Report prepared for Northland Regional Council.

A Review of Methods for Monitoring Estuarine Sedimentation

Prepared by:
Josephine Woods and Dr David Kennedy

School of Geography, Environment and Earth Sciences, Victoria University of Wellington, PO Box 600, Wellington

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Introduction

Estuarine environments are essentially sediment traps, and their evolution from deep embayment through to shallow estuary and onto coastal plain has been described by Roy et al. (1984). The nature of estuarine infill will vary depending on many factors; including time, sediment supply, accommodation space, tectonic and geological controls and the interaction and intensity of wave and tidal power (Hume and Herdendorf 1988; Heap and Nichol 1997). Generally a higher sedimentation rates will occur at lower elevations (Stoddart et al. 1989); however, this is not always the case, with sedimentation often affected by human activities in and around an estuary.

There are many methods for monitoring the accumulation of sediments in estuarine environments. Some of the key methodologies are outlined below. The methodology selected will rely on the characteristics of the location to be studied. Some key considerations that must be taken into account include: bioturbation, current intensity, channel migration, vegetation cover and accommodation space, as well as the location within the estuary.

Vegetated areas of estuaries naturally trap sediments and will usually have a higher sediment accumulation rate (SAR). Sedimentation rates in vegetated areas, particularly those dominated by mangroves are difficult to quantify as bioturbation caused by roots may make dating the upper sedimentary layers of cores meaningless. These areas are also difficult to access, compounding the problem of sedimentation monitoring. Disturbance of vegetation caused by accessing the monitoring site and installation of monitoring equipment can also alter the sedimentation rate. The most common method for monitoring these areas is with stakes (Woodroffe 2003). Marker layers were used to measure the accretion rate of mangroves in New Zealand by Chapman and Ronaldson in 1958, of 1mm/a (Woodroffe 2003)

In New Zealand, and many other locations worldwide, land clearance for agriculture, production forestry and urban development has significantly disturbed the catchments around estuaries. This has led to changes in the sediment dynamics of these systems, often increasing the rates of sedimentation to the detriment of the flora and faunal communities, and leading to a loss biodiversity and ecological value. In the Northland Region of New Zealand, significant disruption has occurred to the catchments of estuaries, especially in the last 100 years. There is, however, a lack of knowledge on how these landuse changes have affected estuarine systems, particularly the changes that have occurred in the sediment regimes. This lack of knowledge severely restricts the ability of resource managers to sustainably manage the natural environment. Northland Regional Council (NRC) has recognized that it lacks quantitative information on the rates of sediment accumulation in estuaries in the region. It also recognizes that this lack of information may hinder the development and implementation of effective plans and polices. In order to address this issue NRC commissioned Victoria University of Wellington to provide advice on a strategy to monitor sedimentation which would complement the existing estuarine monitoring programs.

Short term/modern sedimentation monitoring

Short term or modern sediment monitoring involves taking repeated measurements from the present into the future. It has the potential to be very accurate and can result in a very fine resolution sedimentation rate (i.e. rates that accurately give yearly/seasonally/monthly or even weekly changes). The resolution obtained will depend on the frequency that measurements are taken. However, the accuracy obtained tends to obscure the fact that the data is usually collected over a small slice of time which may reflect a natural fluctuation (such as a stormier period, causing greater flooding), and not necessarily a long term trend. Extrapolation of modern sedimentation rates is not recommended as the trend may reverse over a longer timescale with subsequent erosion or deposition. Short term studies generally highlight spatial and temporal variations, with phases of deposition interrupted by an erosive stage (Woodroffe 2003). This does not negate the usefulness of these methods, which as long as the stability of the site is identified, can be very useful in determining the migration, erosion and infill rates of channels and modern accumulation rates in backwater salt marshes (which usually experience slow infill).

(i) Erosion/Sedimentation Stakes

An erosion stake is a rod or stake that is set upright into the sediment (shown in figure 1). Accretion or erosion is measured by measuring and comparing the height of the rod above the sediment over a known time period. The rod may have measured increments painted onto it for ease of measurements. Horizontal erosion as well as vertical accretion can be measured using stakes. The horizontal distance from the stake to an erosional cut bank (illustrated in figure 2) can be measured to quantify bank erosion (Castillo et al. 2002).

The size and material of the rod is dependent on the energy of the environment in which they are employed. In high energy environments (such as channels and ebb tide deltas) Metal rods (1.5m) are preferred to wooden stakes as metal is more secure against movement. However, 10mm diameter pine stakes have been successfully used in New Zealand to monitor accretion in low flow areas such as mangrove stands (Young and Harvey 1996). Frequency of return times would vary depending on the location. Mudflats, salt marshes, mud basins and mangroves with slow accretion rates can be revisited annually, whilst channel margins, and flood tide deltas should be monitored more frequently.

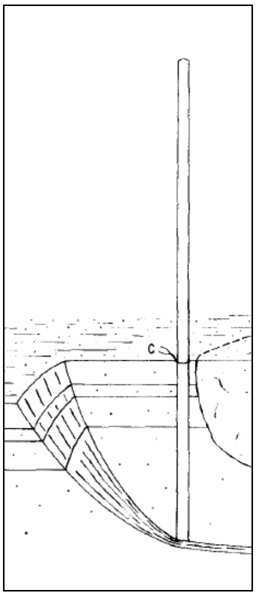


Figure 1. Diagram of an erosion stake showing exposed sediment below and marking (at c) position of measurements (from: Clifton 1969 p556).

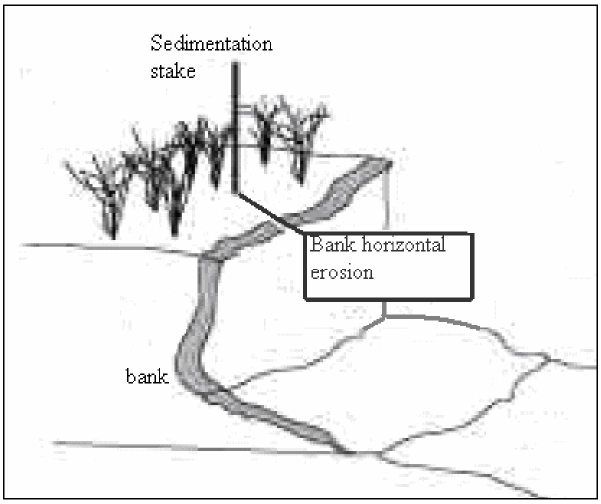


Figure 2. Diagram of sedimentation stake placed above bank to measure horizontal erosion (adapted from: Castillo et al. 2002 p2).

PROS
Measures both erosion and accretion. Has no negative impact on surrounding vegetation and hence can accurately measure deposition rates in vegetated areas. The effects of flood events on sedimentation rates can be quickly assessed.

CONS

Measures only a single point in the estuary, and thus will not correct for surface irregularities. This can be ameliorated by placing two, level stakes 1m apart, running a string between them, and taking a series of measurements from the string to the estuary surface. Stakes are visible to public and may suffer from vandalism. Even if the stakes are placed to sufficient depth a large flood event may dislodge them.

Short term fluctuations in sediment levels may occur due to wave and current action causing scouring at the base of the stakes shown in figure 3 (Clifton 1969; Mead and Moore 2004). However this can be corrected for by ignoring the erosion scour and estimating the top of the nearby unscoured sediment surface using a flat ruler (Ford and Anderson 2005). Scouring will be less if thinner pegs are utilised.

Figure 3. Sedimentation stake showing localized scouring around the peg (from: Gibberd and Carter 2003 p9).

COST

Costs are minimal. Initial set up is very cheap, and collecting measurements requires only minimal manpower.

Table 1. Summary of erosion/sedimentation stakes

	Rating
Ease of Use	Easy
Cost	Low
Labour	Minimal
Ideal environment	Dependent on strength of rod and depth inserted in sediment. Stronger, metal rods placed at depth required for areas with strong currents, ie flood tide deltas or fluvial channels.

(ii) Disturbance stakes.

Disturbance stakes are similar to erosion stakes, with the exception that they have the potential to capture sediment fluctuations. A metal rod is fixed into the sediment and a loosely fitting metal washer is fitted to the rod and allowed to slide so it rests on the surface. The position of the washer (usually the top) is marked with wire. In an erosion event, the washer will drop further down the rod, and the distance between the washer and the wire mark noted on return visits (Clifton 1969). Accretion can be measured between the top of the washer and the surface (if it has been buried) or off the staff as per erosion stakes. This method can capture the maximum erosion and accretion events experienced between sample return times. As with erosion stakes, horizontal erosion can also be measured.

Alternatively, for ease of measurement, two washers connected by a rod can be fitted to the stake (shown in Figure 4). The initial position of the top washer is marked with wire, and the height of exposed rod measured. Drops in the base washer (by erosion) give a corresponding drop in the top washer, which can be measured against the marking wire (Clifton 1969).

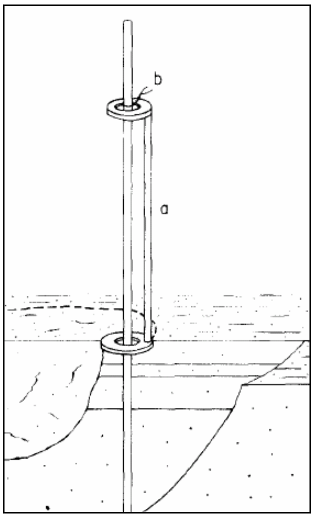


Figure 4. Diagram of a disturbance stake. Base washer falls to lowest erosion events between return visits. Rod (a) connects upper and lower washers allowing measurement of erosion by comparing original marked height (b) with new height of upper washer (from: Clifton 1969 p556).

PRO

Collect three measurements, maximum erosion and accretion on return visits as well as horizontal erosion. This makes it ideal for bars, ebb tide deltas or any areas that experience fluctuations. Has no negative impact on surrounding vegetation and hence can accurately measure deposition rates in vegetated areas. The effects of flood events on sedimentation rates can be quickly assessed.

CON
Localised erosion can occur around the washer (Clifton 1969), and this is difficult to correct for if accretion has buried the washer. If the vertical sediment profile can be carefully revealed using a spade, and if laminations are present it is possible to correct for this localized erosion. The dip of the beds should be measured and then extrapolated through the localized erosion around the stake. The intersection of this extrapolated line and the stake can be used as the point for measurement. Exposing the sediment, however, does remove the accuracy of return measurements.

As with erosion stakes, they are visible to the public and may suffer from vandalism. Rods may also become dislodged in flood events or if not securely driven into the sediment.

COST
Initial set up costs are minimally higher than for erosion stakes (due to price of washer). Welding the connecting rods to two washers will further increase set-up costs. Return measurement costs are minimal.

Table 2. Summary of disturbance stakes.

	Rating
Ease of Use	Relatively easy
Cost	Low
Labour	Minimal
Ideal environment	Dependent on strength of rod and depth inserted in sediment. Stronger, metal rods placed at depth required for areas with strong currents, ie flood tide deltas or fluvial channels.

(iii) Sedimentation Plates
Sedimentation plates are large flat plates which are buried about 20cm beneath the sediment. These plates can be composed of metal or concrete (Gibberd and Carter 2003; STONE 2003; Robertson and Stevens 2008a). They can be made in varying sizes, usually around 20-30cm^2(Gibberd and Carter 2003; STONE 2003). On installation the plates are leveled and the initial depth of sediment above the plates is measured. For a more accurate result an EDM (Electronic Distance Meter) is used for leveling, locating and initial depth measurement (Gibberd and Carter 2003; Mead and Moore 2004). Future measurements are made by inserting a probe into the sediment until the metal plate is hit, and measuring the depth of penetration. Several measurements should be taken from a single plate and averaged to account for any surface irregularities. Locations should be marked with stakes and located with an accurate GPS. The frequency of return times can vary depending on the nature of the site. Muddy backwater areas with slow accumulation rates can be measured every six month or annually, sandier areas with stronger currents may need to be measured more frequently. This method is commonly used by

Environment Waikato (Mead and Moore 2004), and they establish a sampling routine that runs fortnightly for six months after initial set up, and then monthly for a year (Gibberd and Carter 2003).

Figure 5. A sedimentation plate being buried on a tidal flat (Taken from: STONE 2003).

PROS
Easy to install and measure on return visits. Once installed it is unlikely to be disturbed by high water flow or members of the community due to its burial. The effect of events such as floods can be quickly measured, giving a greater understanding of how large events shape sedimentation. Widely used in New Zealand, so rates of sedimentation are more comparable. No problems with scouring as plate is below surface (Gibberd and Carter 2003).

CONS
The disadvantage of this system is that installation removes any vegetation and therefore cannot measure the trapping efficiency of vegetation, or accurately represent sedimentation rates of densely vegetated areas. It is less robust at measuring erosion rates, as this can only be quantified to the depth it was buried.

Where shell material is abundant in the sediment, it can often be difficult to successfully locate the plate for repeat measurements (Gibberd and Carter 2003). Inserting many rods at the same time for measuring can quickly identify if the plate height has been reached (figure 6)

Figure 6. Measuring depth to the sediment plate using knitting needles. Several measurements are taken at once to ensure depth to plate is measured and not depth to an obstruction (from: Gibberd and Carter 2003 p11).

There is a possibility that the weight of the plate could cause compaction of the sediment below causing a false erosional measurement to be recorded. As yet compaction by plates has not been documented. Accurate survey transects linking known survey points with the plate at depth would pinpoint if compaction was occurring.

COST

Costs are minimal. Initial purchase and installation would be the highest cost, and ongoing costs dependent on frequency of return visits.

Table 3. Summary of sedimentation plates.

	Rating
Ease of Use	Easy
Cost	Low
Labour	Minimal
Accuracy/resolution	Fine
Ideal environment	Areas without vegetation such as: mudflats, central mud basins. Areas of low to medium flow rates.

(iv) Sediment traps

A sediment trap can be any object of known area that has the potential to catch sediment. The trap is installed and left to accumulate sediment for a period of time. Traps must be clearly marked with stakes and locations recorded via GPS. On returning, the trap is removed and the accumulated mud is carefully collected, dried usually at 60°C for 3-7 days (depending on grain size, finer sediments usually take longer to dry) and weighed (Culberson et al. 2004). The accumulation rate is then expressed as g cm^{-2} yr^{-1}(Van Santen et al. 2007). This system allows modern sediment to be collected and analysed. Some of the types of sediment trap are outlined below.

<u>Canvas sheet.</u> A thin piece of canvas, of known dimension is spread out and secured to the ground with pegs (large vegetation interfering with the canvas should first be removed). The canvas should be rough to allow sediments to accumulate. The location is marked with pegs or GPS equipment. Over time, the sheet becomes buried as sediment is deposited. On returning, the canvas is removed and the accumulated mud is carefully collected for analysis (Van Santen et al. 2007).

<u>Circular pipe</u>. A pipe, (often PVC but can be metal) is closed at one end and placed into the sediment with the opening 200-250mm above the sediment surface (Ford and Anderson 2005). In New Zealand traps are sometimes around 36mm diameter and 500mm deep (Ford and Anderson 2005), and pipes should be in excess of a 5:1 (length:width) ratio to prevent resuspension of any trapped sediment (WRP 1993).

<u>Filter paper</u>. Glass fibre filter papers are fitted into plastic Petri dishes (~70 mm in diameter). Glass fibre should be used over wood fiber as it does not degrade in the natural environment. They are anchored to the sediment with wire staples passed through the paper and holes drilled into each dish (Culberson et al. 2004). On collection, (at maximum 3 months) the filter paper is removed, oven dried and weighed.

<u>Circular plates.</u> Plexiglas circles (~15-cmdiameter) with about a l-cm hole in the middle are attached to the surface by metal rod secured with a wing nut. The upper surface of the plate is sanded so that sediments will not be washed off. Sediment is collected by cutting around the edge of the disk with a knife and scooping the material into a zipper-lock bag with a spatula (WRP 1993).

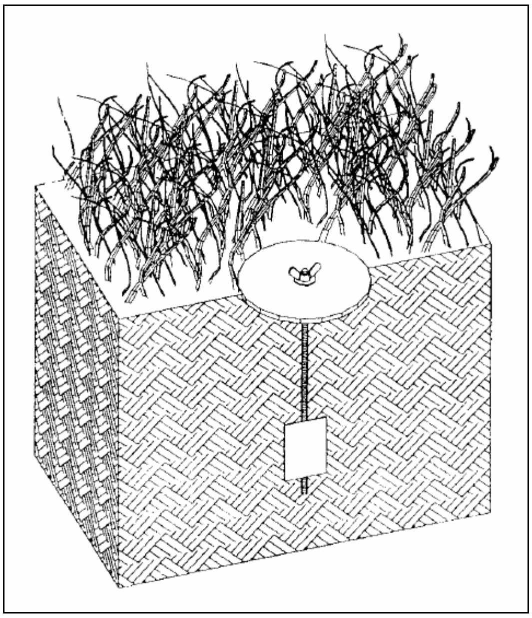


Figure 7. Circular plate sediment trap (from: WRP 1993 p2).

PROS
Easy to install and to measure. Because the sediment is collected and removed, grain size characteristics can be determined simultaneously, giving an indication as to the nature of the sediment deposition.

Circular plates and circular pipes. These types of sediment trap are more robust and are less likely to be removed via erosion.

Filter paper. Very accurate, as the collection device is weighed with the sample, no material is lost in processing.

CONS
Allows only one temporal measurement, as the trap is removed for analysis. Several traps may be placed to return to at different times, to compensate for this. Erosion rates cannot be determined using this method. Measurements are less comparable to other methods of determining SARs, as sediment traps are the only method that measures by weight (g cm^{-2} yr^{-1}) and not by depth (mm yr^{-1}).

Canvas sheet. As the material is light, it is more likely to be eroded and lost in heavy floods than a sedimentation plate. As with sedimentation plates, this method is not appropriate for densely vegetated areas, however the canvas may fit between sparse vegetation and gain an accurate measure of accumulation rates.

Circular pipe.
In tidal areas where water fluctuations are large the cylinder is unlikely to be installed so that it remains submerged throughout a sampling period. This type of trap is also likely to

overestimate sedimentation, as the pipe prevents resuspension, an action that is not insignificant in an estuarine environment (WRP 1993).
Filter paper. Traps need to be monitored weekly or fortnightly for condition (Culberson et al. 2004). Only useful for short term studies (max 3 months) and in areas of very low to no significant water flow, as the filter paper is not very robust, and easily deteriorates.

COST
Very cheap to install. Analysis is relatively cheap, as sediment need only be dried and weighed.

Table 4. Summary of sediment traps.

	Rating
Ease of Use	Fairly easy
Cost	Low
Labour	Minimal
Accuracy/resolution	Fine
Ideal environment	Backwater areas (marshes, tidal flats) of low flow, that do not experience significant erosion.

(v) Artificial marker horizons
Sand is evenly distributed (at least 1cm thick) over the surface of 1 m^2 plots, giving a clear textural contrast with underlying silt or clay (Stoddart et al. 1989). Alternatively silica flour, iron filings or kaolinite (feldspar clay) may be applied instead of sand (WRP 1993; Ellison 1999; Woodroffe 2003; Van Santen et al. 2007). Almost any substance can be utilised, as long as the marker horizon is significantly different from the underlying deposits, and can be easily recognised. Marker horizons that have been deposited naturally or inadvertently have also been used to estimate SAR's, flood deposits (which differ in grain size) have been used, and in Tairua estuary sawdust deposited between 1864 - 1909 from historical kauri log milling was successfully used as a marker horizon (Hume and Gibb 1987).

Plots must be clearly indicated with stakes or mapped with an accurate GPS for easy identification of sample sites on future returns. On return the accumulation of sediment above the marker horizon is measured as shown in figure 8. This can be done either in the field cutting a vertical profile with a spade or sharp field knife, or by collection of a sample in a plastic tube pushed into the ground. Care must be taken as pushing in a tube can cause compaction (Stoddart et al. 1989). The best method is collection of a small core using a modified aluminium drink can, as the thin wall prevents compaction and the can shape ensures measurements remain vertical (WRP 1993). As with other methodologies, return frequency varies with the hydrological nature of the site, although Stoddart et al (1989) suggests a 6 monthly return interval.

Figure 8. Example of measuring accretion using a marker horizon (from: USGS 2003)

This methodology is of most use for studies on a shorter time scale (less than 10 years), as marker layers become difficult to find on the long term scale (40 plus years) (Stoddart et al. 1989).

PRO
This method is advantageous in that it can be used in vegetated areas of marsh and would measure both organic accumulation and fluvial/tidal deposits. It is also not technically difficult, infield measurements only requiring an accurate measure. It is non destructive, and measurements are not influence by the interference of the measuring equipment (such as with stakes and plates).

CON
This method is highly susceptible to the possibility of being reworked and lost by bioturbation. Hence this method would not be appropriate for use in areas with abundant fauna. Destructive sampling reduces the longevity of this method and there is a potential difficulty in relocating plots (Stoddart et al. 1989). It is only suitable for areas undergoing accretion, that do not experience erosion associated with flow events (eg channels or ebb-tide deltas), as this could cause erosion and removal of the marker horizon. For areas that experience tidal inundation a heavy material (sand, iron filings) should be applied as lighter markers (such as kaolinite) may quickly be washed away. This method does not appear to be utilised in New Zealand so any issues arising from application to the New Zealand environment are unknown. It is also important to know the sedimentation history of the estuary as coarse layers may relate to different energy conditions that have existed during different stages of estuarine evolution.

COST
This method would be cheap to undertake, (sand can be obtained from the sandier parts of the estuary as a marker) and require minimal labour.

Table 5. Summary of marker horizons.

	Rating
Ease of Use	Easy
Cost	Low
Labour	Minimal
Accuracy/resolution	Fine
Ideal environment	Any back water areas that rarely experience erosion. Ideal for vegetated areas. Not appropriate in areas with high fauna populations.

(vi) Surveying

Surveying, also know as bed level monitoring, provides data on cross shore shape of intertidal area. Survey equipment such as an EDM (Electronic Distance Meter) or dumpy level is used to survey a transect of the estuary. This essentially gives the topography along a line. By taking repeated surveys over time of the same transect, the accumulation and erosion of sediment can be measured by comparing changes in elevation over time. This method is often used in conjunction with sedimentation plates to accurately place the plate and monitor a cross section of the estuary (Gibberd and Carter 2003). Most EDM's have an accuracy of <5mm, so the limitation on accuracy depends on the consistency of the user.

PRO

Data collected monitors a transect of the estuary, rather than the accretion and erosion of a single point. Useful for comparing with finer scale methods to determine if the rates measured are only an anomaly of the site monitored. Can be used to monitor all estuarine environments that are accessible by foot

CON

Accuracy limited to machine and user capability. This method would be useful for quantifying medium scale change, and less useful for exact measures of sediment accumulation.

COST

Initial cost of purchasing equipment is very high, c. $1000 for a dumpy level set or $25,000 for an EDM. However, return trips would simply cost in manpower.

Table 6. Summary of surveying.

	Rating
Ease of Use	Moderate – hard (some training required)
Cost	Moderate-high (esp. if equipment needs to be purchased)
Labour	Low (Minimum 2 persons)
Accuracy/resolution	Medium
Ideal environment	Anywhere accessible by foot. Difficult in very soft sediment and strong/deep currents

(vii) Bathymetric Surveys

Comparison of bathymetric surveys repeated over time can give an indication of accretion and erosion. The simplest method of obtaining bathymetric data would be to use a highly accurate GPS system along with depth sounders. A detailed picture of bathymetry can be produced, however sedimentation rates may be difficult to quantify due to the large scale bed changes (channel migration or bedforms) that will naturally alter over time. Changes in depth caused by wind waves and tidal changes must be corrected for.

PRO

Deep channels and areas of stronger currents can be monitored. Large scale changes in estuarine shape and function can be assessed, and the whole estuary can be monitored.

CON

Difficulty in accessing shallow areas, even on spring high tides. A high amount of computer processing would be required. Bathymetric surveys are more likely to indicate broad scale trends of sediment change, not accurately determine SARs, as the estimated error is usually 2-3cm (Reeve 2008).

COST

High

Table 7. Summary of bathymetric surveying.

	Rating
Ease of Use	Moderate- technical skill required
Cost	High
Manpower	Moderate
Accuracy/resolution	Medium - coarse
Ideal environment	Areas inundated by sufficient water depth to allow boat access

(viii) LIDAR

Light Detection And Ranging (LIDAR) is similar in theory to RADAR, light is transmitted to a surface and reflections off the surface are measured by a detector. The properties of reflected and refracted light are used to construct a digital elevation model. LIDAR is usually attached to a light aircraft, and can map underwater surfaces. Similar in concept to bathymetric surveys, and like bathymetric surveys LIDAR is still not accurate enough with an error of 15cm (NOAA no date), to measure annual change in sedimentation rates, but excellent for large scale change.

PRO

Major advantage is that LIDAR can cover all areas of an estuary. LIDAR can also simultaneously produce vegetation mapping as it analyses the properties of the reflected and refracted light.

CON

Error margin of ± 15cm means that data obtained is very coarse and would not be suitable to quantify yearly accumulation rates, although continual refinements in technology means the accuracy of this method is constantly being increased.

COST

High

Table 8. Summary of LIDAR.

	Rating
Ease of Use	Expert technical skill required
Cost	High (many $10’s of thousands)
Manpower	Moderate
Accuracy/resolution	Coarse
Ideal environment	All areas

Medium to Long Term Studies.

Estuaries have been forming and infilling for the last 7,500 years since sea level reached close to its approximate position, so monitoring of modern or short term sedimentation rates reveals only a very small slice of overall trends in estuarine infill. Medium to long term studies, which involve collecting a core, contextualise these annual measurements. A core gives stratigraphic evidence on the type and rate of infill. It also reveals pertinent background information regarding the amount of past and present accommodation space which can reveal if modern sediments are bypassing the estuarine system. A core can also reveal if an estuary has rapidly infilled, and whether present day erosion or accretion is simply a product of continued surface sediment reworking by waves, tides and currents.

(i) Coring
A core is a sample of the vertical profile of the estuary which allows identification of the varying sediment layers at depth. Coring involves taking a vertical sample of the estuarine sediments. As sampling involves pushing and compacting the sediments down, a measure of compaction should always be taken after the core is inserted. Depths should then be corrected for compaction.

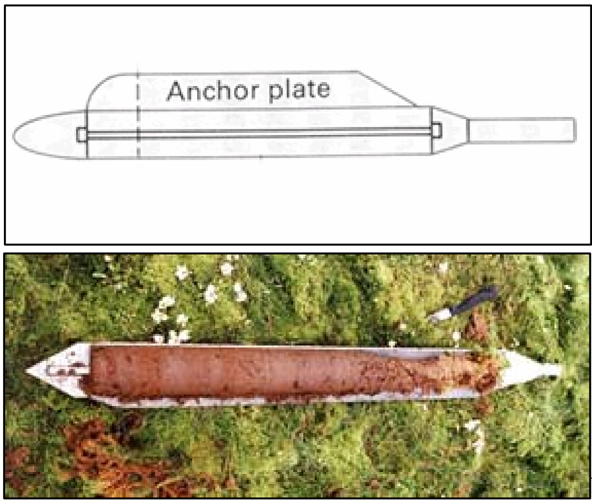
Hand coring is the simplest method, where a PVC pipe (up to 1m long) is carefully inserted into the sediment slowly by hand (figure 9 a). The core is then carefully dug out of the mud (figure 9 b) and kept vertical during transport until the pipe is cut lengthways and opened (Robertson and Stevens 2007a). This method would require at least two people for careful transportation.


a)

b)

Figure 9. a) Inserting a sediment core by hand. b) Digging out the core for removal (from: Robertson and Stevens 2007a p9)

A Russian type/ D-corer is a simple tool for collecting cores. It has a sharp penetrating point at one end, a movable sampling chamber inside a barrel, and a revolving fin along the length of barrel (LR 2008). It is recommended for use only in peats and bogs where the sediment has enough consistency to maintain its shape (Newnham et al. 1995). To get to greater depths the corer has extension poles. It would require only one person to collect a core using this method.



a)

b)

Figure 10. Russian type/ D-corer. a) in schematic cross section, b) with sediment core (from: LR 2008).

To obtain an intact core to a depth greater than 1m, a piston corer, or vibracorer is used. An aluminium or PVC pipe (often c. 6m long x 75 mm wide) is forced vertically into the sediment. Core collection is aided by the vibrations of the vibracorer, or the action of the piston corer. The core is sealed with an airtight bung to prevent loss of sediment, and the core removed, usually by winch and a tripod (Figure 11). If the tripod is high enough, and diving equipment is available, this method can also be used underwater, to depths of c. 4m. These methods are more labour intensive, with three or more people required for core collection. Coring by these methods is also more costly.

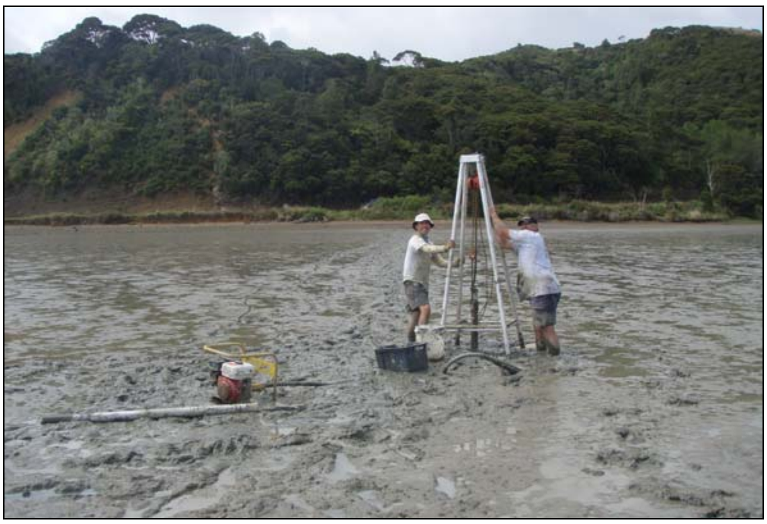


Figure 11. Vibracoring on an estuarine mud flat.

Dating Methods

In order to obtain a SAR from a core, dates must be established correlating to depths in the core stratigraphy. The basic concept relies on the presumption that the age of sediments increases with depth. Once a layer is dated, its age and depth are used to calculate a SAR. The more dates obtained, the more accurate the SAR, and variations in SARs over time can be detected. Accuracy of interpretation will depend on the method of sampling. Coarse sampling, although cheaper might not reveal short time scale changes in rates of infill, and produce a longer average where the actual rate may fluctuate greatly. However, SARs based on dating methods are dependent on sediments from historical periods being preserved, and not subsequently eroded or never deposited. Careful interpretation of the depositional environment can ensure misinterpretation of SAR is avoided. It is also common and best practice to confirm a chronology with at least two independent dating methods (Allen et al. 1993). Some of the main dating methods are outlined below.

The key factor that can confound any stratigraphic dating method is bioturbation or sediment mixing. Fauna that lives within the sediment, or flora that grows upon it, can cause sediments to mix. Strong currents and wave action can also disturb the sediment profile, and cause younger sediments to be mixed with and deposited under older ones. A method for calculating the amount of mixing and bioturbation that is occurring uses the radio isotope 7-beryllium (^{7}Be). ^{7}Be has a half life of only 54 days, thus if sediment is not mixed ^{7}Be should only be present in the very surface of the core. The depth that ^{7}Be is detected indicates the depth of bioturbation (Robertson and Stevens 2007a).

(i) ^{137}Cs

Caesium (^{137}Cs) is a radioactive isotope with a half life of 30.17 years and does not occur naturally in the environment (WRP 1993). Atmospheric nuclear weapons tests in the 1950’s and 60’s introduced the radioactive isotope ^{137}Cs into the atmosphere. Analysis of the concentration of ^{137}Cs in a sediment profile usually reveals a strong spike correlating to 1953. Thus ^{137}Cs dating can only really indicate post and pre 1953 layers in a sediment profile. To accurately determine where the ^{137}Cs peak it located in a profile, the intervals between sediment samples should be small. A larger interval between samples equals a larger uncertainty in core dating. Longer cores are preferred (>1m) in order to sample pre 1945 sediments free of ^{137}Cs (Reeve 2008). The concentration of ^{137}Cs in a sample is measured via gamma ray spectrometry.

PRO

The ability to pinpoint a specific date makes ^{137}Cs excellent for correlation with other dating methods (such as pollen or ^{210}Pb) which may not have a confirmed accuracy on their own. ^{137}Cs is also an excellent way to integrate sedimentation rates over a 30 to 35 year period, thereby by taking into consideration periods of resuspension or erosion that are often lost in short term methods (WRP 1993).

CON
Bioturbation and sediment mixing is an issue for accurate dating. Erosion of catchment soils which already contain ^{137}Cs can potentially 'spike' the sediment record (Oldfield and Richardson 1981).

COST
Because the accuracy of dating depends on the frequency of sampling ^{137}Cs dating is expensive.

Table 9. Summary of ^{137}Cs dating. Summary does not include coring or sub sampling.

	Rating
Ease of Use	Expert analysis required
Cost	High (costs depends on lab used)
Age limit	1945-53

(ii) ^{210}Pb

Lead 210 (^{210}Pb) dating takes advantage of the disequilibrium between ^{210}Pb sourced in situ and atmospherically sourced ^{210}Pb. In situ ^{210}Pb (termed supported ^{210}Pb) is formed from the radioactive decay (through a series of steps) of radium 226 (^{226}Ra), and due to the long decay rate of ^{226}Ra (~1600 years) the two isotopes are in radioactive equilibrium. If only supported ^{210}Pb were in a sedimentary profile, the concentration of the isotope would be constant with depth. In the atmosphere the parent of ^{210}Pb, Radon 222 (^{222}Rn) gas decays to ^{210}Pb. After it has formed in the atmosphere it falls to the earth and is incorporated into soils, glacial ice, and lacustrine and estuarine sediments. This atmospheric (unsupported) ^{210}Pb is in excess of the supported ^{210}Pb, thus the surface sediment has a higher concentration of ^{210}Pb which decreases exponentially with depth as the isotope decays, until the constant supported concentration is reached. This exponential curve and the ^{210}Pb half life (22.3 years) are used to calculate the age of the sediment profile and thus the SAR. The ^{210}Pb and ^{226}Ra concentrations are measured using gamma ray spectrometry.

PRO
Can accurately date sediments and provide a continuous record of SAR which can be used to link and fill in the gaps of dates obtained from other dating methods.

CON
As with all dating techniques, bioturbation and sediment mixing limits the accuracy of this method. There is the possibility that unsupported ^{210}Pb has been deposited via erosion of catchment soils in addition to atmospheric fallout, thus giving a false high concentration (Oldfield and Richardson 1981). There is also evidence in New Zealand that the high sedimentation rates have significantly diluted atmospheric unsupported ^{210}Pb so that the normal curve of concentration (greater at surface, declines at depth) is replaced with a constant supported concentration (Goff et al. 1998; Swales et al. 2005;

Stevens and Robertson 2007). The ^{210}Pb chronology can be validated by comparison with the measured rates of atmospheric ^{210}Pb fallout in New Zealand.

COST

Cost is high, as for a comprehensive ^{210}Pb profile subsamples must be analysed at least every 5cm of core.

Table 10. Summary of ^{210}Pb dating. Summary does not include coring or sub sampling.

	Rating
Ease of Use	Expert analysis required
Cost	High (costs depends on lab used)
Age limit	120-150 years (Cundy and Stewart 2004)

(iii) ^{14}C

Radiocarbon (^{14}C) dating is based on measuring the concentration of ^{14}C in a sample sourced from a living organism. ^{14}C is formed in the atmosphere and becomes incorporated in all living tissues via CO_2. All living tissues have a constant concentration of ^{14}C in balance with the ^{14}C source. Upon death, the ^{14}C in the organism decays at a half rate of 5,730 years (Worsley 1990). Thus any part of a living organism younger than 35-50ka can be dated by ^{14}C (Worsley 1990).

The type of material that can be dated by ^{14}C includes: wood (including charcoal), peat, shells, bone, or soil organic matter (Worsley 1990). Even the microscopic foraminifera fossils, (often found in estuarine sequences) can be successfully dated. A sample from a single organism will give a more accurate result than combining several entities in a sample. The position and amount of deterioration of a sample should be carefully noted. Ideally the sample will have died in life position; hence its stratigraphic position represents the historical sediment surface. For each sample the level of contamination and possibility of organism death occurring at a different time to its stratigraphic position must be assessed. If a sample appears battered or damaged, it may well have been reworked to a higher position in the core.

Contamination of samples occurs where ‘old’ or ‘young’ carbon is introduced to their environment. ‘Young’ carbon can be introduced post death by live plant roots penetrating to deeper levels or deposition of other modern carbon (Worsley 1990). This influence can usually be negated by cleaning and removing the outer layers of samples. ‘Old’ carbon is introduced to an organism during its lifetime by several means. If the geology of the catchment contains ancient carbon sources such as coal or limestone, any samples recovered will yield ‘old’ dates. Such samples are contaminated and will yield dates greater than 50ka. Even with estuaries without a source of ‘old’ carbon in their geology, ocean bodies act as reservoirs for carbon. In New Zealand, the ocean yields dates 300 years older than reality and thus this correction is applied (Swales et al. 2005). Modern day use of fossil fuels has led to a higher ratio of old carbon being added to the atmosphere, contaminating samples in the industrial age with ‘old’ carbon. For this reason samples older than 500 years should be dated, or else a correction applied (Swales et al. 2005). Samples post nuclear testing (1945 onwards) are not possible to assign a specific date to, however analyzing these samples does disclose their age as ‘modern’.

There are two methods for analyzing ^{14}C. The conventional method counts the rate of ^{14}C disintegration by beta particle emissions and uses approximately 10 g of original material. It is an indirect measure of ^{14}C and can only ever give counting statistics, i.e. a deviation from the mean value. The alternative method, AMS gives a direct count of ^{14}C atoms and requires a much smaller mass of material to date (Worsley 1990). Sample mass needed is as little as 5g for conventional dating, (although a greater mass yields better results) whilst AMS requires as little as 60 micrograms. The age is reported as years before present, where present is 1950 AD (Worsley 1990).

PRO
This method is advantageous as the long half life of ^{14}C mean that SAR rates can be determined from estuarine creation (~7000 years ago) to present. Thus giving an entire picture of an estuaries history. Any shells, wood or forams found in a core can potentially be dated to yield a chronology.

CON
Reworking of sediments can deposit old shells higher in record, giving an over estimation of age. Samples need to be carefully selected in order to avoid selection of reworked or contaminated material. Samples should also be assessed to determine if any corrections for oceanic reservoir affects need to be applied. The period of analysis is also lengthy a period of 6-8 weeks.

COST
C14 is accurately measured at the Waikato Radiocarbon Dating Laboratory within the University of Waikato. Current costs (as of Nov 2008) are $525 for radiometric dating and $775 for AMS dating (New Zealand dollars) (WRDL 2008).

Table 11. Summary of ^{14}C dating. Summary does not include coring or subsampling.

	Rating
Ease of Use	Expert analysis required, some training required for sample selection
Cost	$525 (standard method), - 775 (AMS method) per individual shell/wood/sediment sample (Waikato Lab)
Age limit	30-50000 years

(iv) Pollen analysis

Vegetation changes, whether climatic or anthropogenic are often preserved in the pollen record (McGlone 1989). Each species has a uniquely shaped pollen grain or spore (palynomorph) which can be deposited in an estuarine sediment record either from direct airborne deposition on the estuary surface or washed in as runoff or with eroded soil. Change in the abundance and type of pollen in the sediment profile usually represents a change in the abundance and type of vegetation present in the catchment. The time periods that can be identified by pollen analysis are 1) pre-human indigenous forest; 2) settlement by Maori (1350 AD ± 100), identified by increasing charcoal and bracken mixed in with indigenous forest; 3) European settlement (1800's) , rapid reduction in native forest species; 4) Modern sediments (post 1945) with a rapid increase in exotic species, especially pine and grass (Swales et al. 2005).

Sediment from a core is sampled at measured intervals and chemically processed to separate the pollen from the sediment. Palynomorphs (pollen and other similar type grains) are identified and counted using a microscope, usually at least 250 palynomorphs are counted and the pollen profile expresses the percentage of pollen for each species down core (Horrocks et al. 1999). Some of the factors that must be considered when interpreting a pollen profile are; the time lag between species introduction and pollen preservation, distance of pollen dispersal from source, supply rate and bioturbation.

PRO

Can be very accurate, especially in estuaries where an historical date for the first pine plantation is available. The method can identify SARs with historical periods of interest, eg pre-human, post European.

CON

Estuaries that are dominated by eroded soils may be dominated by palynomorphs that represent the age of the eroded soil, and not of the age of sediment deposition. However, as soils tend to degrade all but bracken spores due to their acidity, a estuarine core dominated by bracken spores indicates a high input of eroded soils (Swales et al. 2005). Bioturbation, or erosion may disturb the pollen profile, making accurate calculations of SAR difficult. Relies on historical records of change in vegetation, which may not be continuous or long enough.

Pollen analysis has an OSH issue, as separation of the pollen from the sediment requires the use of hydrofluoric acid. For this reason only skilled technicians should undertake pollen analysis.

COST

High

Table 12. Summary of pollen analysis. Summary does not include coring or subsampling.

	Rating
Ease of Use	Expert analysis required
Cost	High. Requires specialist laboratory
Age limit	Historical European or archaeological Polynesian.

(v) Tephra

Ash deposits from volcanic eruptions, if identified in a stratigraphic core can be used in much the same way as artificial marker layers to calculate SAR's. They are also excellent for checking dates obtained from alternate methods. Using specific marker beds sedimentation can be calculated post any specific eruptive event. To do this geochemical analysis needs to be conducted to identify the specific ash and relate it to the timing of eruption. It must also be determined that the ash is derived primarily from airfall rather than reworked from the estuaries hinterland. Such identification needs to be undertaken by professional researchers and is only recommended to be conducted in association with an estuarine coring programme.

Table 13. Summary of tephra analysis. Summary does not include coring or subsampling.

	Rating
Ease of Use	Expert analysis required
Cost	High. Requires specialist laboratory
Age limit	>1,000,000 years

Techniques used in New Zealand

Table 13 catalogues the methodologies used in New Zealand to monitor or quantify sedimentation rates. The most common method for analysing modern accumulation is sedimentation plates. For longer term analysis, a combined approach is most commonly used, dating sediments using several methods (^{210}Pb, ^{137}Cs, ^{14}C and pollen analysis) as comparisons of methods validates SARs obtained.

Table 14. Summary of the sediment monitoring methodologies used in reports and articles of New Zealand estuaries. ARC = Auckland Regional Council; CHHFL = Carter Holt Harvey Forests Ltd; DOC = Department of Conservation; ES = Environment Southland; EW= Environment Waikato; GWRC= Greater Wellington Regional Council; JA = Journal Article; MT = Masters Thesis; NRC= Northland Regional Council; PCC= Porirua City Council; SAR; Sediment Accumulation Rate; TDS = Tasman District Council; UW = University of Waikato.

Method	Government body	Use in New Zealand	Comments
Sedimentation plates	GWRC and PCC	Porirua harbour (Robertson and Stevens 2008b)	Part of 'fine scale' monitoring program
	EW	Southern Firth of Thames and Raglan Harbour (Gibberd and Carter 2003)	Shelly material often hinders accurate measurement
	TDC	Motupipi (Robertson and Stevens 2008a)	
	ES	New River Estuary (Robertson and Stevens 2007a)	
		Waituna Lagoon (Stevens and Robertson 2007)	
		Waikawa Estuary (Robertson and Stevens 2007b)	
Sediment traps	ARC	Okura estuary, Whitford estuary (Ford and Anderson 2005)	
Sedimentation stakes	ARC	Okura estuary, Whitford estuary (Ford and Anderson 2005)	
	EW	Southern Firth of Thames and Raglan Harbour (Gibberd and Carter 2003)	Localised scouring around stakes led to inaccurate measurement, stakes were abandoned for sedimentation plates
Hand coring	ES	New River Estuary (Robertson and Stevens 2007a)	
		Waikawa Estuary (Robertson and Stevens 2007b)	
Russian	NRC	Hokianga harbour (GeoEnvironmental Consultants	

type/D-Corer		2003)	
Livingston piston corer	EW	Raglan harbour (Swales et al. 2005)	
		Firth of Thames (Swales et al. 2008)	
PVC pipe	EW	Raglan harbour (Swales et al. 2005)	
^{137}Cs	NRC	Hokianga harbour (GeoEnviornmental Consultants 2003)	
	EW	Raglan harbour (Swales et al. 2005)	Absent from some cores, sediments greater than 150 years old
		Firth of Thames (Swales et al. 2008)	
	MT UW	Whitianga (Reeve 2008)	
	GWRC	Pauatahanui (Porteous 2005)	
	ES	New River Estuary (Robertson and Stevens 2007a)	Sediment mixing gave results that conflicted with ^{210}Pb dates
		Waituna Lagoon (Stevens and Robertson 2007)	
		Waikawa Estuary (Robertson and Stevens 2007b)	
^{210}Pb	NRC	Hokianga harbour (GeoEnviornmental Consultants 2003), Raglan harbour	High input of 'clean' sediment (with no unsupported ^{210}Pb) hindered the calculation of a chronology
	EW	Raglan harbour (Swales et al. 2005)	Absent from some cores, sediments greater than 150 years old
		Firth of Thames (Swales et al. 2008)	
	JA	Whangamata Harbour (Sheffield et al. 1995)	
	MT UW	Whitianga (Reeve 2008)	
	ES	New River Estuary (Robertson and Stevens 2007a)	Sediment mixing gave results that conflicted with ^{137}Cs dates
		Waituna Lagoon (Stevens and Robertson 2007)	Exponential decay curve not present, data not used.
		Waikawa Estuary (Robertson and Stevens 2007b)	
Pollen analysis	EW	Raglan harbour (Swales et al. 2005)	Exotic pollen species unexpectedly absent from some cores, sediments older than 150 years.

		Firth of Thames (Swales et al. 2008)	Unable to calculate SAR, probably due to high percentage of palynomorphs sourced from eroded soils
	JA	Whangamata Harbour (Sheffield et al. 1995)	Minor bioturbation causing some error on SAR.
		Great Barrier Island, Awana Bay (Horrocks et al. 1999)	
	CHHFL	Wharekawa Harbour (Swales and Hume 1995 in: Jones 2008)	
		Whangamata Harbour(Swales and Hume 1994 in: Jones 2008)	
	DOC	Whangapoua estuary (Hume and Dahm 1992 in: Jones 2008)	Bioturbation and physical mixing of sediment made calculation of sedimentation rates difficult.
	GWRC	Pauatahanui (Porteous 2005)	
^{14}C	EW	Raglan harbour (Swales et al. 2005)	
		Firth of Thames (Swales et al. 2008)	
	DOC	Whangapoua estuary (Hume and Dahm 1992 in: Jones 2008)	
	JA	Whangamata Harbour (Sheffield et al. 1995)	^{14}C date inaccurate due to reworking of sediment (shown by comparison with ^{210}Pb.)
	CHHFL	Whangamata Harbour (Swales and Hume 1994 in: Jones 2008)	
		Wharekawa Harbour (Swales and Hume 1995 in: Jones 2008)	

Recommendations

The type of sediment monitoring method required depends on the nature of the location and the purpose of the study undertaken. Vegetated sites should be monitored with low impact methods, such as artificial marker horizons, surveying or staking. Ebb tidal deltas, or other high energy environments such as channels require robust methods capable of withstanding currents or be measured using remotely via bathymetric or LIDAR surveys. If a picture of fine scale sediment movement is required, disturbance stakes give the best resolution. However sedimentation plates, stakes, marker horizons and traps can also achieve a fine scale resolution if return visits are made more frequently. A broad understanding of estuarine change could be achieved using surveys, but would not have the fine scale resolution.

Most short term sedimentation methods are meaningless without knowledge of the estuarine development and infill over the Holocene. It is important to understand the context of estuarine development. If an estuary has infilled rapidly after sea level rise to present day levels (~6,000 years ago (Kennedy 2008)), then accommodation space for further deposition is not available, and sediments will bypass the estuary. The top meter of sediment may be reworked by tidal and fluvial channels, and may be under either erosional or depositional processes at present. This reworking can leave a coarse lag layer of shell material or sands and gravels, which are later buried when channels migrate away from the area. Such modern processes do not necessarily reflect long term trends. To determine if an estuary has reached its sediment accumulation capacity, and thus contextualize modern deposition/erosion processes, coring to depth and dating sediments is recommended. Modern/present day rates of deposition are meaningless unless the long term stratigraphy and SAR is understood.

An important consideration when interpreting data is the influence of a rising sea level. Sea level is rising approximately 1.7 ±0.5 mm (Kennedy 2008) in New Zealand. This is creating greater accommodation space in estuaries for sediment accumulation. In some situations it may be the case that coarser material is still bypassing the system, but finer muds are being deposited.

For the monitoring of sedimentation rates, the following methods are recommended:

I. A one-off coring to depth of the estuary. Ideally 3 cores should be taken along the axis of the estuary in the mid-low intertidal regions of the basin. If there is a particular area of interest (eg. an ecological monitoring site) then a single core can be taken in the intertidal parts of that site, or just outside of it to reduce interference with the monitoring. Further coring may not be necessary if there is little depth or sediment zonation within the system; however, if significant variation exists coring may be needed at each individual site.
II. The cores should be dated at minimum using ^{210}Pb, ^{137}Cs and at least 2-3 ^{14}C dates located at depth. Pollen dating would also be advantageous if it can be afforded. It is recommended that dating be concentrated on 1-2 cores that are representative of the depositional environments of interest. Changes in

sedimentology between cores can then be used to relate the detailed chronology from the single core to other sites. Spreading dates between several cores can cause misinterpretation of long term change, unless a detailed chronology already exists for that specific estuary.

III. Short term monitoring sites should be established in key areas of the estuary. The type of method used is dependent on the location and the outcomes desired, but the most recommended are sediment plates or artificial marker layers. For a more comprehensive understanding of sediment change, monitoring sites should be surveyed (using an EDM or similar methodology) as part of an annual transect through the site of interest, surveys orientated perpendicular to the main channel of the estuary. Return times should be at least annually, but more frequent sampling (monthly or quarterly) is recommended to establish a base line, or if conditions fluctuate.

IV. The number of sediment plates/markers layers needed will depend on the detail of required of the study. For the Northland region (as per the project brief) it is suggested that 1 plate be placed at each ecological monitoring site at the highest and lowest parts of each site (2 in total per site). In addition to this 2-3 additional plates should be placed at similar sites within the estuary as well as in the main intertidal sediment zone. For example if a sea grass bed is being monitored on a wide mud flat, then one other sea grass site should have a plate installed as well as placing 2 plates on the surrounding intertidal mud flats. The intertidal sediment flats are seen as a key area for monitoring as they are most sensitive to sea level rise and sedimentation. This is because a small change in elevation can led to very large changes in the degree of tidal inundation and therefore ecology of the sites.

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