analysis by Bill Vant. Environment Waikato document #1156868.
[33] Hicks and Shankar, 2003.

The table below lists the five case-study estuaries, the corresponding catchment area and sediment yield (in tonnes per year). This can be divided by the catchment area to give the amount of sediment generated per square kilometre per year (known as specific sediment yield).

Table 6: Sediment yield for five Coromandel estuaries calculated using the Hicks and Shankar (2003) model.

Estuary	Catchment area (km^2)	Sediment yield (tonnes/year)	Specific sediment yield (tonnes/km^2/year)
Tairua	282.4	22,802.8	80.7
Whangamata	51.7	5048.8	97.7
Whangapoua	106.6	6266.2	58.8
Wharekawa	92.1	8928.2	96.9
Whitianga	432.6	29,987.7	69.3

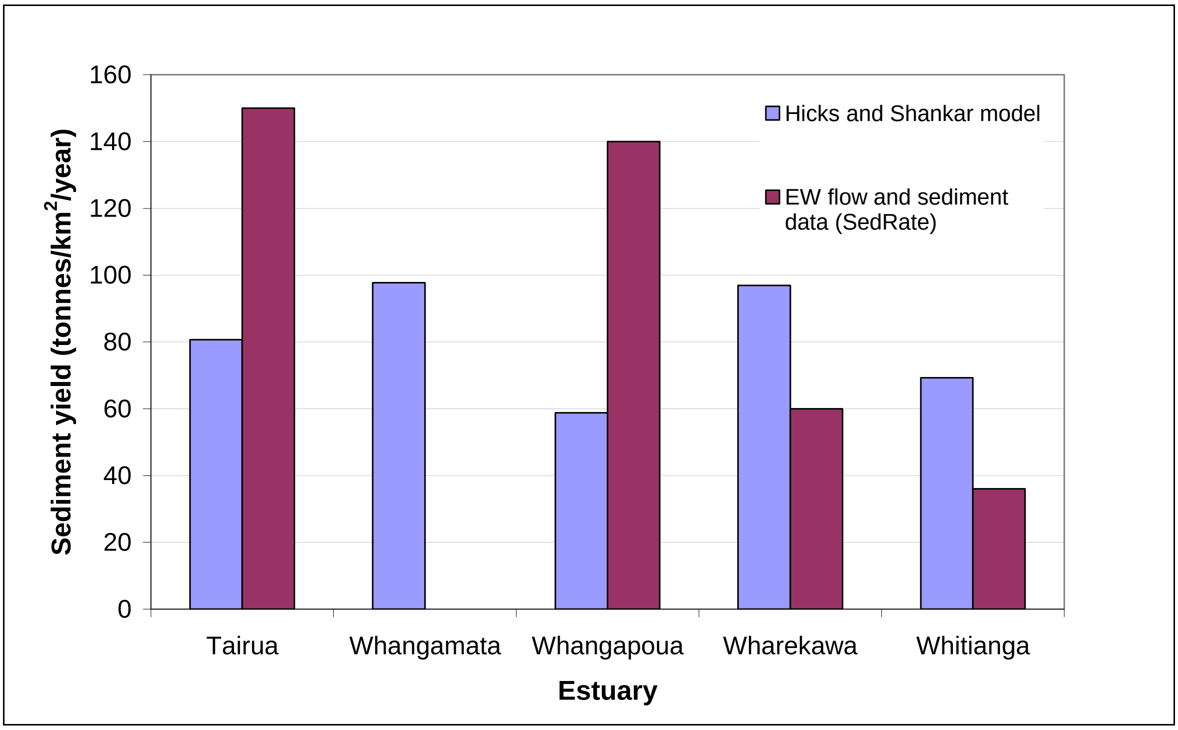

Figure 7: Specific sediment yields (tonnes/km^2/year), calculated using the Hicks and Shankar (2003) model and calculated from Environment Waikato measured flow and sediment data (using SedRate), from the catchments of the Coromandel case-study estuaries.

The model estimates the suspended sediment yield range for estuaries on the east coast of the Coromandel to be approximately 60 to 100 tonnes/km^2/year. This range is similar to that estimated by SedRate of 36 to 150 tonnes/km^2/year. The variability between the sediment yield estimates for each estuary using the measured loads (SedRate) and the modelled loads (Hicks and Shankar), suggests that we should be cautious of the level of confidence we place in them. However, the sediment yield values given by the two methods range within those for areas of similar land use and topography (as shown in Tables 3 and 4).

The model uses quite a coarse grid and it is possible that calculating sediment yields for catchments at this scale compromises the accuracy of the model. The model is calibrated using mixture of catchments with a variety of land uses and therefore is not expected to be accurate enough to identify land use effects (Murray Hicks, personal communication). This is likely to be a major shortcoming because land use greatly influences sediment yield.

Both the SedRate and the Hicks and Shankar model estimate suspended sediment yield without inclusion of a bed-load estimate. It has been reported that bed-load transport to the coast equates to between 3-10 per cent of the total load. Sediment transport in rivers can be influenced by waves of bed-load material ('slugs'), possibly generated by landslides, large storms or changes in land use.[34]

Sediment cores

Studies undertaken by NIWA have used sediment cores to provide estimates of sediment deposition rates in Wharekawa, Whangamata and Whangapoua harbours.[35] [36] [37]

The studies were undertaken in the early-mid 1990s and used pollen and carbon radio isotope techniques to date sediments. Bioturbation and physical processes can mix sediment layers, reducing the techniques' accuracy. There are newer and more accurate techniques now available using X-Radiographs and radio isotopes (see the next section of this report for more information).

It should be acknowledged that rates of sediment deposition measured within specific locations in an estuary may not necessarily be the same as the average rates across the estuary; for example, shallow, upper estuary creeks are low energy environments that are predisposed to greater sediment deposition.

Estimates of sediment deposition obtained by sediment dating differ again from the estimates of yield from the catchments obtained using SedRate and the Hicks and Shankar model. The following example illustrates the magnitude of the variability.
The table below summarises the values for sediment yield/deposition obtained for Wharekawa Harbour using the three different methods.

Table 7: Sediment yield/deposition estimates obtained for Wharekawa Harbour.

Method	Sediment yield/deposition (tonnes/year)	Specific sediment yield/deposition (tonnes/km^2/year)
Environment Waikato flow and sediment data (using SedRate)	5,000	60
Hicks and Shankar (NIWA) model	8,928	96.9
Swales and Hume (NIWA) sediment core data	12,000 – 17,000	183 – 252

The data in Table 7 would suggest that sediment deposition (core data) is much greater than sediment delivery (measured and model data). The difference could be due to import of sediment from the open coast, and/or the estimates for sediment yield are inaccurate, and/or the estimates of sediment deposition are skewed by cores being taken from highly depositional environments.

In principle, measurements in the streams draining the catchment, and calculation of the resulting load using a tool like SedRate would provide the best method of determining sediment delivery to an estuary. However, the estimates for catchment sediment yields are extrapolated from measurements from one stream per catchment. If conditions vary between sub-catchments then that extrapolation could be inaccurate. In addition, bed-load is not taken into account in either the Environment Waikato data (SedRate) or the Hicks and Shankar model.

[34] Hicks *et al*, 2004.
[35] Swales and Hume, 1994.
[36] Swales and Hume, 1994.
[37] Hume and Dahm, 1992.

Evidence exists of ‘slugs’ of bed-load material contributing sediment to Coromandel estuaries. A recent report into sediment sources by NIWA, described a delayed bed-load transport event in Whangapoua Harbour where bed-load material was gradually washed down the Opitonui River as a well defined layer that was about 20 cm thick at the leading edge (Figure 6). A bed-load layer (red-brown in colour and several centimetres thick) was later confirmed to be present on the intertidal flats in the estuary. [38]

Figure 8: Leading edge of coarse bed-load material slowly moving down the Opitonui River channel in Whangapoua Harbour, 5 February 1999 *(From Gibbs, 2006, photo by Ron Ovenden).*

Questions

- Why the discrepancy between sediment yield estimates (SedRate and Hicks and Shankar model) and sediment delivery estimates (cores)? For example, does bed-load contribute more to total sediment yield than 3–10 per cent?

- Where should future research or monitoring of sediment yield or sediment deposition be directed?

Sediment cores: X-Radiograph and radio isotope techniques

There are now newer and more accurate techniques than those used in the studies carried out in Whangapoua, Wharekawa and Whangamata harbours. X-radiographs and radio isotopes, such as Caesium-137 (^{137}Cs) and Lead-210 (^{210}Pb), supplemented by the use of mixing models and Beryllium-7 (^{7}Be) are used to assess surface mixing zones and sediment accumulation.

These techniques have been used at Whaingaroa (Raglan) Harbour (Swales *et al*, 2005), Whitianga (Reeve 2008) and in the southern Firth of Thames (Swales *et al*, 2005 and 2007) to identify relative sediment accumulation rates on the intertidal flats and within the fringing mangrove forests. No comparative assessments have been carried out between rates determined using these recent techniques and those used in the earlier Coromandel studies.

[38] Gibbs, 2006.

Storage in streams

The residence time of bed-load sediment in streams is largely unknown. It is likely that there is a considerable lag (in the order of decades) between reduced catchment sediment yield and sediment deposition in the estuary.[39] Therefore, it is possible that the effects of improved land management practices on catchment sediment yield are not immediately noticed. However, it would be expected that stream storage would be greatest in systems with a low slope. Streams in the Coromandel typically flow down steep slopes; therefore storage would most likely be limited to lowland areas.

Questions

- Is gully erosion a significant source of sediment in the east coast Coromandel?
- Is there a significant amount of sediment stored within lowland streams in the Coromandel?

Riparian vegetation

Riparian vegetation benefits stream life, whether in areas of pasture or plantation forest. Shading and habitat provided by vegetation is very important in maintaining the biodiversity of the stream. For example, many insects require riparian vegetation for part of their life cycle, the leaf litter provides food and wood provides habitat.

On pastoral land, riparian buffers prevent stock from damaging stream banks, which could otherwise contribute sediment.

In plantation forest, riparian vegetation could trap sediment and associated nutrients produced after logging. Run-off is often concentrated in channels, however, consequently a riparian buffer may not prevent sediment from entering a stream.[40]

Recent forestry research suggests that the root systems of riparian vegetation stabilise the bank, thereby reducing streambank erosion. The study also found:

- streambank erosion was greatest at harvested sites, while no bank erosion occurred in native forest reaches.
- mean bank erosion was significantly different between pre- and post-harvested sites with and without riparian zones.[41]

How does land use (production forest, native forest or pasture) impact on erosion?

Research shows that, compared to pastoral farming, closed canopy forest significantly reduces erosion (especially landsliding) during large storm events. This suggests that some areas of hill country (those with steep slopes and erodable soils) may be inappropriate for pastoral farming use.

A study in the erosion-prone hill country, near Gisborne, measured the incidence of landsliding under different vegetation types before and during Cyclone Bola (1988). The study found that native forest and exotic plantation forest more than 8 years old provided the best protection against the formation of landslides, both before and during the extreme rainfall event. An intermediate level of protection was provided by regenerating scrub and exotic pines 6 to 8 years old. The greatest damage occurred on pasture and in exotic forest where trees were less than 6 years old.[42]

[39] Swales and Hume, 1995.
[40] Quinn, 2005.
[41] Boothroyd *et al*, 2004.
[42] Marden and Rowan, 1993.

A study in steep (>30°) to rolling (17 to 20°) hill country near Whatawhata in the Waikato region found that a pasture catchment exported three times more sediment than an adjacent native forest catchment. Streams draining native forest had lower temperature, sediment and nutrient concentrations and higher water clarity than those draining pine forest and pasture.[43]

A native species used for erosion control is kanuka (*Kunzea ericoides*). Production forestry is usually of *Pinus radiata*. Forest cover of any type (native or exotic) is effective in protecting against landslides; however, it is the age of the forest cover that is important. At 9 years of age, both kanuka and *P. radiata* afforded a comparable level of protection against landsliding. For the first 9 years of growth, kanuka was more effective because stand density was higher than *P. radiata*.[44] However, there is no known cost effective method of establishing large areas of kanuka, planted at the level of density required to afford these benefits (Grant Blackie, Environment Waikato, personal communication).

Sediment is generated during and following the harvesting of plantation forest. Soil disturbance and compaction, channel disturbance and the absence of any vegetation results in both increased slopewash and stream flow. This leaves the soil susceptible to erosion and landslides, and streams susceptible to channel erosion during any rain event. Impacts of this kind are usually highest in the first 1 to 2 years following harvest.[45] Two to three years following harvesting, the root systems of the harvested trees begin to break down. For approximately 6 years following harvesting there is a risk of accelerated erosion because the young replanted trees do not have sufficient root systems to bind the soil.[46] After about year 6, the new trees have sufficient canopy to intercept large volumes of rainfall and the root systems of these trees are able to bind the soil.[47] (Vince Udy, Environment Waikato, personal communication).

Landslides occurring within areas of plantation forest can be a major cause of coastal sedimentation. It should be noted, however, that landslides are more noticeable on harvested slopes than slopes under tall vegetation, and that landslides occur in all land use types. Vegetative cover, slope, storm intensity and duration, are all important factors controlling landslide severity. Research indicates that a great number of landslides are found in areas of native forest. Native forest is often located at a higher altitude than plantation forest and on steeper slopes, increasing the likelihood of sediment generation. Landslide failure most commonly occurs on slopes greater than 20°, though most landslides occur on slopes between 25° and 35°.[48]

[43] Quinn and Stroud, 2002.
[44] Marden, 2004.
[45] Marden and Rowan, 1997.
[46] Marden and Rowan , 1993.
[47] O'Loughlin, 1985 and Watson *et al.*, 1999.
[48] Phillips and Marden, 1999.

Summary

Sources and delivery of sediment

Conclusions

- Landslides have been identified as the main contributor of sediment supply to estuaries.
- Factors predisposing areas to landsliding include steep slopes, weathering (especially high rainfall), and deforestation.
- On the steep Coromandel slopes, exposed to frequent high intensity rainfall events, pasture would generate much more sediment than an equivalent catchment under forest.
- Estimates of sediment yield/deposition in five east coast Coromandel estuaries range from approximately 60 to 140 tonnes/km^2/year (models for different estuaries), 115 tonnes/km^2/year (Opitonui Stream study, flowing into Whangapoua Harbour), 183 to 252 tonnes/km^2/year (Wharekawa sediment cores) and 664 tonnes/km^2/year (Whangamata sediment cores – see case study).
- Riparian vegetation greatly improves in-stream habitat and reduces streambank erosion.
- Sediment is generated during and following harvesting of plantation forest. Research in Napier reported that sediment yield tripled during harvesting (from the mature forest state) and then nearly doubled again in the 2-3 years post-harvest. It is very likely that for the 6-8 years following harvesting there is a risk that accelerated erosion (most importantly, landsliding) can occur.

Information gaps

- Which of the sediment yield/deposition estimates (SedRate, Hicks and Shankar model or sediment cores) yield the most reliable results? Are there newer methods we should consider using to more accurately pin down the sediment yield in our catchments/sedimentation rates in our estuaries?
- Detail on the amount of sediment stored in streams and the contribution of bed-load and gully erosion to sediment yield for the east coast Coromandel estuaries.
- Comparison of sediment yield between native and exotic forest over an entire forest rotation.

Further research

- Conducting sediment core research using ^{210}Pb and ^{137}Ca methods at Wharekawa Harbour should be considered because it is an estuary where very little tidal flushing occurs and so it is possible that there is a good sediment record. Would it be possible for these methods to pick up stable periods of catchment land use (such as the 30 year period after initial forest plantings and before the first harvesting) and assign a sediment yield/sedimentation rate to that period? This could then be compared with other periods of time, such as when harvesting was occurring. However, uncertainty over the storage time and amount of sediment in streams may limit this type of study.
- The Hicks and Shankar model does not consider land use; Sandy Elliot at NIWA Hamilton is working on an improvement that will include land use. (Murray Hicks, personal communication).

Case studies

Tairua Harbour

Figure 9: Tairua Harbour *(Digital photographic imagery sourced from Terralink International Limited, 2002. COPYRIGHT RESERVED).*

Tairua Harbour is a barrier enclosed river estuary, 6 km^2 in area, 51 per cent of which is intertidal. It is sheltered from the sea by the Pauanui sand spit and Paku Mountain. The Tairua River catchment consists mostly of typical Coromandel steepland, often rising abruptly from the lowlands. The total catchment area is 282 km^2, almost half of which is indigenous forest.

Table 8: Land cover in the Tairua Harbour catchment, (from the Land Cover Database II).

Land cover	Area (ha)	Percentage of Tairua catchment
Indigenous forest	13,108	46.4
Planted forest	4294	15.2
Primarily pastoral	4148	14.7
Scrub	6003	21.2
Urban	294	1.0
Other	410	1.5

Sedimentation of Tairua Harbour has long been of concern. A report by the Hauraki Catchment Board (in 1977) stated that it seemed “fairly certain that the tidal compartment is under attack” from greatly increased sediment flow over the previous 100 years. The report went on to say that “there is an urgent need for a comprehensive catchment scheme aimed….at a plan of land use which will conserve native forest, and will create an appropriate compromise between “production” and “protection” for the purpose of controlling the entry of sediment into the river system”.[49]

[49] Harris, 1977

Ecological information

Saltmarsh vegetation, grading into a freshwater swamp in Duck Creek, has been described as ecologically significant. There is an extensive area of seagrass on the intertidal flats of Tairua Harbour. Saltmarsh and mangroves are present in the mouths of creeks and streams, such as Pepe Stream. The invasive weed, *Paspalum,* is present in many areas of the estuary.

Mangrove coverage was estimated to be 12 ha in 1983.[50] From aerial photography dated 1995, the mangrove extent was estimated to be 38 ha, suggesting the estuary area covered by mangrove has more than tripled in just over a decade.[51] Environment Waikato is commissioning mapping of the estuarine vegetation again in 2007/08.

As part of an AEE (Assessment of Environmental Effects) into the proposed Tairua Marina, studies into the ecology of Tairua Harbour were undertaken between 2000 and 2002.

The diversity of estuarine and coastal bird species in Tairua Harbour is very high, and includes 10 threatened or at risk species, including the nationally endangered reef heron, New Zealand dotterel and the grey duck.[52]

Cockles, wedge shells and pipi beds in the estuary are ecologically significant. A high density pipi bed is present in the low tide channel from Tairua wharf to Pauanui wharf. Shellfish (cockle and pipi) abundances are reported to have decreased over the previous decade.[53]

Many fish species (including rockfish, yellow-eyed mullet, kahawai, variable triplefin, trevally, flounder, parore, grey mullet, eels, snapper and stingray) have been recorded as being present in the estuary.[54]

Sediment yield estimates

We have two estimates of sediment yield for the Tairua catchment. The SedRate estimate is nearly double that of the Hicks and Shankar model, and of the two the Hicks and Shankar model estimate is likely to be more accurate, as the SedRate estimate is based on only a small dataset (46 samples for Tairua, compared to, for example, 1157 for Whangapoua).

Table 9: Comparison of sediment export estimates for the Tairua catchment.

Method	Catchment sediment yield (tonnes/year)	Specific sediment yield (tonnes/km^2/year)
Environment Waikato flow and sediment data (using SedRate)	42,000.0	150.0
Hicks and Shankar (NIWA) model	22,802.8	80.7

Sediment deposition estimates

A study carried out in the mid-1980s estimated the sedimentation rates in the lower Tairua estuary using a marker bed of saw dust, wood chip and sawn plank debris (derived from kauri log milling) deposited on the estuary shore between 1864 and 1909. Estimates of the sedimentation rate between 1933 and 1984 were spatially variable, ranging from 2 to 22 mm/year, with an average of 6 mm/year. [55]

[50] Graeme, 1998.
[51] Extent of Coastal Habitats Indicator, Environment Waikato Website.
[52] Larcombe, 2003.
[53] Bouma, 2007.
[54] Coffey, 2003.
[55] Hume and Gibb, 1987.

Sediment grain size

Bioresearches have carried out an environmental monitoring programme, required for a coastal permit, for Pauanui Waterways Ltd since 1994. As part of that programme sediment samples were taken from within Tairua estuary. In 1998, the monitored sites consisted of mostly medium/fine sand.

It appears that monitoring of the estuary sites ceased after the 1998 survey. The 1998 data however, could provide a useful baseline of sediment grain size in Tairua Harbour.

Table 10: Sediment grain size (percentage dry weight) for estuary bed sites in Tairua Harbour. (After Bioresearches, 1998).

N.B. 'Silt and clay' equals sediment grain size <0.063mm.

Site	Year	Silt and clay (%)
H1 (harbour, T12:626-592)	1998	0.17
H2 (harbour, T11:640-605)	1998	0.24
H3 (harbour, T11:640-617)	1998	0.08
H4 (harbour, T11:643-603)	1998	2.99

Summary

Tairua Harbour

Conclusions

- Tairua Harbour provides habitat for a wide variety of plant and animal species. The small estuary area (6 km^2) compared with large catchment size (282 km^2) and small tidal prism (5 million m^3) are likely to predispose this estuary to infilling.
- The increase in mangrove coverage from 12 ha in 1983 to 31 ha in 1995 suggests sedimentation may have had an effect on the estuary. A figure for current mangrove coverage is expected to be available in 2007/08.
- Almost half the catchment is in native forest, 21.2 per cent is in scrub, 15.2 per cent in plantation forest and 14.7 per cent in pasture.
- The sedimentation rate in the lower estuary has been estimated to have averaged 6 mm/year between 1933 and 1984.

Information gaps

- There has been little monitoring of biological communities in the estuary although it has been reported that the extent of shellfish beds has declined.
- There are no known estimates of pre–settlement or post–1984 sedimentation rates.

Whangapoua Harbour

Figure 10: Whangapoua Harbour *(Digital photographic imagery sourced from Terralink International Limited, 2002. COPYRIGHT RESERVED).*

Whangapoua Harbour is a large (10.8 km^2), shallow (80 per cent is intertidal), barrier-enclosed lagoon. It has a large tidal prism relative to catchment area; consequently the estuary is well flushed, and much of the terrestrial sediment is eventually transported into the open sea. The estuary has extensive intertidal flats, seagrass beds, saltmarsh and mangroves, providing habitat for benthic invertebrates and feeding ground for fish and wading birds.

Whangapoua Harbour is classified as an area of outstanding wildlife habitat and in the Waikato Regional Coastal Plan is deemed an Area of Significant Conservation Value (ASCV).

The Whangapoua catchment covers an area of 107 km^2 and is mostly in exotic pine plantation. Native forest and scrub are present only on the very steep ridges, above the pine forests, whereas on the valley floor there are extensive areas of pasture.[56]

Table 11: Land cover in the Whangapoua Harbour catchment. (From the Land Cover Database II).

Land cover	Area (ha)	Percentage of Whangapoua catchment
Indigenous forest	2154	20.2
Planted forest	5755	54.0
Primarily pastoral	1777	16.7
Scrub	759	7.1
Urban	39	0.4
Other	179	1.7

There have been a number of studies conducted in Whangapoua Harbour and its catchment.

[56] Gibbs, 2006.

Sediment cores

A study in 1992 used pollen and radiocarbon dating of sediment cores to estimate sedimentation rates. Two cores were taken from the intertidal flats near the Opitonui River mouth. The study found that prior to human settlement sedimentation rates were 0.03 to 0.08 mm/year. This slightly increased to 0.12 to 0.13 mm/year following Polynesian settlement. Following European settlement sedimentation rates increased again, to 0.9 to 1.5 mm/year. The study noted that there were problems associated with pollen dating, notably the effects of physical and biological mixing, and recommended that more detailed work was needed to resolve the issues.[57]

Sediment core methods

Sediment cores provide a measure of historical sedimentation rates. A core usually consists of a PVC or metal pipe forced into the estuary floor. When the pipe is removed it provides an intact vertical profile of sediment which can then be subjected to various analysis techniques, such as pollen and radiocarbon dating. Newer techniques are now available, using other radio isotopes, mixing models and X-Radiographs, as earlier described in the section 'Sources and delivery of sediment'.

Pollen grains from terrestrial vegetation, such as radiata pine, native trees and bracken, can be identified within the sediment core. A change in the abundance and type of pollen in the core indicates a change in vegetation type that can be linked to events such as native bush clearance. Historical documents can identify when such changes occurred and an estimate of sedimentation since the vegetation change can therefore be calculated.

In estuarine environments, shell (bivalve and mollusc) fragments are usually used for radiocarbon dating. If the radiocarbon date of the shell layer can be estimated then the sedimentation rate can be calculated by measuring the depth of that shell layer in the core. A naturally occurring radioactive carbon isotope, carbon-14 (^{14}C), occurs in living material. The rate of decay of carbon-14 is known, (its half-life is 5568 years), and by measuring the amount of carbon-14 in a sample (such as a shell fragment), the age of the sample can be determined.[58] Appendix 2 provides as an example, a sediment core from Whangamata Harbour, with shell and pollen layers indicated.

Whangapoua Harbour monitoring

NIWA has monitored a number of sites (varying between 6 and 9) in Whangapoua Harbour for Ernslaw One (the monitoring programme is required by the forestry consent conditions) since 1993. The main aim has been to obtain estimates of the species and density of benthic animals at each site, supplemented by other information such as sediment particle size and density of seagrass cover.

Ecological changes in the estuary have been found to be beyond those of natural variability and are likely to be linked to terrestrial sediment input.[59] Since 1993 there have been gradual declines in the abundance of species that are known to be sensitive to sedimentation.[60] Fewer changes have been observed in the Mapauriki arm (where no forest harvesting has occurred), than in the Opitonui and Owera arms (where forest harvesting has occurred). This suggests a link between forest harvesting and the changes observed.

A major storm in March 1995 resulted in sediment deposition at all the sites monitored. A layer of orange mud up to 10 cm thick covered some areas. This sediment had been removed by late 1996 by resuspension and transport away from the monitoring sites. Sites at the Owera arm, however, showed large changes in animal communities, and

[57] Hume and Dahm, 1992.
[58] Mead and Moores, 2004.
[59] Halliday *et al*, 2006.
[60] Hewitt, 2001.

seagrass beds have not yet recovered. This supports other research that has shown even transitory sediment deposits can affect benthic communities. The knock on effect that a decrease in prey species can have on larger animals is of concern and largely unknown. For example, it is likely that a significant decrease in bivalve species, such as that observed in Whangapoua, would adversely impact on shorebird species. However, a more detailed study would be needed to reach any firm conclusions.

The review of the Whangapoua Harbour monitoring (2006) found that there was a statistically significant relationship between the extent of forest harvesting in subcatchments, and the decline in benthic communities sensitive to increased sedimentation in associated arms of the estuary.[61]

Aerial photographs have been used to measure mangrove and seagrass cover. From 1945 to 1978 the percentage cover of mangroves in Whangapoua Harbour remained relatively stable at about 12 per cent. Since then, mangrove cover has increased to about 26 per cent. The table below summarises the changing vegetation distribution in Whangapoua Harbour. The data from 1945 and 1995-2006 were derived from aerial photographs.[62] The data from 1985 were derived from an extensive baseline survey.[63]

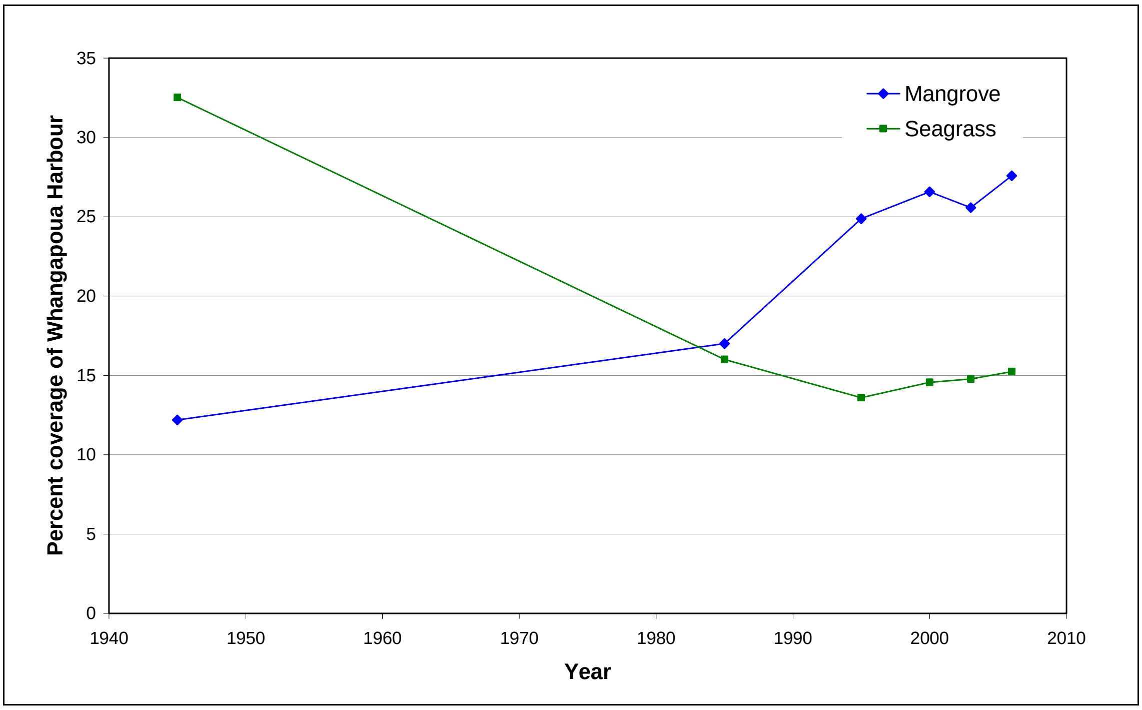

Figure 11: **Change in percentage cover of mangrove and seagrass in Whangapoua Harbour from 1945 until 2006.**

Whangapoua Forest streams monitoring

NIWA has monitored six streams in Whangapoua Forest for Ernslaw One (the monitoring programme is required by the forestry consent conditions) since 1992.

Streams in mature exotic pine forest are generally similar to those in native forest in their habitat characteristics. Streams in pasture differ. For example, they are less shaded, narrower, the temperature is more variable and they will contain more fine sediment.

Steams in catchments that had recently been logged sometimes showed a decrease in water clarity (associated with levels of suspended sediments). However, this effect

[61] Halliday *et al*, 2006.
[62] Halliday *et al*, 2006.
[63] Miller, 1987.

generally only persisted for 1 to 2 years after logging and even logged streams had higher clarity than pasture streams.

Measurements of channel widths suggested that retaining a riparian buffer during logging substantially reduced streambank erosion. Therefore, the importance of riparian buffers in protecting streambanks against erosion is expected to increase with stream size (because stream power and bank height tends to increase with catchment area).[64]

Sediment yield measurements

Table 12: Comparison of sediment export estimates for the Whangapoua catchment.

Method	Catchment sediment yield (tonnes/year)	Specific sediment yield (tonnes/km^2/year)
Environment Waikato flow and sediment data (using SedRate)	15,000	140
Hicks and Shankar, 2003 (NIWA) model	6,266	58.8

The sediment export estimates in the table above are quite different. SedRate used data from the Opitonui Stream and assumed it was representative of the catchment as a whole. However, it appears that Opitonui Stream significantly differs from other major freshwater inputs (that is, Owera and Otanguru streams.) A study into variations in sediment properties in Whangapoua Harbour found that fine particles (kaolinite clays) are abundant in Owera and Otanguru streams but are much less so in Opitonui. Grain size analysis showed Opitonui Stream contained much coarser sediment than Owera and Otanguru.[65]

Opitonui Stream suspended sediment analysis

Suspended sediment has been sampled in Opitonui Stream (downstream of the Opitonui and Awaroa Stream confluence), which drains into Whangapoua Harbour, by Environment Waikato since 1991. The catchment for this area is largely exotic pine on the mid to lower slopes and native forest on the highest slopes. Harvesting began in the Opitonui catchment in 1993.

NIWA analysed the data and found that over the 13 years from 1992 to 2004 the average sediment yield was 115 tonnes/km^2/year, but ranged from 10 to 279 tonnes/km^2/year. The largest yield occurred in 2001, the second largest in 1995, both associated with large rainfall events. The lowest yields occurred during the 1992 to 1994 period. The sediment yield calculated by SedRate (which used the same data plus that collected from 2004 to 2006) was 140 tonnes/km^2/year.

The study found a significant relationship between suspended sediment yield and peak discharge but found that "…no clear relationship emerged between sediment yield and forestry activities". However the authors stressed that there were several factors that may have 'clouded' a relationship, including the patchy nature of rainfall and forest harvesting and the lack of good quality sediment yield data from before catchment harvesting began.[66]

Harbour sediments study

A study undertaken by Max Gibbs (NIWA) attempted to determine the most likely sources of soil from the catchment in the estuary area. Soil particles contain specific compounds that act as naturally occurring markers. Using a technique called

[64] Quinn, (Environment court evidence, 2005).
[65] Hamilton, 2003.
[66] Wild and Hicks, 2005.

‘compound specific stable isotopic analysis’, the source of soil and relative proportion of each soil source can be established.

Seven sites, some located on the estuarine flats (sites H0, H1, H2 and H3) and some on the estuarine arms (sites HE1, HE2 and HE3), were used for analysis. The diagram below shows the relative proportions of each soil source (areas covered in pasture, exotic pine and native forest) found at each site. At the sites on the estuarine flats, a proportion of the sample could be traced back to areas covered in seagrass. Exotic pine plantations were found to contribute a substantial amount of sediment to most areas of the estuary.

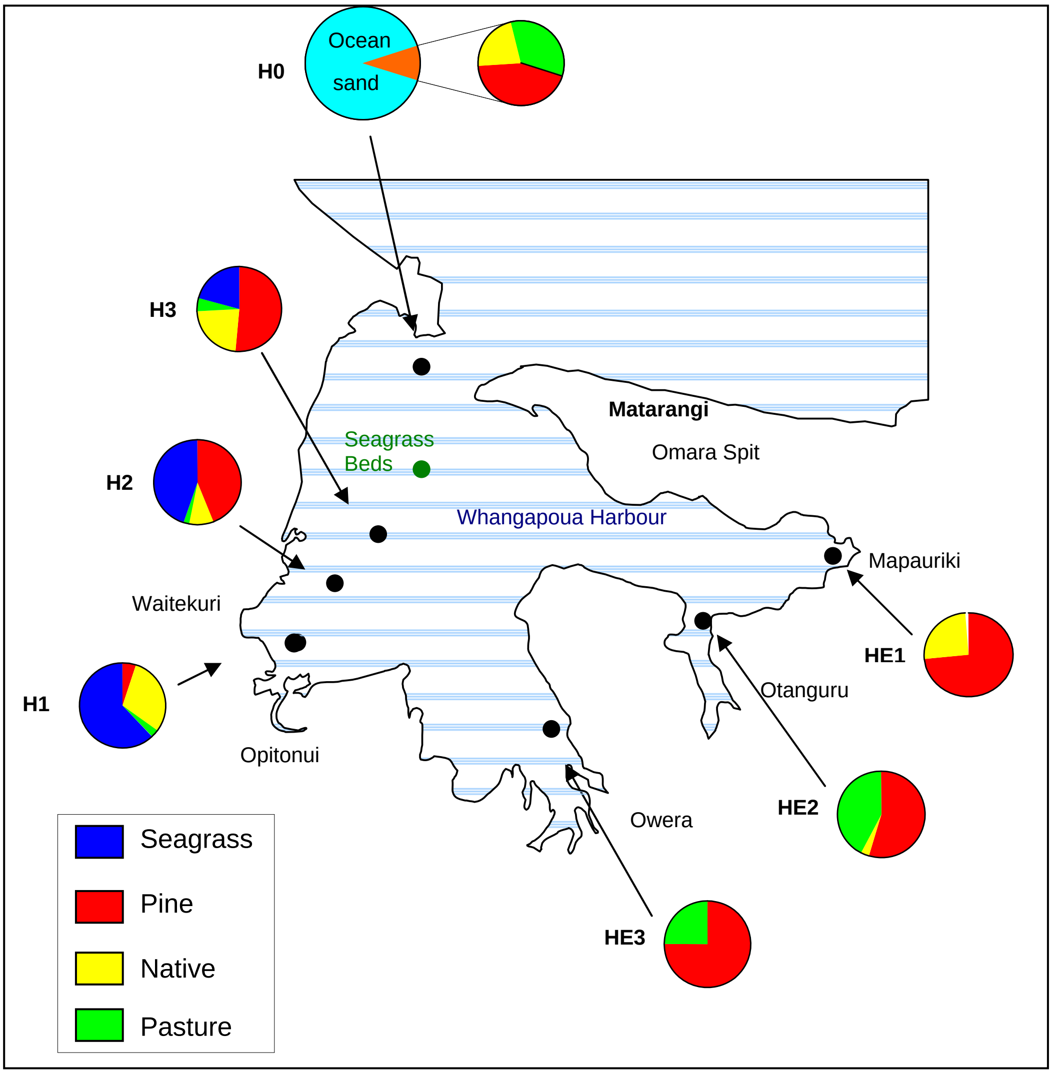

Figure 12: Sources of sediment at seven sites in Whangapoua Harbour *(After Gibbs, 2006)* N.B. Site H0 is located at the harbour mouth and the sediment sample was mostly of a marine source. Of the catchment derived sediment, the relative proportions of the different sources are given.

Forest harvesting occurred mainly in the Owera and Opitonui catchments prior to the sediment source study. The high proportion of sediment from pine forest observed in the Mapauriki arm (where no forest harvesting had occurred), likely reflects the ability of tidal and wind driven currents to move sediment around the estuary.

The effects of sedimentation in this estuary are likely to be two-fold. There is infilling from deposition of coarser terrestrial sediments (sands and gravels) mobilised during storm events, and detrimental effects of transitory deposition of fine sediment on plant and animal communities.

The sediment study concluded that fine clays, responsible for smothering seagrass beds and benthic animals after flood events, such as the March 1995 storm, are moved out of the estuary by wave and tidal action. Therefore, there may be adverse effects of sedimentation occurring in Whangapoua Harbour, without an apparent increase in fine sediments. Flood events, which occur regularly on the Coromandel Peninsula, deposit a layer of fine clays over the seabed. This may damage the plant and animal communities, but then wave and tidal action disperse the sediment and carry it out of the estuary.

Once the sediment is carried out of the estuary it may also have an effect on coastal communities. The review of 15 years of monitoring in Whangapoua Harbour stated that horse mussels (*Atrina zelandica*) had been observed growing, but practically buried in sediment, on the seaward side of the harbour entrance.[67]

Sources and delivery of sediment into Whangapoua Harbour

It is thought that the erosion process responsible for the greatest amount of sediment reaching the estuary is landsliding.

In recent research, sediment generation was measured over a 2 year post harvest period in a 36 ha catchment in Whangapoua Forest. It was found that of sediment generated by landsliding, soil scraping (by logs during harvesting) and slopewash, 88 per cent remained on slope (that is, the great majority of sediment did not enter the river system). Of the 12 per cent that did enter the river system, 72 per cent was produced by landsliding, 26 per cent by soil scraping, and 2 per cent by slopewash. This study concluded that little can be done to manage the prevention of landslides apart from identifying those areas most at risk (for example, very steep slopes) and considering their exclusion from commercial forest use.[68]

In large storm events, large amounts of sediment can be generated that will dominate deposits in estuaries. A study conducted in Whangapoua following a storm in 1995 concluded that 51 per cent of total storm sediment production was from native forest, 38 per cent from land administered by Ernslaw One (production forestry) and 12 per cent from private holdings.[69]

Sediment fingerprinting

Whangapoua Harbour sediment sources are the focus of doctoral research by Brendan Roddy (University of Waikato). The purpose of the research is to fingerprint sediment samples from the estuary by sampling source areas in the catchment by land use. Soil samples will be analysed for trace elements by X-Ray fluorescence, ICP mass spectrometer, and radionuclide analysis.

The aims are to determine the:

- relative importance of land use (native forest, exotic forest, agriculture) on sediment generation;
- processes (surface, subsurface, streambank erosion) generating the sediment;
- relative effects of soil type and slope on sediment generation.[70]

[67] Halliday *et al*, 2006.
[68] Marden *et al*, 2006.
[69] Marden and Rowan, 1995.
[70] Roddy, 2007.

Summary

Whangapoua Harbour

Conclusions

- Whangapoua Harbour has been the focus of a great number of studies. The estuary has a large tidal prism relative to catchment area and so will most likely flush out some sediment, especially fine mud. However, even transitory deposition of sediment can impact on the benthic communities.
- Land use in the Whangapoua catchment is predominantly exotic forest (54 per cent). Native forest and pasture account for 20 per cent and 17 per cent, respectively.
- Sediment core analysis has estimated pre-human settlement sedimentation rates at 0.03 to 0.08 mm/year and post-European settlement sedimentation rates at 0.89 to 1.5 mm/year. This represents a 10 to 30 fold increase.
- There is evidence to suggest sedimentation is having an adverse effect on benthic plant and animal communities. The knock-on effect on predator species is of concern but is largely unknown. The results from long-term monitoring show a correlation between forestry harvesting and the decline in plant and animal species sensitive to sedimentation.
- Mangrove cover in the estuary has more than doubled, and seagrass cover more than halved, over the past 50 years.
- The harbour sediment study indicates that exotic pine plantations have contributed a large amount of sediment to certain parts of the estuary. Further information on the relative importance of sediment sources may be provided by Brendan Roddy's research over the next few years.

Information gaps

- The sediment core study was conducted in 1992 and there may be a need for a more recent assessment of sedimentation rates, using the newer techniques available.

Further research

- It is hoped that research by Brendan Roddy will help to determine the relative importance of land use on sediment generation.

Whangamata Harbour

Figure 13: Whangamata Harbour *(Digital photographic imagery sourced from Terralink International Limited, 2002. COPYRIGHT RESERVED).*

Whangamata Harbour is 4.4 km^2 in area, 90 per cent of which is intertidal. Planting of exotic pine forests began in the late 1920s. Whangamata Harbour catchment covers an area of 52 km^2, the major land cover being plantation forest. Unlike other areas of the Coromandel (where widespread deforestation began in the mid 1800s) the Whangamata catchment was not deforested and converted to pasture until the 1900s/1910s.

Table 13: Land cover in the Whangamata Harbour catchment (from the Land Cover Database II).

Land cover	Area (ha)	Percentage of Whangamata catchment
Indigenous forest	1557	30.1
Planted forest	2207	42.7
Primarily pastoral	590	11.4
Scrub	425	8.2
Urban	318	6.1
Other	76	1.5

Sediment core studies

There have been two studies undertaken in Whangamata Harbour that attempt to determine sedimentation history by analysis of sediment cores.

Study no. 1: Sheffield et al, 1995

This study suggested that sedimentation rates in Whangamata Harbour have increased from 0.1 mm/year in pre-Polynesian times, to 0.3 mm/year after, the increase attributed to Polynesian agricultural practices. After the 1880s and associated European clearance of the catchment and later development and felling of production forestry, sedimentation rates increased to about 11 mm/year. A core taken adjacent to the causeway (on the Moanaanuanu arm), suggested that the sedimentation rate increased from 2 mm/year (1920s to the 1970s) to 15 mm/year (1970s to 1980s). The causeway was constructed in 1976.[71]

Bioturbation (the mixing of sediment layers by benthic animals) may have had an effect on the accuracy of the measurements. It is likely that the deposition rates near the causeway are not representative of the whole estuary, but are a result of the influence the causeway had on sediment deposition in that area.

Study no. 2: NIWA
A comprehensive investigation was conducted by NIWA, which used a variety of methods to determine sedimentation history including:

- probing
- sediment thickness
- sampling surface sediments
- analysis of aerial photographs
- analysis of sediment composition
- radiocarbon and pollen dating of sediment cores
- an assessment of the ability of tidal and wave currents to flush sediment from the estuary.

This study concluded:

> "*Rapid sedimentation of the Whangamata Estuary is a relatively recent phenomenon*."

It was found that pre-settlement (undisturbed forest) sedimentation rates were between 0.10 and 0.18 mm/year. The higher end of this range of values was for the upper and middle reaches of the estuary, indicating slightly elevated sedimentation rates in these areas. Polynesian (700 years B.P.) and early European (1880 until 1920) eras were largely absent from the sediment cores, suggesting sediment deposition during these periods was negligible. Widespread clearing of native forest did not occur until the early 1900s. Establishment of exotic pine forest commenced in the late 1920s on the western margins of Whangamata estuary (some of these stands are now in their third rotation), and later exotic reforestation commenced on the eastern margins of the estuary.

The late European sedimentation rate (1940s until present) was found to be 5 mm/year, that is, thirty times the pre-settlement sedimentation rate. The sediment has coarsened when compared with earlier layers, which is a trend associated with land cover change and indicates that the sediment is catchment derived.

From the sediment core data it was calculated that 0.732×10^6 tonnes of sediment have been deposited on the intertidal flats since the 1940s. This is equivalent to a rate of 14,622 tonnes/year or 664 tonnes/km^2/year.[72] In this case the calculation of sediment accumulation was specific to the intertidal flats of the upper and middle estuary (catchment area 22 km^2), affected by forested catchments and commercial forestry operations. It is interesting to note that this estimate is nearly three times greater than the annual sediment yield calculated for the total Whangamata catchment (52 km^2) using the Hicks and Shankar model. This may indicate that the Hicks and Shankar model sensitivity in this case may not be sufficient to identify the effects of deforestation under a commercial forestry regime, resulting in significant underestimation of sediment due to commercial forestry activities.

Tidal current analysis showed that the intertidal flats are depositional environments, with a high potential for future rapid sedimentation. However, there appears to be

[71] Sheffield *et al*, 1995
[72] Swales and Hume, 1994

generation of sufficient wave action to remove fine muddy sediment from most of these areas, indicating that the sediment deposition values are, in fact, also likely to be underestimates. In the upper reaches of the estuary tidal and wave currents are weak and fine mud will be deposited. Aerial photography and core data suggest the lower estuary is dominated by flood tide delivered marine sediments.[73]

Table 14: Comparison of sediment export estimates for the Whangamata catchment.

Method	***Calculated for 52 km² Whangamata catchment***	
	Catchment sediment yield (tonnes/year)	**Specific sediment yield (tonnes/km²/year)**
Environment Waikato flow and sediment data (using SedRate)	No data	No data
Hicks and Shankar (NIWA) model	5,048.8	97.7
Method	***Calculated for 22km² sub-catchment (draining to upper-middle estuary)***	
	Mean annual deposition (tonnes/year)	**Specific mean annual deposition (tonnes/km²/year)**
Swales and Hume (NIWA) core data	14,622	664

Estuarine vegetation

Mangrove expansion is confined to the upper and middle reaches of the estuary. Sedimentation raises the intertidal flat level, allowing mangroves to become established. Mangrove and seagrass coverage was documented in Turner and Riddle (2001). The 10 ha decrease in mangroves between 1995 and 2007 is partly because of mangrove clearance of at least 3.4 ha.

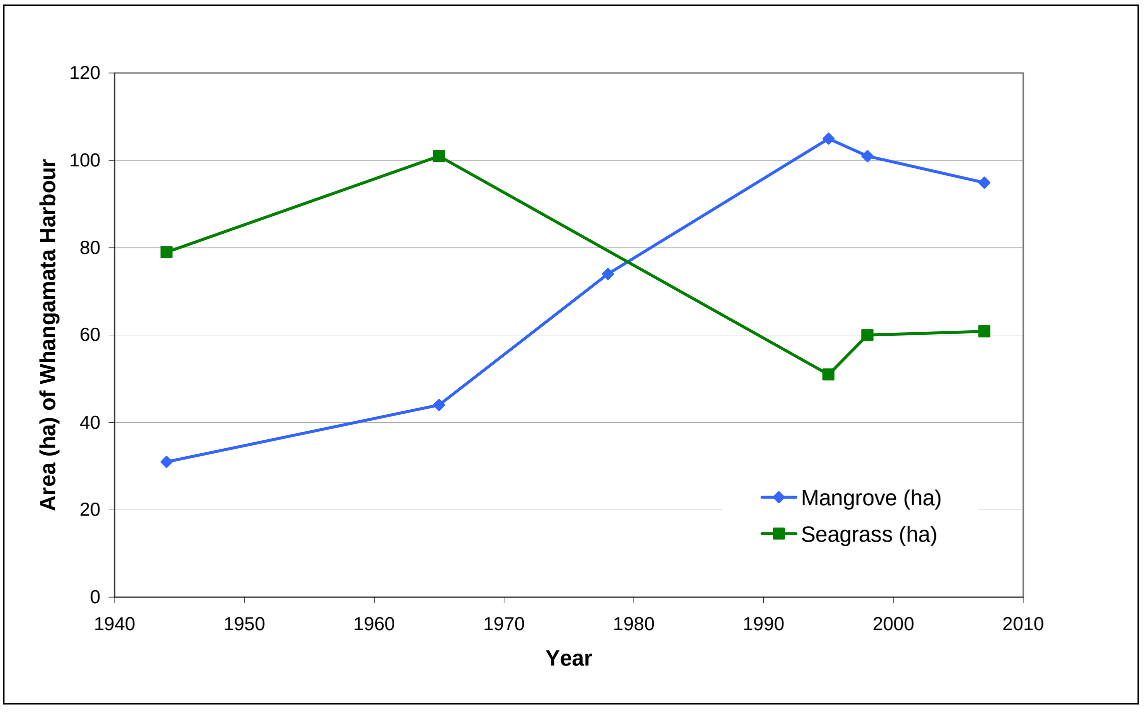

Figure 14: Change in extent of mangrove and seagrass in Whangamata Harbour from 1944 until 2007.[74 75]

[73] Swales and Hume, 1994.
[74] Turner and Riddle, 2001.
[75] EW, GIS analysis, 2007.

Summary
Whangamata Harbour

Conclusions

- Whangamata Harbour catchment consists of 43 per cent plantation forest, 30 per cent native forest and 11 per cent pasture.
- The sediment core study estimated that pre-European settlement sedimentation rates were in the range of 0.10 to 0.18 mm/year in Whangamata Harbour. From the 1940s until present the average sedimentation rate has been estimated at 5 mm/year but may be as high as 15 mm/year in some areas of the estuary, such as near the Moanaanuanu causeway. Rates of deposition are expected to be higher in sheltered areas of the estuary, such as near the causeway.
- There has also been a rapid expansion of mangrove and a decline in seagrass around the same time as the rise in sedimentation rates. Mangrove coverage has tripled and seagrass almost halved in the estuary over the last 50 years.
- The estimate for sediment yield from the Hicks and Shankar model (5048 tonnes/year – for the entire 52 km^2 catchment) is much lower than the estimate for sediment deposition (14,622 tonnes/year – for *just* the 22 km^2 sub-catchment). The sediment deposited has been identified as catchment derived.

Further research

- Estimate recent sedimentation rates and refine current estimates for historical rates using new sediment core techniques.

Wharekawa Harbour

Figure 15: **Wharekawa Harbour** *(Digital photographic imagery sourced from Terralink International Limited, 2002. COPYRIGHT RESERVED).*

Wharekawa Harbour is a small estuary, almost completely enclosed at the harbour mouth by the Opoutere sand spit and a rocky headland.

As with other estuaries in the Coromandel, the steep slopes, highly erodible soils and high intensity rainfall events predispose the estuary to infilling. This is amplified in

Wharekawa Harbour by a large catchment size (92 km^2) relative to a small estuary area (1.9 km^2) and a weak tidal regime.[76]

Table 15: Land cover in Wharekawa Harbour catchment, (from the Land Cover Database II).

Land cover	Area (ha)	Percentage of Wharekawa catchment
Indigenous forest	2932	31.8
Planted forest	4582	49.7
Primarily pastoral	1119	12.1
Scrub	467	5.1
Urban	14	0.2
Other	100	1.1

Before European settlement, the catchment would have been covered in dense native forest. In the 1880s widespread catchment deforestation began and by the mid-1890s much of the catchment had been logged. The logs were transported to the coast along rivers, which would have had a significant impact on sediment generation and transport. As well as eroding the river channels, the damming and subsequent release of water in trip dams would have created conditions similar to frequent, high intensity flooding.

Exotic forest was established in the 1930s and harvesting commenced in the mid-1970s. Skyline harvesting techniques (designed to minimise soil disturbance and sediment generation) were introduced in the early 1980s.

Sediment core studies

As for Whangamata Harbour, NIWA conducted a comprehensive investigation (methodology as described in the Whangamata case study) into the sedimentation history of Wharekawa Harbour.

It was found that the sedimentation rate pre-European settlement (when the catchment cover was native bush) was about 0.1 mm/year. From 1880 to 1945 (the period during and immediately following catchment deforestation) the sedimentation rate was in the range 3.6 to 7.2 mm/year. From 1945 to present the sedimentation rate was on average 5 to 8 mm/year. However, in the vicinity of the Wharekawa River mouth, the sedimentation rate was found to be as high as 20 mm/year.

The cores show a gradient in sedimentation rates, decreasing towards the estuary mouth. This implies that it is catchment derived sediment that is responsible for the infilling of the estuary. However, recently (within last 20 years) fluvial sediments have begun to be deposited in the lower estuary, which combined with the infilling of the lower estuary by marine sands (evident from flood tidal deltas), will reduce the tidal prism and increase the likelihood of inlet closure.[77]

Core analysis indicates that, on average, 28 cm of sediment has been deposited in Wharekawa Harbour (landwards of the flood tidal delta, and representing a catchment area of 66.5 km^2) in the previous 50 years. This equates to sediment deposition of between 183 and 252 tonnes/km^2/year. This value can be compared with other estimates of sediment yield that we have for Wharekawa Harbour. As with the data for Whangamata Harbour, the estimates of sediment yield are substantially less than those for sediment deposition.

[76] Bouma, 2007.
[77] Swales and Hume, 1995.

Table 16: Comparison of sediment export estimates for the Wharekawa catchment.

Method	*Calculated for 92 km² Wharekawa catchment*	
	Catchment sediment yield (tonnes/year)	**Specific sediment yield (tonnes/km²/year)**
Environment Waikato flow and sediment data (using SedRate)	5,000.0	60
Hicks and Shankar (NIWA) model	8,928.2	96.9
Method	*Calculated for 66.5 km² sub-catchment*	
	Mean annual deposition (tonnes/year)	**Specific mean annual deposition (tonnes/km²/year)**
Swales and Hume (NIWA) core data	12,000 – 17,000	183 – 252

The surface sediments in the estuary are mainly of medium to coarse sand, but around the Wharekawa River mouth there are significant quantities of coarser catchment derived sands and gravels. Fine, muddy sediments are limited to mangrove areas. The mangroves reduce current velocities, which allows for the deposition of these fine suspended sediments. Elsewhere, fine sediment is transported away and out of the estuary. This is supported by the lack of muddy sediment in the sediment cores.

Aerial photographs, taken in 1944 and 1993, show that the area of intertidal flats in the upper estuary now colonised by mangroves has increased considerably.[78] In 1983 the extent of mangrove was reported as being 20 ha.[79] From aerial photography, mangrove extent was estimated to be 49 ha in 1995, suggesting that mangrove area more than doubled in just over a decade.[80] Environment Waikato is planning to map the estuarine vegetation again in 2007/08.

Seabed level monitoring and biological monitoring

As part of the requirements to meet their forestry consent conditions, Rayonier (and formerly Carter Holt Harvey) monitor Wharekawa Harbour. The monitoring includes seabed level and biology and has been carried out by Bioresearches on a yearly basis since 1997.

Between May 1997 and April 2006 overall seabed levels rose by 37.3 mm. This equates to a sedimentation rate of 4.1 mm/year. The majority of the sediment entered the estuary in the year preceding April 1999 and the year preceding April 2006. The seabed level data suggest that between April 2001 and April 2004 more sediment left the estuary than entered the estuary. However, it appears from the report that the seabed level data has been averaged over transects incorporating both channels and intertidal flats. This may not accurately reflect the actual sedimentation rate on the intertidal flat because channels are often sites of scouring; the intertidal flats are sites of sediment deposition.

Forest harvesting in the Wharekawa catchment occurred in 1997-1999 and 2003-2006. For the four main catchments that drain into Wharekawa Harbour (Wharekawa River, Tawatawa Stream, Kapakapa Stream and Wahitapu Stream), there was no statistically significant correlation between harvesting and sedimentation for the same time period, or for catchments harvested one year prior to seabed level change. A significant

[78] Swales and Hume, 1995.
[79] Graeme, 1998.
[80] Extent of Coastal Habitats Indicator, Environment Waikato website.

positive correlation was found between forest harvesting for the entire Wharekawa Harbour catchment and seabed level change in the lower estuary (that is, that closest to the sea). However, there was no analysis done to test the correlation between sedimentation and catchments harvested 3-6 years previous, which is the generally accepted period of maximum possible erosion.[81]

There is also evidence that individual storm events are largely driving sedimentation in Wharekawa Harbour. Deposits of large amounts of fine sediment were observed following a flood in April 2006.[82]

Biological monitoring shows that the abundance of mud snails (*Amphibola crenata*) in Wharekawa Harbour has decreased since 1997, and that the abundance of cockles has also declined at five of the seven monitoring stations. At several sites in the estuary, seagrass percentage cover has shown a significant decrease since 1997. The monitoring programme has been in place for 9 years and subjecting the data to statistical analysis would help determine whether the changes observed show clear trends.

Sources of sediments

Similar to the Whangapoua Harbour sediment sources study, Environment Waikato contracted NIWA to determine the sources of soil, by land use and by sub-catchment, deposited in Wharekawa Harbour.

Results indicate that contributions from pine ranged from 1 to 23 per cent, pasture from <1 to 10 per cent, native forest from <1 to 3 per cent and slip <1 to 13 per cent. It was found that silt (flood material) contributed high proportions (29 to 95 per cent) of the estuary sediments. In the mid to upper-estuary, sediment contributions are gradually burying older sediments and seagrass beds, and were found to have come mostly from the Wharekawa River sub-catchment.

The results of this study draw attention to the impacts of extreme weather events, the severity and frequency of which have been increasing in recent years. The practice of removing vegetation on steep land will worsen sediment production during extreme weather events and long after such an event has occurred, material deposited in river channels may continue to be discharged into the estuary.[83]

[81] O'Loughlin, 1985 and Watson *et al.*, 1999.
[82] West, 2006.
[83] Gibbs and Bremner 2007.

Summary
Wharekawa Harbour

Conclusions

- Wharekawa Harbour is very shallow (90 per cent is intertidal). The sedimentation rate has increased from 0.1 mm/year pre-European settlement to between 5 and 8 mm/year (1945 to 1995), thought to be a result of sediment input from the catchment.
- Land use in the catchment is 50 per cent exotic forest, 32 per cent native forest and 12 per cent pasture.
- The seabed level monitoring carried out over the last decade gives us an indication of present day sedimentation rates (4.1 mm/year), which suggests that sedimentation has decreased slightly in recent years. However, it is still forty times that of pre-European sedimentation rates.
- As in the other case study estuaries in this report, rapid mangrove expansion has occurred in Wharekawa Harbour.
- The estimates for sediment yield (SedRate and Hicks and Shankar model: 60 and 96.9 tonnes/km^2/year, respectively) are much lower than those for sediment deposition (sediment cores: 183 to 252 tonnes/km^2/year).
- The sediment sources study indicates that high proportions (29 to 95 per cent) of the estuary sediment is silt (flood material).
- The future of the estuary depends on the ability of tidal and wave driven currents to flush catchment derived sediment out of the estuary, as well as good land management practices to limit the amount of sediment generated in the catchment.

Information gaps

- Measurement of mangrove coverage is sparse (limited to two occasions in 1983 and 1995).

Further research

- A sediment core study using newer techniques should be considered, as it might be possible for these methods to pick up stable periods of catchment land use (such as the 30 year period after initial forest plantings and before the first harvesting) and assign a sediment yield/sedimentation rate to those eras. These could then be compared with other periods of time, especially those when the catchment was undergoing change. However, uncertainty over the storage time of sediment in streams may limit this study to some extent.
- Estuarine vegetation will be mapped in 2007/08.

Whitianga Harbour

Figure 16: Whitianga Harbour *(Digital photographic imagery sourced from Terralink International Limited, 2002. COPYRIGHT RESERVED).*

Whitianga is the largest harbour on the Coromandel Peninsula (12.9 km^2). The surrounding catchment (433 km^2) has both hilly and steep terrain.[84] Behind a narrow entrance, the estuary consists of a series of sheltered inlets and bays, and is recognised to have very high landscape and wildlife values. The most prominent man-made structures within the harbour are a recent canal housing development, and the Whitianga marina.

Table 17: Land cover in Whitianga Harbour catchment (from the Land Cover Database II).

Land cover	Area (ha)	Percentage of Whitianga catchment
Indigenous forest	19095	44.1
Planted forest	3076	7.1
Primarily pastoral	9297	21.5
Scrub	11180	25.8
Urban	284	0.7
Other	332	0.8

Estuarine vegetation

Mangrove forests cover a large proportion of the estuary, and some areas contain trees as tall as 8 metres. Large seagrass beds are not found in the main estuary basin but can be found in side-arms of the estuary. Farmland has been extended into the estuary (at the expense of saltmarsh habitat) on low-lying areas around river mouths. Distribution of the invasive weed *Paspalum* is patchy, but it is present in some areas, such as the Waiwawa River mouth.[85]

[84] Miller, 1987.
[85] Graeme, 1999.

From aerial photo analysis [86] it is evident that the coverage of mangroves has changed little between 1944 and 2003. What has changed however is the density of mangrove vegetation, with roughly half of the 4.6 km^2 mangrove habitat only sparsely covered in 1944, whereas over 90 per cent of the 5.3 km^2 of mangrove habitat measured in 2003 is densely vegetated.

A baseline survey undertaken in 1985 found that seagrass covered 11 ha of the estuary, and rush meadow 69 ha.[87] From a study of aerial photographs taken in 1995, it was estimated that seagrass coverage had fallen to 5 ha.[88] This study also measured mangrove coverage (Figure 17), with results similar to those reported by Reeve (2008). It is expected that the estuarine vegetation will be mapped again in 2007/08 by Environment Waikato.

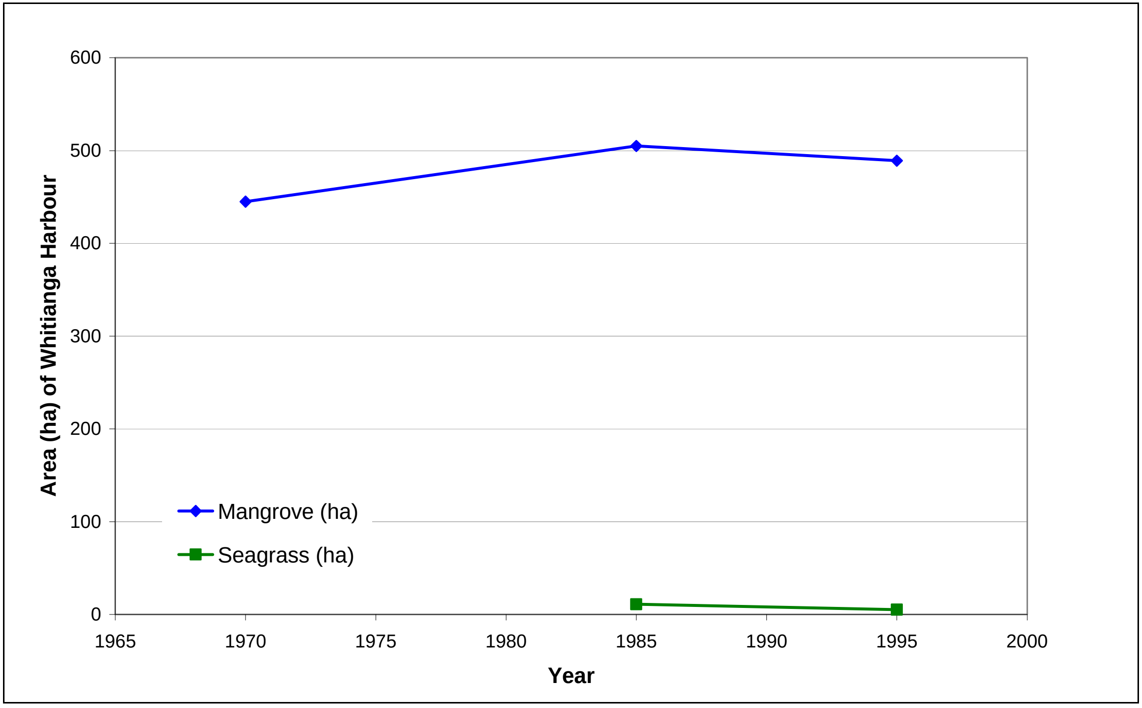

Figure 17: Change in extent of mangrove and seagrass in Whitianga Harbour from 1970 until 1995.

Estuarine fauna

To meet the requirements of consent conditions Whitianga Waterways commissioned Bioresearches to undertake annual biological monitoring in Whitianga Harbour from October 2001. The monitoring was undertaken to determine if there were any adverse effects of the canal development. Between October 2001 and October 2006 the abundance of cockles has declined significantly at some sites and has increased at other sites.

The threatened reef heron has been observed in the canal system and several bird species were recorded using the estuary and canal system at low tide.

Sediment grain size

In 2006 the total silt and clay content of the estuary monitoring sites was between 1.3 and 39.3 per cent (Table 18).[89] The data shows fluctuation over time, with some sites showing increases in sediment silt and clay content and one site showing a decrease.

[86] Reeve, 2008.
[87] Miller, 1987.
[88] Extent of Coastal Habitats Indicator, Environment Waikato website.
[89] Bioresearches, 2007.

Sedimentation rates

A recent postgraduate study has provided sedimentation rates at depositional zones within the harbour.[86] Sediment cores were collected in four arms of the estuary, and ^{210}Pb dating undertaken. Results suggest that recent sedimentation rates ranged from 4.9 mm/year to 9.6 mm/year. This is considerably lower than the 21.6 – 31 mm/year determined for the underlying sediments, which was related to earlier deforestation effects (pre-1960).

Table 18: Whitianga Harbour sediment silt and clay content, 2002 to 2006 (from Bioresearches, 2007).

Site	Year	Silt and clay (%)
E2	2002	6.5
	2004	12.3
	2006	7.52
E3	2002	15.1
	2004	16.6
	2006	17.73
E4	2002	2.7
	2004	0.8
	2006	1.26
E5	2002	14.2
	2004	67.2
	2006	39.28

Sediment yield estimates

The table below shows the two estimates of sediment yield for Whitianga catchment. The Hicks and Shankar model is nearly double that of SedRate. The SedRate estimate is approximate; it was based on a small data set (31 samples, compared with 1157 samples for Whangapoua).

Table 18: Comparison of sediment export estimates for Whitianga catchment using SedRate and the Hicks and Shankar (2003) model.

Method	Catchment sediment yield (tonnes/year)	Specific sediment yield (tonnes/km^2/year)
Environment Waikato flow and sediment data (using SedRate)	15,000.0	36
Hicks and Shankar (NIWA) model	29,987.7	69.3

Summary

Whitianga Harbour

Conclusions

- Out of the five estuaries studied in this report Whitianga Harbour catchment contains the least percentage of plantation forest (7 per cent). Forty-four per cent of the catchment is in native forest, 22 per cent pasture and 26 per cent is native scrub.

- Mangrove expansion has occurred in Whitianga Harbour, but not to the extent observed in other estuaries in the Coromandel (44 hectares increase from 1940s to 1995 in Whitianga, a very large estuary, compared to for example, >70 ha increase over the same time period in Whangamata, a much smaller estuary). The specific sediment yield estimates (from SedRate and the NIWA model) are the lowest (36 tonnes/km^2/year) and second lowest (69.3 tonnes/km^2/year) values from the five case study estuaries covered in this report. Although, the sediment estimates should be treated with caution, it does suggest that there is relatively less sediment generated in the Whitianga catchment than in the other four estuaries.

- ^{210}Pb dating results suggest recent sedimentation in the arms of the estuary range from 5 to almost 10 mm/year whereas sedimentation rates prior to the 1960s were up to 30 mm/year.

Harbour and catchment comparison

Table 19: **Available information on the five case study estuaries and their catchments.**

<table>
<tr><th colspan="3"></th><th>Tairua Harbour</th><th>Whangapoua Harbour</th><th>Whangamata Harbour</th><th>Wharekawa Harbour</th><th>Whitianga Harbour</th></tr>
<tr><td rowspan="5">Land use (% of catchment)</td><td colspan="2">Indigenous forest</td><td>46.4</td><td>20.2</td><td>30.1</td><td>31.8</td><td>44.1</td></tr>
<tr><td colspan="2">Plantation forest</td><td>15.2</td><td>54.0</td><td>42.7</td><td>49.7</td><td>7.1</td></tr>
<tr><td colspan="2">Primarily pastoral</td><td>14.7</td><td>16.7</td><td>11.4</td><td>12.1</td><td>21.5</td></tr>
<tr><td colspan="2">Scrub</td><td>21.2</td><td>7.1</td><td>8.2</td><td>5.1</td><td>25.8</td></tr>
<tr><td colspan="2">Urban</td><td>1.0</td><td>0.4</td><td>6.1</td><td>0.2</td><td>0.7</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td colspan="3">Harbour area (km^2)</td><td>6</td><td>10.8</td><td>4.4</td><td>1.9</td><td>12.9</td></tr>
<tr><td colspan="3">Catchment area (km^2)</td><td>282</td><td>107</td><td>52</td><td>92</td><td>433</td></tr>
<tr><td colspan="3">Tidal prism (million m^3)</td><td>5.02</td><td>8.5</td><td>3.9</td><td>3.1</td><td>12.6</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td rowspan="3">Sediment yield estimates (t/km^2/year)</td><td colspan="2">Stream measurements (SedRate)</td><td>150</td><td>140</td><td>-</td><td>60</td><td>36</td></tr>
<tr><td colspan="2">Model (Hicks and Shankar, 2003)</td><td>80.7</td><td>58.8</td><td>97.7</td><td>96.9</td><td>69.3</td></tr>
<tr><td colspan="2">Sediment cores</td><td>-</td><td>-</td><td>664</td><td>183 - 252</td><td>-</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td rowspan="4">Sediment deposition estimates
(mm/year)</td><td rowspan="4">Sediment cores and marker bed study</td><td>Pre-settlement</td><td>-</td><td>0.03 - 0.08</td><td>0.10 - 0.18</td><td>0.1</td><td>-</td></tr>
<tr><td>1880 - 1945</td><td>-</td><td rowspan="3">0.9 - 1.5</td><td>-</td><td>3.6 - 7.2</td><td>-</td></tr>
<tr><td>1933 - 1984</td><td>6</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>1945 - present</td><td>-</td><td>5</td><td>5 - 8</td><td>-</td></tr>
</table>

N.B. Tidal prism figures from Hicks and Hume (1996), Hume and Herdendorf (1993), and Hume and Herdendorf (1992).

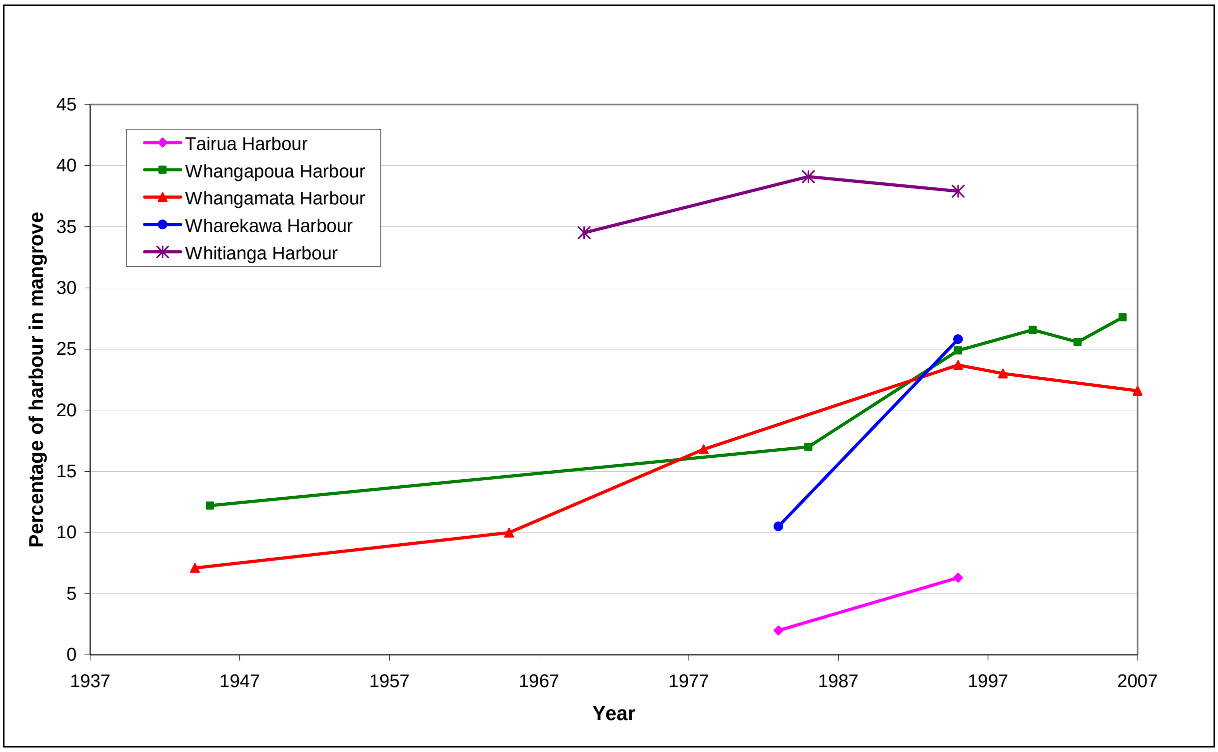

Figure 18: Change in percentage cover of mangrove over time (1944-2007) in Tairua, Whangapoua, Whangamata, Wharekawa and Whitianga harbours.

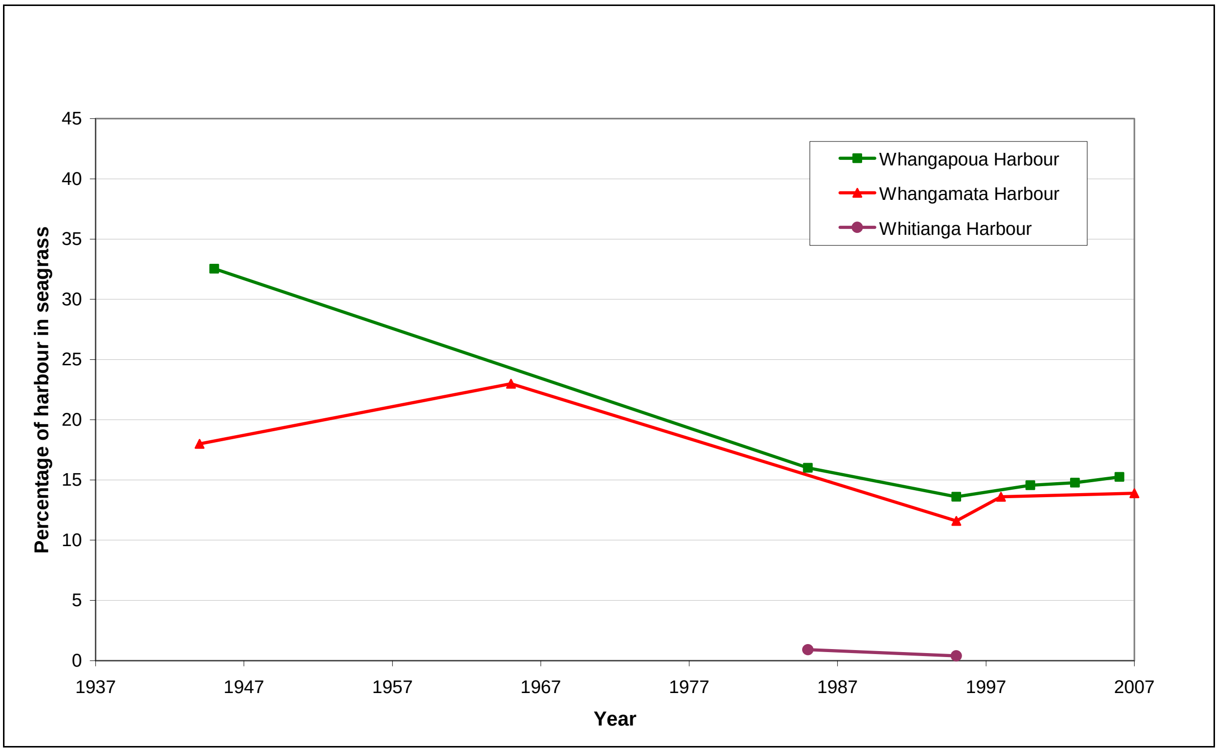

Figure 19: Change in percentage cover of seagrass over time (1944-2007) in Whangapoua, Whangamata and Whitianga harbours.

Conclusions

The estuaries reported on here were created when river valleys were inundated by sea level rise about 6500 years ago. Since that time sediment, eroded from the catchments, has been gradually infilling the estuaries. The narrow harbour entrances, sand spits and hydrodynamic regimes ensure that sediment is mostly retained within the estuaries. Therefore, there is a natural progression towards infilling.

The current rate of sedimentation observed in many Coromandel estuaries (approximately 5 mm/year) is much greater than the current rate of sea level rise (1.6 to 1.8 mm/year). However, it is predicted that sea level rise will increase to between 4 and 6 mm/year. Therefore, there is the potential for sea level rise to offset some of the effects of sedimentation (Vernon Pickett, Environment Waikato, personal communication).[90]

Sedimentation and erosion

Slopes in the Coromandel are very prone to erosion and therefore the estuaries of the Coromandel are prone to sedimentation. This sedimentation has very likely been accelerated by land use change. The large scale land clearance that occurred in the 10 to 30 years after European settlement very likely initiated erosion that resulted in some infilling of east coast Coromandel estuaries. Rates of sedimentation obtained from sediment core studies suggest that pre-settlement sedimentation rates were around 0.1–0.2 mm/year and post settlement sedimentation rates rose to between 1 and 8 mm/year.

Studies elsewhere in New Zealand have linked large scale deforestation with sedimentation in estuaries.

- Nichol *et al* (2000) reported that land clearance following European settlement caused an acceleration of the natural process of estuary infilling in Whangape Harbour, Northland, and that mass movement (landsliding) represented a major source of sediment to the estuary.

- Recent work by Swales *et al*. (2007) has reported that following catchment deforestation and river engineering works (occurring 1850s to 1920s), the southern Firth of Thames and lower Waihou River received a mud influx, (approximately 44 million m^3). This initiated a sequence of large scale environmental changes, including rapid mangrove expansion that began in the 1950s. The sediment accumulation rate in the Firth of Thames has averaged approximately 20 mm/year on the bare mudflats over the past 50 years. Rates on the mangrove forest fringe have averaged 50-100 mm/year.

In the estuaries studied in this report there is an apparent discrepancy between the calculations of sediment delivery (sedimentation rates obtained by sediment core studies and the marker bed study) and sediment yield (obtained from direct measurement of suspended sediment in streams and models). Several hypotheses can be made as to the cause(s) of the discrepancy. For example, bed-load (possibly as large 'slugs' of material delivered during storm events) may contribute significant amounts of sediment to estuaries. This load would be undetected by the SedRate measurements and Hicks and Shankar modelled sediment yields which measure suspended sediment only. Also, it may be that sediment yields vary greatly across the catchment (invalidating the assumption that measurements from one stream are sufficient to calculate sediment yield for a whole estuary's catchment), perhaps related to land use effects, such as forest harvesting. A major limitation of the Hicks and Shankar model is that it does not take into account land use effects. It is important to note that the apparent discrepancy may be due to the complexity of the systems

[90] Swales and Hume, 1995.

involved. Estuaries are dynamic; the movement of sediment around, into and out of estuaries is complicated and the movement of sediment through catchments is poorly understood.

It is difficult to precisely quantify the contribution of sediment from different land uses to current sedimentation in estuaries. However, studies have indicated that production forestry has contributed a substantial amount of sediment to the estuaries in recent years.

Sediment core analysis has provided estimates of sedimentation rates that span many decades, but in order to effectively manage ongoing sedimentation, contemporary rates are needed.

It is likely that shallow landslides are the biggest source of sediment to estuaries. They occur mainly on steep land, in both native and exotic forests, and are primarily caused by the very steep slopes and intense rainfall events. Removal of the vegetative cover on these slopes further increases the risk of landsliding.

Although research has suggested that a similar magnitude of landsliding occurs in areas of native forest as in exotic pine, native forest is mainly found on very steep areas, above the pines, and is therefore associated with areas of greater landsliding risk. Landsliding most commonly occurs on slopes greater than 25°.

It is generally accepted that soils under mature exotic forests are no more prone to erosion than soils under native forest, but recently harvested areas do expose the soil to erosion for a period of time (probably up to 8 years). This does raise some questions.

- If the area were not clear felled the soils would likely be better protected from erosion, especially landsliding. Would selective logging be a viable option?

- What are the benefits and costs of excluding production forestry and pastoral farming from particularly vulnerable parts of the landscape?

- Could slopes that are considered a high landsliding risk (for example, over 25°) be retired from production forestry, as suggested in the Marden *et al.* (2006) paper?

Agriculture or pasture on the steep slopes of the Coromandel would generate more sediment than either exotic or native forestry and so may not be an appropriate land use in these areas. Current production forestry management practices aim to minimise erosion and some resource consent conditions require forestry companies to carry out mitigation measures.

The regeneration of native forest (as an alternative to production forest) on steep slopes may not be a viable option due to the slow growth rate of native species, (thereby exposing the slope to landsliding for longer than if the exotic production forest were harvested and replanted). However, it is possible that some areas (especially those on very steep slopes) are not suitable for production forestry harvested every 30 years. Maybe a longer rotation should be considered for certain areas to minimise harvesting impacts.

A soil conservation management strategy should also be considered, rather than solely conducting more research and monitoring in an effort to determine a culpable land use (which is likely to be highly catchment specific). It is recommended that harbour and catchment management plans are made for specific locations, where critical areas for sediment management are identified and measures put in place to control erosion and sediment entry into the river system.

Effects of sedimentation on estuarine plants and animals

The five estuaries discussed in this report have been classified as Areas of Significant Conservation Value (ASCVs). All are productive ecosystems supporting high biodiversity. Rare and threatened bird species, such as the New Zealand dotterel, are known to use the estuaries as feeding and/or breeding grounds.

Any decline or degradation of habitat will affect these communities, threatening biodiversity and productivity. Estuarine communities are adapted to cope with sedimentation, but the accelerated rate of sedimentation resulting from changes in land use is thought to have resulted in declines in species abundance and habitat degradation.

Mangrove expansion is a very real area of concern for some communities in the Coromandel. Although it should be noted that methods for estimating past mangrove extent have varied, it is clear that there has been a period of rapid mangrove expansion over the last 25 years or so in the majority of estuaries on the Coromandel Peninsula. Increased sedimentation raises the intertidal flat level, which allows mangroves to become established in areas that were once too frequently inundated by the tide. The mangroves trap fine sediment, further increasing sedimentation. Mangrove expansion has the potential to reduce the area of intertidal flat in an estuary, reducing habitat for benthic invertebrates and thereby reducing prey species for larger fauna. However, mangroves provide habitat for other species, so it is important to retain some mangroves in our estuaries. In the future, mangroves may protect the coast from the effects of predicted sea level rise.

The effects of sedimentation on estuarine communities should not be viewed in isolation. The cumulative effects of other threats (such as pollution, habitat loss through development, fishing pressure and invasive species), combined with the effects of accelerated sedimentation, could place serious pressure on those communities.

Information gaps

Key information gaps identified in this report include the following.

- The discrepancy between the estimates for sediment delivery and sediment yield produced by core studies, field measurements and computer models suggests we cannot be certain of the rate (especially the current rate) of sediment accumulation in estuaries.

- Linking the sediment that is contributing to contemporary estuary infilling with specific land uses is difficult. There is a need to measure sediment yield from different land uses, movement of that sediment into streams and the deposition of that sediment in the estuary. It is uncertain whether this is feasible.

- Data (from sediment cores) suggest that pre-European and pre-Polynesian sedimentation rates in estuaries were very low (0.1 to 0.2 mm/year) in comparison to sedimentation rates post-European settlement (1 to 8 mm/year). The sediment yield in native forest re-growth is likely to be greater than in re-planted production forest, and it is uncertain whether it would be possible to return to those pre-human settlement sedimentation rates.

- Estimates of sediment yield from plantation forest over an entire rotation require long-term monitoring and as yet result there are no studies comparing sediment yield in exotic and native forest on the same slopes and exposed to the same rainfall. Without such a study it would be hard to conclusively state that under similar conditions exotic forestry produces more, less or the same amount of sediment as native forest.

- Also uncertain is:
  - how much sediment is stored in streams and their floodplains and for how long?
  - what is the contribution of streambank erosion to the overall sediment yield from a catchment?
  - does bed-load contribute more to total sediment yield than currently thought (that is, 3–10 per cent)?

Further research

- *Sedimentation rates in estuaries*
  The sediment cores from Whangamata, Whangapoua and Wharekawa were collected over a decade ago and there are now newer, more accurate methods available. The lack of information on current sedimentation rates and variation in sediment yield estimates highlights the need to use newer sediment core methods to build up a more reliable picture of current sedimentation rates. Management of land use could be better facilitated if contemporary sedimentation rates were known.

- *Tracking sediment*
  Sediment ideally needs to be linked with land use. NIWA and the University of Waikato sediment sources/fingerprinting studies coupled with new sediment core analysis might go some way to achieving this. However, uncertainty over a number of other variables, such as amount of sediment and time spent stored in streams, amount of sediment transported as bed-load (especially in slugs of material during storm events), makes it difficult to track sediment from sources to the estuaries.

- *Impacts in estuaries*
  Although there is evidence to indicate that sedimentation is having a negative impact on estuarine communities, not much is known about the severity of the impacts. Estuarine flora and fauna are resilient, and those present in our estuaries now are likely to be adapted to sediment deposition and high concentrations of suspended solids. Estuaries integrate many different threats (for example, nutrients, sediments and contaminants), so it can be difficult to link sedimentation with ecological effects. Long-term monitoring of the extent of estuarine habitats, sediment characteristics (for example, grain size and bed height) and benthic fauna abundance and diversity, can be analysed to establish whether there is a correlation between land use changes and the effects of sedimentation.

  Investigations into the 'sedimentation carrying capacity' of estuaries could potentially be done, using predictive modelling and data from elsewhere in New Zealand. Such research would aim to identify what a sustainable level of sedimentation might be, given the ecological and hydrodynamic characteristics of an individual estuary.

  The most obvious effect of sedimentation appears to be rapid mangrove expansion. Observed to a greater or lesser degree in all east coast Coromandel, this event is likely to induce a positive feedback effect whereby an initial expansion of mangrove caused by sedimentation will induce further sedimentation and then further mangrove expansion. Recent work in the Firth of Thames determined that the extensive mangrove forest present in the southern firth has developed over the last 50 years as the result of only 4 or 5 major seedling recruitment events (that coincided with extended periods of calm weather).[91] It is possible that there may be a ‘tipping point’ associated with a rise in sedimentation rates, at which rapid mangrove expansion occurs. Knowledge of sedimentation rates within mangrove habitat of other estuaries in the Waikato region would be beneficial; as would some

[91] Swales *et al*, DRAFT.

understanding of the processes of sediment remobilisation should the mangroves be removed.

- *Soil conservation strategy*
  Critical areas for sediment management could be identified in the catchments and measures implemented to control erosion and the amount of sediment entering the river system.

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Appendix 1: Catchment land cover

Data obtained from Land Cover Database II.
(Metadata: DOCS# 933628)

Percentage of Catchment by LCDB2NAME_ORIG Vegetation Class

Note: Catchment data sourced from Request: 14933

LCDB2NAME_ORIG	Tairua Harbour	Whangamata Harbour	Whangapoua Harbour	Wharekawa Harbour	Whitianga Harbour
Bare Ground	*0.04*	*0.00*	*0.00*	*0.00*	*0.01*
Coastal Sand	*0.01*	*0.06*	*0.01*	*0.01*	*0.00*
Coastal Wetland	*0.38*	*0.31*	*1.00*	*0.66*	*0.28*
Indigenous Forest	*46.39*	*30.09*	*20.20*	*31.81*	*44.14*
Inland Water	*0.29*	*0.27*	*0.21*	*0.07*	*0.13*
Inland Wetland	*0.27*	*0.00*	*0.26*	*0.00*	*0.00*
Major Shelterbelts	*0.05*	*0.00*	*0.01*	*0.01*	*0.03*
Mines and Dumps	*0.13*	*0.22*	*0.08*	*0.03*	*0.05*
Planted Forest	*15.20*	*42.66*	*53.97*	*49.73*	*7.11*
Primarily Horticulture	*0.29*	*0.57*	*0.04*	*0.16*	*0.26*
Primarily Pastoral	*14.68*	*11.41*	*16.67*	*12.14*	*21.49*
Scrub	*21.24*	*8.22*	*7.12*	*5.07*	*25.84*
Urban Area	*0.73*	*4.88*	*0.08*	*0.15*	*0.45*
Urban Open Space	*0.31*	*1.27*	*0.29*	*0.00*	*0.20*
Willows and Poplars	*0.00*	*0.04*	*0.06*	*0.13*	*0.01*
Checksum:	**100.00**	**100.00**	**100.00**	**99.99**	**100.00**

Catchment area in hectares by LCDB2NAME_ORIG Vegetation Class

LCDB2NAME_ORIG	Tairua Harbour	Whangamata Harbour	Whangapoua Harbour	Wharekawa Harbour	Whitianga Harbour
Bare Ground	10.84	0.00	0.00	0.00	2.25
Coastal Sand	2.84	3.33	1.40	1.36	0.03
Coastal Wetland	105.98	16.00	106.13	60.87	120.78
Indigenous Forest	13108.41	1556.54	2154.04	2931.50	19094.51
Inland Water	80.63	13.79	22.33	6.16	56.73
Inland Wetland	75.56	0.00	28.11	0.00	0.00
Major Shelterbelts	14.82	0.00	1.47	1.21	12.93
Mines and Dumps	36.81	11.37	8.57	3.11	22.49
Planted Forest	4294.26	2207.06	5754.79	4582.49	3075.90
Primarily Horticulture	81.45	29.72	4.03	14.77	112.39
Primarily Pastoral	4148.16	590.47	1776.97	1118.87	9296.58
Scrub	6003.42	425.42	758.84	467.47	11180.02
Urban Area	206.16	252.46	8.10	13.86	195.96
Urban Open Space	87.77	65.46	30.58	0.00	87.92
Willows and Poplars	0.99	1.87	6.64	12.15	4.29
Checksum:	**28258.10**	**5173.49**	**10662.01**	**9213.82**	**43262.79**
GIS Catchment Area (Ha):	**28258.10**	**5173.50**	**10662.01**	**9214.42**	**43263.00**

Appendix 2: Whangamata sediment core

From Sheffield *et al* (1995): A sediment core taken adjacent to the Moanaanuanu causeway in Whangamata Harbour. Type of sediment, and pollen and shell layers are indicated.