ANZECC Guidance for Estuary Sedimentation

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Executive Summary

The Ministry for the Environment is seeking to develop guidelines for sedimentation in estuaries for incorporation into the revised Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ 2000).

Herein we develop recommendations for a guideline for sedimentation in estuaries, which we define as the thickness of sediment accumulation over a given period of time. We recognise that there will typically be episodes of deposition and scouring within any given time period, and that accumulation on any time scale is the net result of particles arriving and leaving the seabed.

The hierarchy for deriving guideline values ideally uses local biological effects data first, and if these are not available uses local reference data. In the absence of these, the default approach is to use regional reference data or generic effects-based guidelines to develop a “Default Guideline Value” (DGV). There are insufficient analysed data examining the relationships between annual sedimentation rates and ecological condition to produce guidelines from local biological effects data. However, there exists a considerable body of experimental data on the responses of soft-sediment macrobenthic communities to fine-sediment deposition in the immediate aftermath of rainstorm “events”. Event-based guidelines would require extensive resourcing and would likely be difficult for widespread implementation, limiting their utility as a primary assessment approach. Therefore, the knowledge of event-scale effects has been adapted to develop a DGV for annual sedimentation rate, which is likely to be more practical.

Our recommendation is for a Default Guideline Value of 2 mm of sediment accumulation per year above the natural annual sedimentation rate for the estuary, or part of estuary, at hand.

The natural sedimentation rate is defined as the rate under native-forested catchment. It is included in the DGV as a baseline to account for estuaries or parts of estuaries with naturally high rates of sedimentation.

Standing alone, the DGV for annual sedimentation rate will not be sufficient for managing sediment effects in estuaries. However, it may provide benefit as a foundation for a broader framework that includes other elements related to sediment stress, such as suspended sediment concentration (SSC), bed sediment particle size distribution (for mud content), and the areal extent of muddy sediment in an estuary.

There is a limited amount of information on natural sedimentation rates. We recognise that natural sedimentation rates will vary by estuary type and also within estuaries of the same type. We used an adaptation of an existing estuary typology to explore how the limited existing information could be extrapolated, but the exercise was inconclusive.

We reviewed methods for measuring sedimentation across a range of space and time scales. Radioisotopic dating of sediment cores can be used to determine natural sedimentation rates. Buried plates (sometimes called “sediment plates”) can be used to measure sedimentation at a point over short time frames, and repeat bathymetric surveys can be used to measure sedimentation over entire estuaries or parts of estuaries. We recommend a combination of methods spanning a range of temporal and spatial scales as the best option for building up a portfolio of data and for assessing the need for management intervention through application of the ANZECC guideline.

Recommendations related to sediment guidance presented in this report include:

1. The proposed DGV should be refined by further development of relationships between annual sedimentation rate and the health/condition of estuaries. We recommend a more complete evaluation and analysis of the current data, which are limited, before further data are collected.

2. A standardised buried-plate methodology should be developed and continuous methods investigated for future application.

3. ANZECC sedimentation guidelines should be used within a wider framework that considers different modes of impact, multiple stressors, cumulative effects, and thresholds. The issue of indefinite resilience, which refers to the ability of an environment to absorb a given amount of a stressor in perpetuity, rather than in a time-bound capacity (Kelly et al. 2015), needs to be explored as well. This will facilitate better assessments and improved management of sediment stress.

4. Estuarine sedimentation and its effects should be better linked to catchment processes, for example, through an assessment of the interdependence of upstream turbidity, estuarine turbidity and estuarine sedimentation. This will facilitate a clearer understanding of erosion pathways and thereby improve targeted management responses in estuaries.

1 Guidelines for sedimentation in estuaries

The Ministry for the Environment (MfE) is seeking to develop guidelines for sedimentation in estuaries that can be incorporated into the revised Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC 2000 Guidelines).

NIWA was contracted to assist in this area. The scope of our work included a review of methods for measuring sedimentation, a collation of accessible New Zealand sedimentation data, a description of a framework for deriving sedimentation guidelines, and an attempt to provide suitable interim guideline values.

1.1 The aim of the ANZECC Guidelines

ANZECC Guidelines are designed to provide authoritative guidance on fresh and marine water quality in order to facilitate the protection of desirable water resource attributes including, for example, aquatic ecosystems, food production, recreation and aesthetics, and cultural and spiritual values (ANZECC & ARMCANZ 2000 paper 4:1).

Guidelines should be based on the philosophy of ecologically sustainable development ("using, conserving and enhancing the community's resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future can be increased" ANZECC & ARMCANZ 2000), which is also a key component of New Zealand's Resource Management Act (1991) ("sustainable management").

ANZECC & ARMCANZ (2000) does not provide guidance on the rates of sedimentation in either marine or freshwater ecosystems. Paper 4:1 includes turbidity and suspended particulate matter (SPM) recommendations inclusive of estuarine environments, although these are developed only for Australian regions. Guidance is not provided for New Zealand estuaries based on New Zealand data; instead it is suggested that the south-east Australian values are used as interim trigger values[1].

ANZECC & ARMCANZ (2000) paper 4:2 Section 8.4 addresses sediment quality but focuses on the sediment as an environment (e.g., the heavy-metal toxicity within sediments on fauna), rather than sediment as a source of stress.

Our task was to provide guidance on setting an ANZECC Guideline for estuarine sedimentation. We acknowledge, but do not address, suspended sediment or sediment-borne toxicants (e.g., chemical) and instead focus on the physical impact of sediment accumulation on the benthos.

Further consideration is needed to link together catchment erosion/management and downstream effects and their interdependencies, for example, how catchment practices affect riverine turbidity and how this in turn relates to estuarine turbidity and sedimentation. In essence, this will require a holistic approach towards sediment management.

1.2 Sedimentation

We define sediments as naturally occurring particles less than 2 mm in diameter. Sediments are sometimes further categorized into sand (0.0625 to 2 mm), silt (0.0039 to 0.0625 mm), and clay

[1] From section 3.3.2.5 addressing excessive SPM: "*Further work is needed to develop a categorisation system for New Zealand estuarine and marine ecosystems. Consideration should be given to the use of interim trigger values for south-east Australian estuarine and marine ecosystems (Tables 3.3.2–3.3.3) until New Zealand estuarine and marine trigger values are developed*".

(<0.0039 mm). Silt and clay are considered to be "fine" particles, and these particles together are called "mud".

Sediments can be delivered to estuaries from the sea (by waves and tidal currents), or by way of rivers that flow from the land (Figure 1). Riverine sediment input begins with the weathering of rock and the erosion of soils, followed by sediment transport in water and by wind. Once the sediment reaches an estuary, it may travel as bedload[2], be held in suspension[3], be redistributed across an estuary, or move offshore. Under calm conditions, sediment can settle out and become part of the bed material.

"Sedimentation" refers to the accumulation of sediment on the bed. Sedimentation rate is controlled by the availability of source material, delivery processes and the capacity of estuaries to retain or export sediment (Jones 2008).

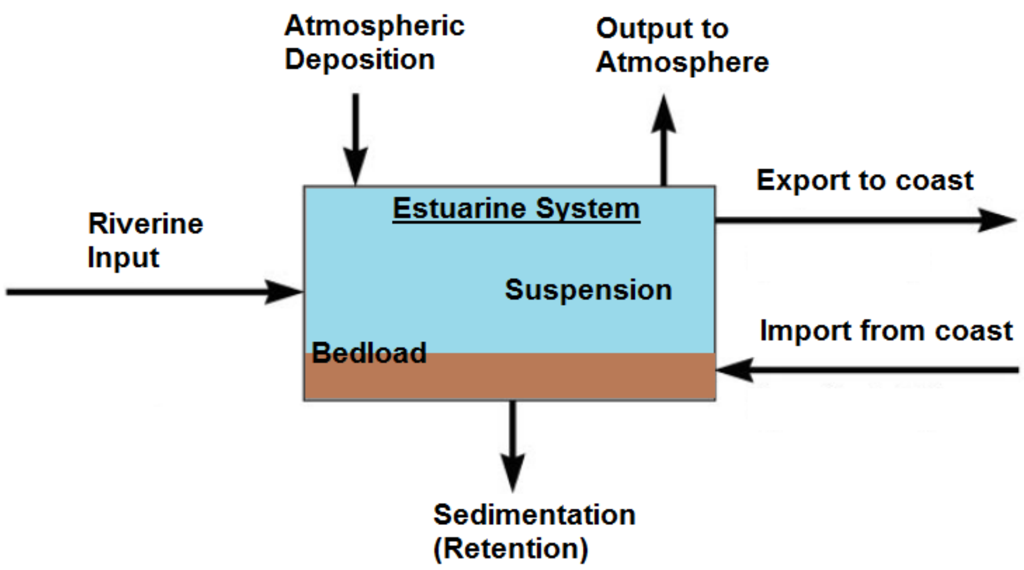


Figure 1: Sediment transport pathways for estuaries, adapted from de Jonge (2000).

1.3 Anthropogenic influence on sedimentation

Herein when discussing the impacts of "sedimentation" we focus on fine sediments, predominantly particles 0.0625 mm in diameter. Although larger particles such as gravels and sands form a part of the terrigenous sediment load to estuaries, they do not have the widespread ecological impacts that fine sediments have.

Although sedimentation is a natural process, there are many human activities that accelerate sedimentation in the coastal environment. Suspended sediment and sediment deposition are now recognised as significant threats in many parts of the world (Thrush et al. 2004). In New Zealand,

[2] Bedload describes the lateral transport of particles in the water just above the seabed. The particles roll, slide or tumble along the seabed due to the motion of the water.
[3] Suspension or suspended load refers to the transport of particles by fluid flow that settle slowly enough such that they may never touch the bed. Water turbulence may keep very fine particles in suspension at any depth in the water column.

catchment deforestation and conversion to pastoral farming and agriculture have increased the rates of sediment runoff from the land. Additionally, since the 1950s, forestry and the harvesting of pine and other exotic timber has expanded, with similar consequences for sediment runoff. A high proportion of sediment is delivered during storms and floods (Hume and McGlone 1986, Oldman 2009). Earthworks associated with urban expansion have also increased the delivery of stormwater and sedimentary material to the marine environment. Although these issues and the potential for sediment impacts are now widely recognised (McKnight 1969, Woods and Armitage 1997; Thrush et al. 2004), empirical information on rates of sediment deposition in New Zealand estuaries, and ecological responses to particular rates of accumulation, is generally lacking.

Short-term “event” sedimentation during and in the aftermath of rainstorms (over hours or days) can have lethal impacts on benthic biota. Many benthic biota are very small (microbes and single-celled algae; meiofauna 0.045 to 0.5 mm; macrofauna 0.5 to 2 mm) and require access to overlying water (for food, oxygen, and nutrients, and to flush away harmful metabolites). Thus, burial under deposited sediment can overwhelm and kill them. This can result in changes in species composition, loss of sensitive species, decline in diversity, and modification of animal behaviours (Hewitt et al. 2003, Thrush et al. 2004, Lohrer et al. 2004, Norkko et al. 2002a). It can also alter microbial activities (which are critical for organic matter degradation and nutrient regeneration), diminish benthic primary productivity, and reduce the oxygenation of surficial sediments (by capping the seabed, clogging sediment pore spaces, and depriving micro- and macrophytes of light)(Berkenbusch et al. 2002).

The consequences of longer-term sedimentation on estuarine communities (over months or years) are not as well studied (Anderson et al. 2004, Townsend et al. 2014). Regardless of the timescale, however, high rates of sedimentation are capable of altering estuarine habitats, modifying ecosystem functions and decreasing a broad range of ecosystem services. This has implications for the benefits that we obtain and the values that we place on the marine environment (Thrush et al. 2013). Suspended sediment and sediment deposition have been identified by local communities as a serious issue, impacting ecological health and amenity value.

Estuarine flats are some of the most productive habitats on the planet (Kennish 2002, Anderson et al. 2004) but they are also complex and dynamic (Roy et al. 2001), meaning that the impacts of sedimentation are difficult to generalise. However, one of the key causes for concern regarding sediment impacts is the potential for legacy effects. Even if strict management is implemented today, the consequences of previous land use decisions may be borne for decades or centuries, with some effects nearly impossible to reverse. To safeguard the functioning of ecological systems and to maintain environmental sustainability, as required under the Resource Management Act (1991), it is vital that sedimentation is limited.

1.4 Definition of sedimentation rate

We define sedimentation rate as the thickness of sediment accumulation over a given period of time.

We recognise that sediment does not necessarily accumulate continuously at a constant rate on an estuarine flat. There will typically be episodes of deposition and scouring within any given time period, and that accumulation on any time scale is the net result of particles arriving and leaving the seabed. For example, an annual sedimentation rate of 5 mm/y could occur from a single 5 mm storm deposit event, 20 mm deposition followed by 15 mm of erosion, a daily deposition of 0.0137 mm, or a variety of other permutations.

1.5 Hierarchy for developing ANZECC guideline values

The current report focuses on deriving guideline values for estuarine sedimentation that, when exceeded, should result in a management response. The guideline should be founded on an understanding of how aquatic ecosystems respond to sedimentation, which in turn should be developed from known relationships between sedimentation rates and measures of ecological condition.

Ideally, guideline values should be set at a point below which the risk to the environment is likely to be low. An exceedance of the guideline value should trigger a management response (i.e., the initiation of further investigations) because of an increased likelihood of significant environmental damage. The hierarchy for deriving guideline values is to first use local biological effects data and, if these are not available, to use local reference data (Figure 2). In the absence of these, the default approach is to use regional reference data or generic effects-based guidelines to develop a 'Default Guideline Value' (DGV) (ANZECC 2000).

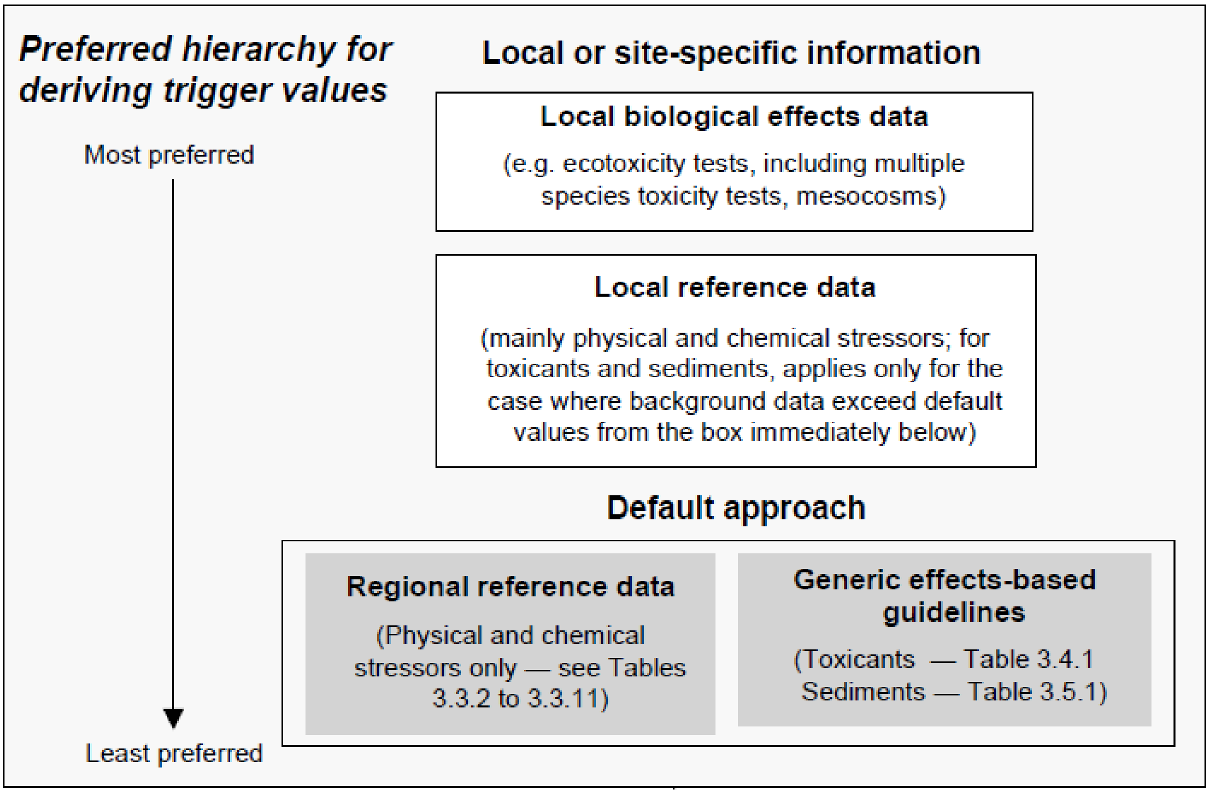


Figure 2: The hierarchy for deriving guideline values, Figure 3.1.2 from Paper 4(1) ANZECC (2000). Trigger values have now been superseded and are referred to as 'guideline' values.

2 Proposed guideline for sedimentation

Studies that have examined the relationships between annual sedimentation rates and estuarine health indicators are generally lacking in New Zealand. Some data are available for event-scale sedimentation but there are only sparse data for longer-term (e.g., annual) sedimentation.

Data were requested from the Environmental Monitoring and Reporting Programme (EMaR, www.lawa.org.nz/explore-data/coastal/) but sedimentation data are not held.

The Regional Councils' Coastal Special Interest Group (C-SIG) provided us with data that they hold. This, in combination with a Ministry for Primary Industries report addressing national marine environment monitoring protocols (MEMP, Hewitt et al. 2014), allowed us to assemble a limited amount of paired data on annual sedimentation rates and ecology (see Appendix A for metadata table). However, only raw data were available; there was an absence of analyses/reports examining the relationships between annual sedimentation rates and ecological condition. Therefore, guidelines could not be developed from "local biological effects data" for annual sedimentation, (Figure 2). Instead, we drew on published information on the ecological effects of event-scale sedimentation (i.e., deposition associated with individual storms). Thus a default guideline value (DGV) was developed.

In the early 2000s, a number of studies were funded by the Auckland Regional Council (ARC) and the Foundation for Research Science and Technology (FRST) to investigate the impacts of fine terrigenous sediments that deposit in intertidal estuarine receiving environments in the immediate aftermath of rainstorms (Norkko, et al. 2001, Ellis et al. 2002, Norkko, et al. 2002a, 2002b, Berkenbusch et al. 2002, Cummings et al. 2003, Thrush et al. 2003a, 2003b, Hewitt et al. 2003, Thrush et al. 2004, Ellis, et al. 2004, Lohrer, et al. 2006a, 2006b, Norkko et al. 2006, Lovelock, et al. 2007, Rodil, et al. 2011). Lohrer et al. (2004)[4] presented results on the impacts of thin deposits (<10 mm) of muddy sediment. This study found that muddy sediment deposited to a thickness of 3 mm in a single event was enough to adversely affect benthic macrofaunal communities (see Case Study Box 1), with negative effects increasing with the thickness of deposited sediment. Adverse effects of thin sediment deposition on macrofaunal communities (in the range of 5mm) have been observed in other New Zealand estuaries, e.g., Rodil et al. (2011) and Reid et al. (2011) (Whangapoua harbour), and also Gibbs and Hewitt (2004) (Mahurangi harbour), so we consider the results of Lohrer et al. (2004) to be appropriate and applicable.

Although we have an understanding (developed from the above-named studies) of the relationship between event sedimentation and ecological effects, we think that event-based guidelines would be impractical and prohibitively expensive for many managers as primary guidance (given the relative unpredictability in space and time of sedimentation events, and the lack of management control over the size and frequency of storms/landslips that deliver sediment). Therefore, we have adapted our knowledge of event-scale effects to develop a DGV based on an annual sedimentation rate, which we think is much more practical[5].

We propose a Default Guideline Value of 2 mm of sediment accumulation per year above the natural annual sedimentation rate for the estuary, or part of estuary, at hand.

[4] Lohrer et al. (2004) is a peer-reviewed scientific publication based on experiments first presented in an Auckland Regional Council Technical Report (Berkenbusch et al. 2002). The technical report is less condensed than the published paper, containing additional experimental details and analysis.

[5] Although we still recommend that event sedimentation could be included as part of a more comprehensive framework (section 4.5)

Our thinking, which follows, is based on the event-scale ecological response data presented by Lohrer et al. (2004) (Case Study Box 1).

- The first step we took was to equate a 3 mm event-deposition thickness, which is known to cause a range of adverse effects, to an approximately annual occurrence. This was supported by the Watershed Assessment Model (WAM) presented by Stroud et al. (1999) for the Okura estuary catchment, Auckland. Their model reported twenty-one 2-3 mm deposition events over a twenty-four year period under land use at the time (Stroud et al. 1999, Berkenbusch et al. 2001). This translates to approximately one event of 2-3 mm thickness per annum. This may or may not be typical of other New Zealand estuaries, though we assume it is for many of them.
- Lohrer et al. (2004) identified significant adverse effects with as little as 3 mm deposition thickness (single event). Therefore, to avoid the initiation of adverse ecological effects, a DGV value needs to be set below the 3 mm threshold. No effects were detected by Lohrer et al. (2004) at 1 mm thickness (single event). Therefore, we propose a DGV at 2 mm/y as a middle ground that is both practical (we have information on frequency) and precautionary (we have information on ecological effects).
- Finally, to factor in estuaries with naturally high rates of sedimentation, we incorporated a natural "baseline" sedimentation into the DGV. The "natural sedimentation rate" is defined as the rate under native-forested catchment. The natural sedimentation rate may vary between different estuaries and within different parts of an individual estuary. As the guideline uses 2 mm/y on top of the natural sedimentation rate, this protects estuaries with naturally high or low rates of sedimentation (providing a guideline appropriate to the estuary or part thereof).

Our proposed DGV was generally supported by the 15 New Zealand experts that attended an estuarine sedimentation guideline workshop (23rd June 2015, Auckland) as a first step. However, most experts supported the tenet that exclusive focus on sedimentation as a metric would not fully address the wider issues of sediment as a stressor in estuarine environments. It was recognised that some guidance was an improvement on no guidance, as long as the operationalisation of the guideline was done remembering that it would not provide full protection.

There are very few catchments in New Zealand presently with 100% native forest cover. Pre-catchment deforestation sedimentation rates have been determined by the dating of sediment cores. For example, estimates of pre-Polynesian annual sedimentation rates in the range of 0.1-0.5 mm/y for the North Island have been found (e.g., Swales and Hume 1995, Swales 2012). For the South Island there are scant data, but there are indications of low rates of sedimentation in some of the less disturbed areas (e.g., Waikawa estuary had an average sedimentation rate of 1 mm/y for the period 1879-1967[6], Robertson and Stevens 2007). Modelling may also be used to determine pre-catchment deforestation sedimentation rates. For any particular area of interest, the natural rate of sedimentation may not be known. In this case, the first consideration would be to use the natural rate of sedimentation from a comparable estuary if one can be identified (see Section 3). In the absence of any information at all, a conservative approach would be to assume a natural annual sedimentation rate of 0 mm/y, which results in a Default Guideline Value of 2 mm/y sediment accumulation.

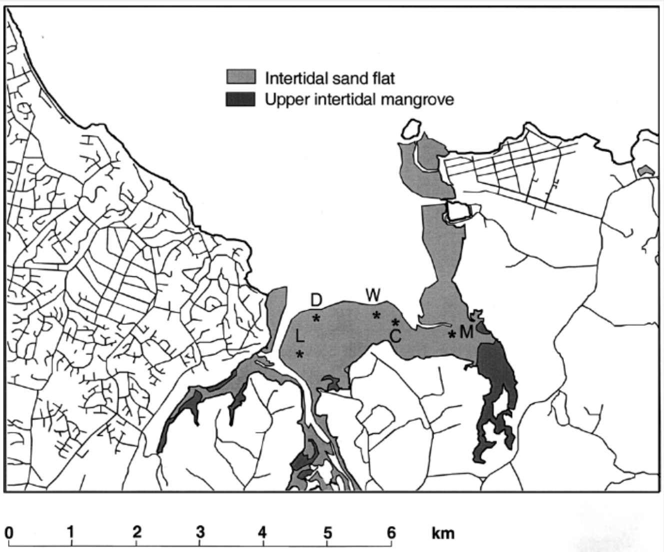
[6] This is not considered a natural sedimentation rate, but is used as an example to show low sedimentation.

Case Study Box 1: Terrestrially derived sediment: response of marine macrobenthic communities to thin terrigenous sediment deposits

Lohrer et al. (2004) examined the response of benthic communities to event-deposition of terrigenous sediment. The study focused on the thickness and frequency at which terrigenous sediment deposits begin to affect the benthos. The study used manipulative experiments in a variety of intertidal habitats in the Whitford Embayment, Auckland, New Zealand. The results of 3 separate experiments, performed at five different sites, were largely consistent with each other.

Experiment 1 was designed to ascertain the thickness of terrigenous sediment sufficient to affect macrobenthic community structure. Five treatments were established at sites C and W (see map) to create gradients of terrigenous sediment thickness: 7, 5, 3 and 1 mm treatments, plus 0 mm controls. Treatments were replicated 4 times per site except for the 7 mm treatment which was replicated 2 and 3 times at sites C and W, respectively. The sites were chosen to represent a variety of intertidal sandflat habitats that encompassed a range of hydrodynamic conditions, sediment properties and benthic community types. Terrigenous material used in the experiment was obtained from a hillside excavation in the Whitford catchment and was dominated by fine particles (78% <63 µm). To quantify the effects of experimental sediment deposition on macrobenthic community structure, 2 cores (13 cm diameter, 15 cm depth) were collected on the final day of each experiment (after 9 to 10 d), sieved over a 500 µm mesh and the communities identified and enumerated. Experimental plots were never completely defaunated, but as little as 3 mm of the terrigenous material was sufficient to significantly alter macrobenthic community structure (measured after 10 days, relative to 0 mm deposition in the control plots). The impact was predominantly negative, with the number of individuals and taxa and the densities of nearly every common species declining as a result of the sediment application. Taxa that may have been negatively affected by experimental sediment deposition included polychaetes (*Prionospio aucklandica, Orbinia papillosa*), gastropods (*Notoacmea helmsi*, *Zeacumantus lutulentus*, *Diloma subrostrata*), decapods (*Halicarcinus whitei*), amphipods (Paracalliopidae, Phoxocephalidae), and bivalves (*Linucula hartvigiana*, *Austrovenus stutchburyi, Macomona liliana*). Large bivalves were less affected than smaller ones, and deeper-dwelling species were less affected than those living at the sediment surface.

The other experiments in this study found that the repeated application of thin terrigenous layers (3 mm thickness, monthly over a 6-month period) resulted in the macrofaunal community composition progressively diverging from controls, and that repeated depositional events did more damage than single ones.



Left: Map of the Whitford Embayment and sites used in the study by Lohrer et al. (2004).

3 An estuarine typology for evaluating natural sedimentation rate

There is considerable variation in the forms and characteristics of New Zealand estuarine systems that is likely to drive variation in the rates of natural sedimentation (Dyer 1997, Hume et al. 2007). As natural sedimentation rates are part of the DGV formulation[7], it is of interest to see if similar types of estuaries have comparable rates of natural sedimentation. An estuarine typology could provide a useful framework for accounting for differences in natural sedimentation rates between different classes of estuaries.

Hume et al. (2007) produced a "controlling factors" approach to estuarine classification in New Zealand (Estuary Environment Classification, EEC) based on abiotic components divided over three levels. Level 1 differentiates global-scale variation based on differences in climatic and oceanic processes. Levels 2 and 3 are most relevant to the current context. Level 2 differentiates hydrodynamic processes in estuaries based on basin morphometry and river and ocean forcings, which results in dividing estuaries into 8 types (A-H). Level 3 differentiates estuaries based on catchment characteristics of geology and land-cover. Catchment geology divides into 5 classes and land-cover divides into the 4 classes of urban, pastoral, exotic and natural.

In adapting Hume et al. (2007) for our purpose, we combine the 8 hydrodynamic process categories with the 5 catchment geology classes, which produces 40 possible classes in total (Table 1). We do not include land-cover, despite this having influence on contemporary annual sedimentation rates, as our focus here is to look at sedimentation under natural conditions (where land cover would all be in the "natural" class).

Table 1: An estuarine typology for sedimentation based on Hume et al. (2007). In total, 40 classes are possible from the 8 hydrodynamic processes and the 5 different geology types (8 x 5). See Hume et al. (2007) for full definitions of class attributes.

	Hydrodynamic Processes	Geology Type
Category A Estuary	very shallow basins, elongate in shape	soft sedimentary
Category B Estuary	elongated basins, simple shape	hard sedimentary
Category C Estuary	mouth of a main river channel connects to shallow lagoons	volcanic weak
Category D Estuary	simple shorelines, wide entrances, open to the Ocean	volcanic strong
Category E Estuary	shallow, circular to slightly elongate basins with simple shorelines and extensive intertidal area	strong plutonic
Category F Estuary	shallow basins, narrow mouths, usually formed by a spit of sand barrier	
Category G Estuary	very deep (up to hundreds of metres), narrow, elongate and largely subtidal basins	
Category H Estuary	deep (tens of metres), narrow, elongate basins and largely subtidal	

Table 2 is a compilation of data on natural annual sedimentation rates from intertidal sites in different estuaries in the North Island. These rates are considered to be natural as they apply to native-forested catchment, predominately prior to human settlement in New Zealand or early into European settlement (before large-scale catchment changes).

[7] Default Guideline Value of 2 mm of sediment accumulation per year above the natural annual sedimentation rate for the estuary, or part of estuary, at hand.

Each row in Table 2 represents data from an individual sediment core[8], with some estuaries having multiple sites. Data have not been standardised to any particular location in an estuary. While there is some replication of hydrodynamic classes in Table 2, there are few geology types. For the hydrodynamic classes B and F, there is only a single geology type (soft sedimentary). This is the same for hydrodynamic class C, which has one geology type (volcanic weak). E is the only class where there are two different geology types (volcanic weak and volcanic strong). We conclude that there are insufficient data to fully explore the typology.

Table 2: Summary of natural sediment accumulation rates (SAR) in North Island estuaries from carbon dating of cores, applied to sediment horizons laid down under native-forested catchment. Data compiled by Andrew Swales from Hume and McGlone (1986), Hume and Dahn (1992), Oldman and Swales (1999), Swales et al. (1997, 2002, 2012, 205), and Swales and Hume (1994, 1995, 2005). HD (hydrodynamics) for estuaries A-H from Hume et al. (2007). Geology covering soft sediment (SS), volcanic weak (VW), volcanic strong (VS), miscellaneous and multiple. Sediment Accumulation Rate (SAR) is in mm per year. *Time period that SAR applies to is predominantly pre-human, but later in a few cases.

HD Class	Geology	Estuary	Sub-system	SAR (mm/year)	Time period
B	Misc	Pakuranga	Tidal Creek	0.4–0.5	Pre-human
B	Misc	Pakuranga	Tidal Creek	0.2–0.3	Pre-human
B	SS	Mangemangeroa Creek	Tidal Creek	0.04	Pre-human
B	SS	Mangemangeroa Creek	Tidal Creek	0.14	Pre-human
B	SS	Lucas Creek,	Tidal Creek	~1.5	Pre-human
C	VW	Wharekawa Hbr		0.11	Pre-1880*
C	VW	Wharekawa Hbr		0.10	Pre-1880*
D	**	Firth of Thames		0.49	Pre-1905*
E	VW	Coromandel Hbr		0.03–0.7	Pre-human
E	VW	Coromandel Hbr		0.43–0.94	Pre-human
E	VS	Whangapoua Hbr		0.08	Pre-human
E	VW	Whaingaroa Hbr	Waitetuna Arm	0.38	Pre-human
F	SS	Mahurangi Hbr	Pukapuka Inlet	0.39	Pre-1850*
F	SS	Mahurangi Hbr	Upper Harbour	0.62	Pre-1850*
F	SS	Mahurangi Hbr	Tidal River	0.77	Pre-1850*

*Some time periods extend to post-human arrival, but as carbon dating measures sedimentation over several thousand years, with most of this period pre-dating large scale catchment changes, the effect on the estimated natural sedimentation rate is considered to be minor (A. Swales, pers. comm.). ** Multiple geology types feeding the estuarine system.

Error! Reference source not found. is a summary of the information inTable 2 organised by hydrodynamic class. **Error! Reference source not found.** demonstrates that only 5 of the possible 8 hydrodynamic classes are present. A key feature of **Error! Reference source not found.** is the wide range in measured natural annual sedimentation rates within classes, and the small differences between classes.

[8] Additional information, including core identification code, information on the calibrated ^{14}C age (years before present), the methods used and the specific data source per row, have been removed due to space limitations. For further information contact Andrew Swales (Andrew.Swales@niwa.co.nz)

Table 3: Variation in sediment accumulation rate for different hydrodynamic classes of estuaries from Hume et al. (2007).

Estuary Type	Minimum SAR (mm/year)	Maximum SAR (mm/year)	Range SAR (mm/year)	Time Period
Type A	x	x	x	x
Type B	0.04	0.5	0.46	Pre-human
Type C	0.10	0.11	0.01	Pre-1880
Type D	0.49	0.49	0	Pre-1905
Type E	0.03	0.94	0.91	Pre-human
Type F	0.39	0.77	0.38	Pre-1850
Type G	x	x	x	x
Type H	x	x	x	x

High within-class variation in annual sedimentation rate is a likely indication of the importance of site position within an estuary from where a core was collected. It is usually the case that some parts of estuaries accumulate sediment more quickly than other parts. Very broadly speaking, most estuaries will have sheltered areas in the upper reaches and in tributary creeks where annual sedimentation rates are relatively high, and exposed areas in central and outer sections, where wind, swell and currents prevent particles from settling and accumulating on the bed. In the latter areas, suspended sediment concentrations rather than sedimentation rates are likely to be the controlling factor on the ecological health. For sedimentation rate data to be useful to test the estuarine typology, data for each estuary would need to be representative of the relative abundance of these different areas, or standardised for a particular type of area.

4 Measuring sedimentation

4.1 Spatial considerations

Monitoring sediment accumulation rates to determine whether or not DGVs have been exceeded for an estuary will require spatially stratified sampling designs. These designs will need to be carefully considered and interpreted because, as previously mentioned, sediment does not accumulate evenly or universally across the spatial extent of an estuary. When monitoring sedimentation, it is recommended to avoid exposed areas and focus on depositional zones and mid-estuarine areas where sediment can potentially accumulate.

It is recommended to avoid averaging sedimentation across all sites in the search for a single univariate statistic for the whole estuary. While this may have appeal (for example, for addressing the question, "does the 'whole' estuary exceed or fall below ANZECC guidelines?"), it is difficult to interpret this statistic meaningfully. An estuary with an "overall" average sedimentation rate below the ANZECC guideline may still contain multiple sites where the levels are exceeded and where management consideration is warranted. Furthermore, if exposed sites with low sedimentation have been included (not recommended), these sites will reduce and 'dilute' the magnitude of the overall sedimentation rate, again failing to instigate a management response. A better approach is to examine estuarine sites individually, or by category, and then initiate a proportionate management response following a review of the data.

4.2 Low rates of sediment deposition and high background variability

Some tidal creeks, mangrove forests and estuaries at the base of large catchments currently have rates of sedimentation in the range of 10-30 mm/y (Hume and McGlone 1986, Sheffield et al. 1995). Sedimentation rates may be substantially lower than this in exposed locations but still sufficiently high to trigger management action given the proposed DGV (2 mm/y above the natural rate of sedimentation). Therefore, methods for measuring sedimentation need to be suitably accurate and precise.

The dynamic and variable nature of estuarine receiving environments complicates the measurement of sedimentation. Estuarine and marine sediments are not homogenous flat surfaces, instead they typically contain many micro-topographic features (Figure 3). The biota inhabiting soft-sediment habitats can have a major impact on sediment surface topography, with mobile animals mixing and reworking sediments (bioturbation), other animals creating vertical relief via burrow and tube structures, and shell hash and plant material (macroalgae, seagrass, mangrove) creating heterogeneity also. Bioturbation commonly alters the sediment surface by 10-20 mm, and for some species in the region of 20-200 mm (e.g., the bivalve mollusc *Arcuatula senhousia*). Sediment surface features can also be generated by physical processes such as tidal currents and waves. In New Zealand estuaries, ripples on the sediment surface are common in exposed sections (ripple heights ~10 to 15 mm). Physical and biological processes generate variation in sediment topography over differing spatial and temporal scales. Methods for measuring sedimentation must detect small changes in seabed height on top of high natural variation. This makes it extremely difficult to measure sedimentation accurately and precisely on short time scales.

Figure 3: Sediment topography in estuaries presents a challenge for mapping small changes in sediment height. Photos of Okura estuary where strong physical and biological features are common on intertidal sandflats (left) and depositional zones in the upper estuary (right).

4.3 Methods for measuring sedimentation

To measure sedimentation rate for comparison against the proposed DGV, standard protocols that are robust and repeatable across a broad range of conditions will need to be developed. Measurement methods will have to be sensitive enough to distinguish changes in sedimentation over appropriate timescales (see Section 4.4.1). Here we provide a synopsis of the strength and weaknesses of a subset of different methods (see Appendix B for further methods and details) and we make recommendations for setting and assessing compliance with guidelines.

Natural and historic sedimentation measures: Coring and dating methods (isotope tracing, caesium-137, lead-210, carbon-dating, pollen-dating) are moderately expensive and generate long-term averages for annual sedimentation rates. The time period of the averaging depends on the isotopes or tracers used and the horizon in the core that one is analysing. Using multiple isotopes increases the confidence in the dating by offsetting the limitation of any single approach. However, the continued reworking of the upper part of the sediment column by biophysical processes (the top 5-10 cm in many cases) generally interferes with the dating of recently deposited sediments. While radioisotopic methods are useful for determining historic and natural rates of annual sedimentation, their applicability to present-day monitoring is limited[9].

Fine-scale contemporary sedimentation measures: Contemporary fine-scale measures of sedimentation principally focus on changes in bed height from a known reference point (e.g., sediment rods, traps, plates). These devices are typically cheap to install, but sampling needs to be conducted at regular intervals, which contributes to ongoing labour costs. They provide information on sedimentation at a point from daily to monthly to yearly temporal scales. There are issues with

[9] Their value in estuaries subject to earthquakes / seismic redistribution of sediments is also limited.

accuracy and with artefacts in the data, including overestimating (e.g., traps that prevent resuspension) and underestimating (scour induced by apparatus protruding from the sediment surface) sedimentation rates (Figure 4).

Buried-Plate method

Of the contemporary sedimentation measures, a standardised buried-plate method (sometimes called a "sediment plate") offers some potential for generating nationwide data in a consistent manner. This method is currently used by many regional councils but has varied appraisals with respect to the variability, accuracy and utility of the data. Waikato Regional Council has >15 years of buried-plate data from Raglan and the Firth of Thames, but have found the data to be highly variable Figure 5, H. Jones pers. comm.). Auckland Council buried-plate data also have high variability (2010-2014 data, average range amongst replicates of 15.6 mm, standard deviation of 6.5 mm) (unpublished data). The source of the variability is not yet clear; some may be real (accumulation rates are likely to differ over time and space), some may be due to the difficulties of acquiring accurate and repeatable measurements (measurement error), and some may be attributable to "outlier" factors (Northland Regional Council plate data were compromised by colonisation by a sediment accumulating species, *Arcuatula senhousia*).

The effectiveness of the buried-plate method varies in different circumstances. It may be most effective in sheltered areas that are free from ripples and high rates of biological reworking, when a high number of replicate measures are taken from individual plates, when there is high consistency between replicate plates, where measurements are taken carefully and precisely, and where equipment is arranged to avoid biases. However, there are also situations where the data can be erroneous if the design is incorrect, when there is disruption to the monitored area (Figure 4), and where averages are accepted without a consideration of variance. High levels of precision and accuracy cannot be assumed with the buried-plate method, and it is vital that managers evaluate the method as they locally apply it. The buried-plate method would benefit from a national review with a thorough assessment of its precision and accuracy, and a characterisation of the conditions under which it is most effective. Additionally, the development of a standardised methodology in line with a national marine environment monitoring protocol (Hewitt et al. 2014) would be useful, as currently there are multiple variations of this method in use. Below we provide some basic guidance and aspects in need of further consideration:

1. Care is needed to select sites that are representative of an estuary and that are suitable for the measurement of sedimentation. One should avoid areas where sedimentation is prevented due to high exposure and/or strong tidal currents (where other measures of sediment stress are more appropriate, e.g., suspended-sediment concentration).

2. Each site should ideally have a minimum of four plates to capture within-site variability. Plates should be separated by approximately 10-40 m in a line or square formation (plates in the four corners of the square).

3. Plates should be made from a robust material such that the action of measuring sediment depth by inserting a rod into the sediment and making contact with the plate does not alter the position or the integrity of the plate. If a firm mesh is used, it is important that this mesh can withstand repeated contact with the measuring rod without bending. Plate material should be of sufficient quality (e.g., treated/coated mesh, marine grade concrete) so the integrity is not compromised over the time scale

of measurement, which may be many years. Plate material should be selected with a consideration of the environment for deployment as there is evidence to suggest that under extremely muddy conditions (very soft, deep, mud) paving slabs can sink further into the sediment (therefore, mesh may be more suitable). A ‘fitness for purpose’ assessment should precede the choice and deployment of plates.

4. Plates should be buried to a depth where they are stable. This is usually 30 cm or deeper. Sufficient care should be taken to ensure that plates are level (perpendicular to the vertical plane).

5. After plates have been deployed it is good practice to allow a ‘bedding in’ period before measurements are collected, e.g. 3-6 months. This is because the sediment surface may still be uneven from the burial process or there may be disruption around the site, and it may take multiple tidal cycles for this to re-equilibrate.

6. It is recommended that the absolute level of each buried plate is initially measured by a qualified surveyor (after the ‘bedding in’ period), and if possible at intervals thereafter (e.g., 5 yearly). The first measurement of sediment depth from the plates is critical because this is used as the baseline from which accumulation (or scour/erosion) is subsequently measured.

7. A systematic approach is needed in the configuration and demarcation of buried plates within a site, and across multiple sites and estuaries. This is so plates are easy to locate and sample repeatedly over time. Marker pegs are commonly used, but these must be a sufficient distance away from the plate. Figure 4 demonstrates a pitfall where marker pegs have been placed too close to the plate (<1 m) and have caused scour over the area of sediment where sedimentation is being measured (which invalidates any data collected). It is recommended that marker pegs are located ~5 m away from each plate on a horizontal axis. A 5 m length of rod or tape measure can be laid along the sediment surface from the peg to rapidly locate the centre point (below which the plate is buried). Marker pegs should not be solely relied upon to locate sites/plates as these are fallible (human intervention, weathering over time, etc.). Accurate waypoint coordinates of plate locations are needed (i.e., GPS records).

8. Sediment depth is measured by inserting a ‘depth rod’ into the sediment until the plate is reached. The depth rod should be (a) strong, so that it does not bend and is not hindered by shell hash, (b) thin, so as not to displace large volumes of sediment during measurement, which can disrupt the sediment matrix, and (c) marked at cm and mm intervals to facilitate measurement.

9. Plates should be of a sufficient size that they are easy to hit with the depth rod and so that multiple measurements of sediment depth can be collected from their surface. It is recommended that plates should not be smaller than 45 x 45 cm.

10. Estuarine surfaces have topographic features created by benthic organisms and hydrodynamic processes. These should be measured and captured in replicate measurements; the sediment surface should never be smothered flat.

11. Collecting multiple replicates is an essential step in determining the variability as well as the average rate of sedimentation for a plate. The number of replicates required is

affected by the natural variability in sediment topography, although it is recommended that a minimum of 5 and preferably 10 measurements are collected per plate. Variance around the mean of a plate and around the mean of the 4 plates per site (avoiding pseudo-replication in variance statistics) should be reported.

12. The required frequency of measurements is influenced by multiple factors but plates should be monitored twice per year at a minimum and preferably quarterly, bimonthly or monthly.

13. Care should be taken to minimise human disturbance around sites during sampling. The use of mud-shoes or plywood boards (to distribute weight and minimise foot prints) may help to minimise impacts to very soft sediments. Consideration should be given to the impact of sampling on the integrity of the measurement (i.e., is disturbance such that the sedimentation measure cannot be trusted?). This may include observing the site at intervals (1 day, 2 days, a week, two weeks) after sampling to see if the remnants of disturbance persist.

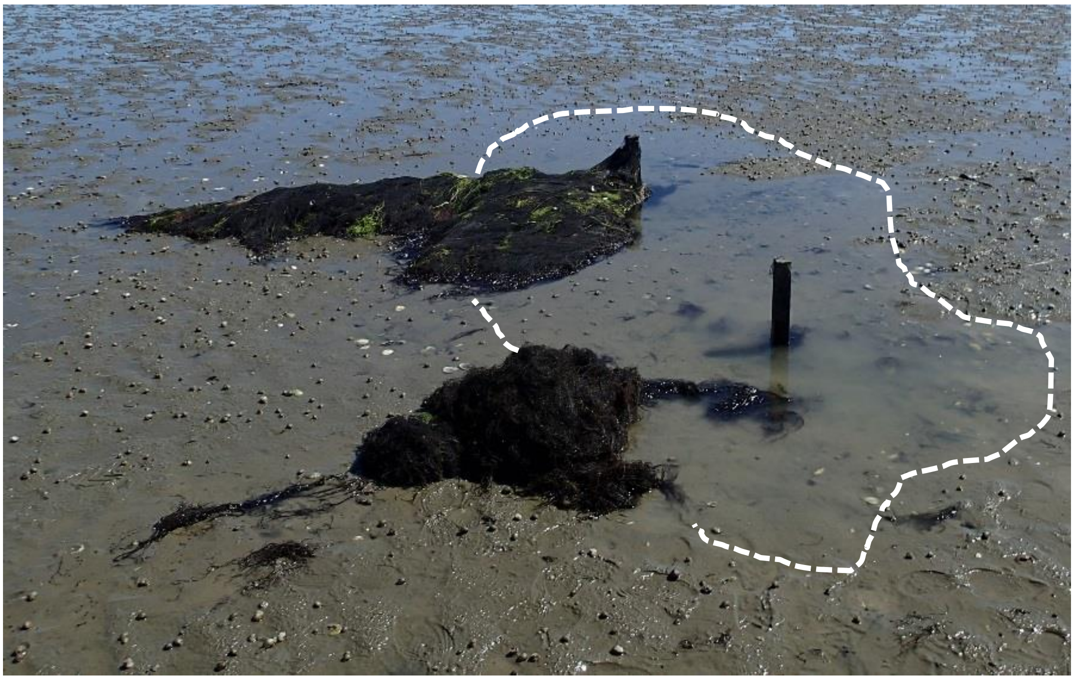


Figure 4: A buried plate where scour has occured. The plate is buried between the two pegs and a deep scour depression can be seen (white lines). The scour is caused by macroalgae catching and pivoting on pegs with the ebb and flood of the tide. This could have been avoided if the pegs were spaced further apart, a greater distance away from the plate.

Broad-scale contemporary sedimentation measures: Broad-scale measures evaluate the deposition of sediment through changes in bed height across transects or over defined areas of the seabed (e.g., beach transects, bathymetric surveys, LIDAR, RTK). Bathymetric surveys are typically conducted infrequently, repeated every 5-10 years, with changes in seabed height used to calculate average annual sedimentation rates. The major benefit is that this moves beyond the point-scale and provides spatially averaged sedimentation rates in specific habitats or across entire estuaries. A limitation of broad-scale techniques is that the accuracy has historically been low. For example, Mead and Moores (2004) reported measurement errors of 30-50 mm elevation for bathymetry surveys. However, technology is improving, and measurements over large areas smooth out the point-scale instrumental error. This type of surveying may prove to be a viable option for monitoring average annual sedimentation rates and assessing against ANZECC guidelines. A downside is the time and expense, especially as at least two surveys per estuary (5-10 years apart) would be required to generate average annual sedimentation rate data.

4.4 Monitoring and applying guidelines

There is no single measurement technique that stands out in superiority; all methods have weakness or flaws in different situations. Therefore we recommend the use of multiple complementary methods to provide perspective and reference and to increase confidence. A combination of fine-scale and broad-scale approaches will help to evaluate sedimentation over multiple spatial and temporal scales and to build a greater portfolio of information for assessing the need for management intervention (through application of the ANZECC guideline).

We recommend a tripartite approach of :

1. **One-off** - dating of sediment cores for an historical perspective on sedimentation and to determine natural sedimentation rates, which are required for the calculation of the default guideline value. Ideally, different parts of each estuary will be sampled.

2. **Periodic** - broad-scale bathymetric surveying every 5-10 years, done by qualified marine surveyors using the latest technology (e.g., RTK GPS positioning systems, high-frequency digital sounders). Survey errors will need to be evaluated and reported.

3. **Frequent** - Fine-scale buried-plate monitoring at monthly to quarterly intervals, using multiple plates with standardised methodology in locations where the technique has been shown to be effective. Continual evaluation of the method will be required.

4.4.1 Timescale

In areas where there is high annual deposition (e.g., 30 mm/y; Hume and McGlone 1986, Sheffield et al. 1995) most methods would be able to detect the exceedance of the ANZECC default guideline value quite readily. However, if an estuary has an average sedimentation rate of 3 mm/y, while the sedimentation monitoring method has an accuracy of +/- 20mm, then ~7 years would likely be required to reliably demonstrate change. Ultimately, extended periods of monitoring will help to increase the size of datasets and the ability to detect long-term trends (Figure 5).

Figure 5, as an example, shows high month-to-month variation in buried-plate depth for a single plate at Kaiaua in the Firth of Thames between March 2003 and April 2014. The data show a trend of 0.14 mm sediment accumulation (over the top of the plate) per month, which corresponds to an average annual sedimentation rate of 1.71 mm/y (significant general linear model, t=2.56, P = 0.0123), and is less than the 2 mm/y DGV (in the absence of natural annual sedimentation rate data, assumed to be zero). Nevertheless, the significance of the short-term variability on the ecosystem condition is also of interest. There are many months where the sediment depth changes by well over 2 mm, which suggests a dynamic sedimentary environment.

Figure 6 shows variability in plate depth for Mangemangeroa Creek, Auckland. Here, differing levels of variability in different parts of the estuary are evident. Further research is needed to determine the ecological significance of short-term variation in sediment deposition/erosion relative to the longer term annual sedimentation rate. Ecological monitoring that accompanies the sedimentation data may help to explain the significance of the fluctuations to the biota.

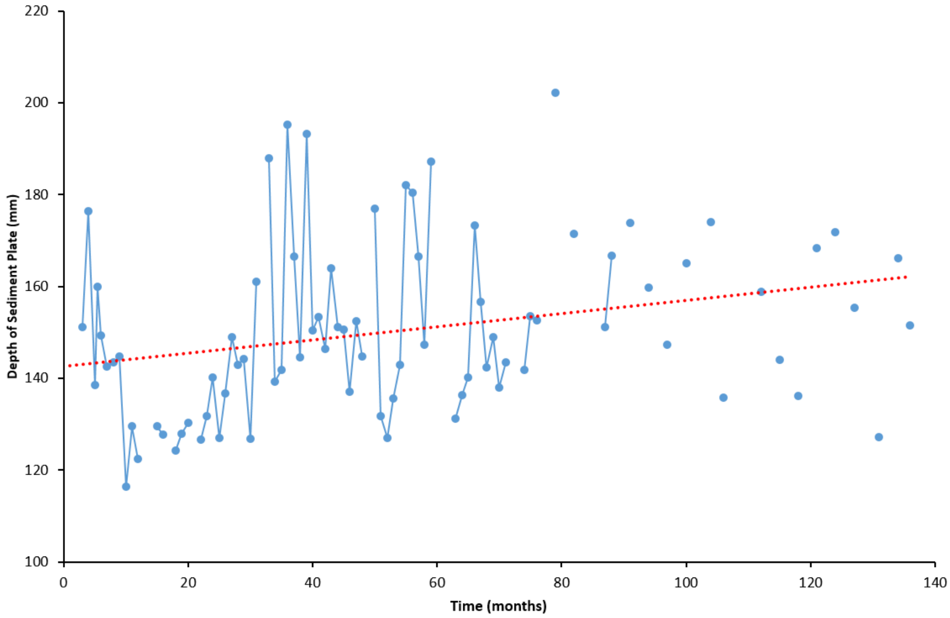


Figure 5: An example of buried-plate data from Kaiaua, Firth of Thames. For the first 6.5 years buried plates were sampled monthly (dots joined by lines), but reduced to quarterly sampling thereafter (dots, no lines). The data demonstrate considerable month to month variation, possible long-term (greater than annual) cycles and an indication of an upward trend over the 11 years of monitoring (linear least squares regression fit to the whole data set depicted by the dotted red line; $y = 0.14x + 142.68$ $R^2 = 0.075$).

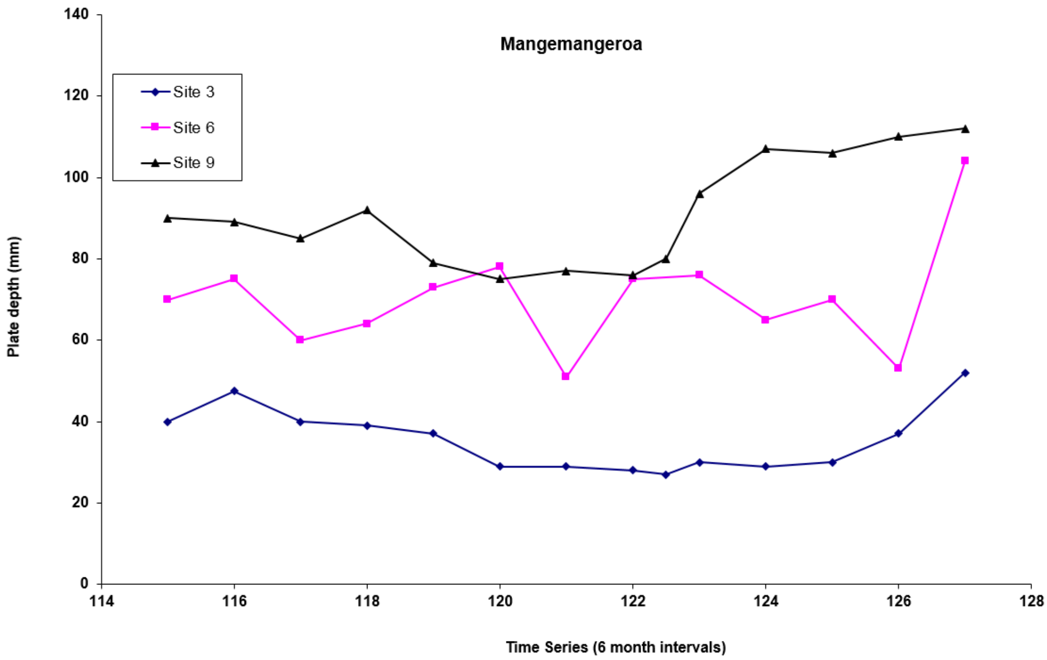


Figure 6: An example of buried-plate data from Mangemangeroa Creek, Auckland over a 6 year period. Some sites have higher variability than others (relatively low at site 3, which is towards the mouth of the estuary, high at sites 6 and 9, which are in the mid and upper estuary, respectively).

4.5 A multi-criterion framework that considers other manifestations of sediment-related stress

Annual sedimentation rate can be a useful indicator of sediment stress. However, not all sediment stress is represented by sedimentation and thus will not be detectable from this measure alone.

There are two key aspects to consider here. Firstly, it is important to be clear on what the guideline is designed to achieve and to avoid over-interpretation (i.e., falsely arriving at the conclusion that *annual sedimentation rate is low, therefore, sediment is not a significant stressor in this estuary*). Secondly, ANZECC guidelines for sedimentation should be nested alongside other indicators for a more complete evaluation of sediment stress (Figure 7).

A more complete framework should include:

- **Suspended sediments:** High concentrations of sediment particles can be held in suspension when hydrodynamic energy (waves, currents, turbulence) prevents particle settling (Dyer 1997). Suspended-sediment concentration (SSC) can still be high in environments where sedimentation is low (e.g., intertidal flats near Auckland Airport in Manukau Harbour; Harris et al. 2015). Suspended sediments can be deleterious for marine benthic fauna when concentrations are high enough to clog respiratory or feeding structures. Many species are known to be highly sensitive to suspended-sediment stress (Hewitt et. al. 2001, Norkko et al. 2006). Estuaries with high sediment loading from their catchment and riverine inputs can have persistently high levels of suspended sediment, despite daily exchange and export to the coastal marine environment. Guidelines might include various measures of suspended sediments, including effects on optical properties (light penetration, visual clarity).
- **Areal extent of muddy substrate:** Sustained sedimentation, even at rates below the proposed DGV, may result in a long-term muddying of the seabed. The long-term implications of fine-sediment deposition are likely to include an increase in bed-sediment mud content and an increase in the spatial extent of muddy substrate. The ecological implications of increasing mud content are the loss of mud-sensitive species from benthic communities, reduced biodiversity, the loss of large functionally important species, reduced functional redundancy, and altered biogeochemical fluxes and cycles (Thrush et al. 2004 and references therein, Pratt et al. 2014, Hewitt et al. 2012). A recommendation that 'the areal coverage of muddy substrate in an estuary should not be increase from its current extent' could form the basis of a guideline.
- **High-magnitude, short-duration storm events:** Storm-related sediment loading can have major impacts on benthic communities, yet monitoring may fail to record these episodes. For example, spikes in SSC after storms often subside after several cycles of tidal flushing, and thick sediment deposits eventually erode away, yet the ecological legacy of these effects can be long-lasting. Further work is needed to determine guidelines for event sediment loading and to understand relationships between annual sedimentation and the frequency/severity of storm events.

The multifaceted and various ways in which sediment stress can manifest in estuaries suggests that a direct focus on ecological communities is prudent. Benthic ecological (macroinvertebrate) monitoring is conducted by a majority of regional councils (Hewitt et al. 2014), and data are used worldwide to assess ecological health and stress impacts (Weisberg et al. 1997, Borja et al. 2000, Anderson et al. 2002, Bremner et al. 2003, Rodil et al. 2013). The inherent sensitivity of benthic ecological communities (containing multiple species of varying functional types, with varying tolerances to sediment stress, that are sedentary and long-enough lived to integrate conditions over several months to years) often makes them better indicators of sediment stress than the measures of the sediments themselves[10]. Particularly because species loss has implications for the types and amounts of benefits that humans derive from estuarine systems, ecological community monitoring must remain a priority.

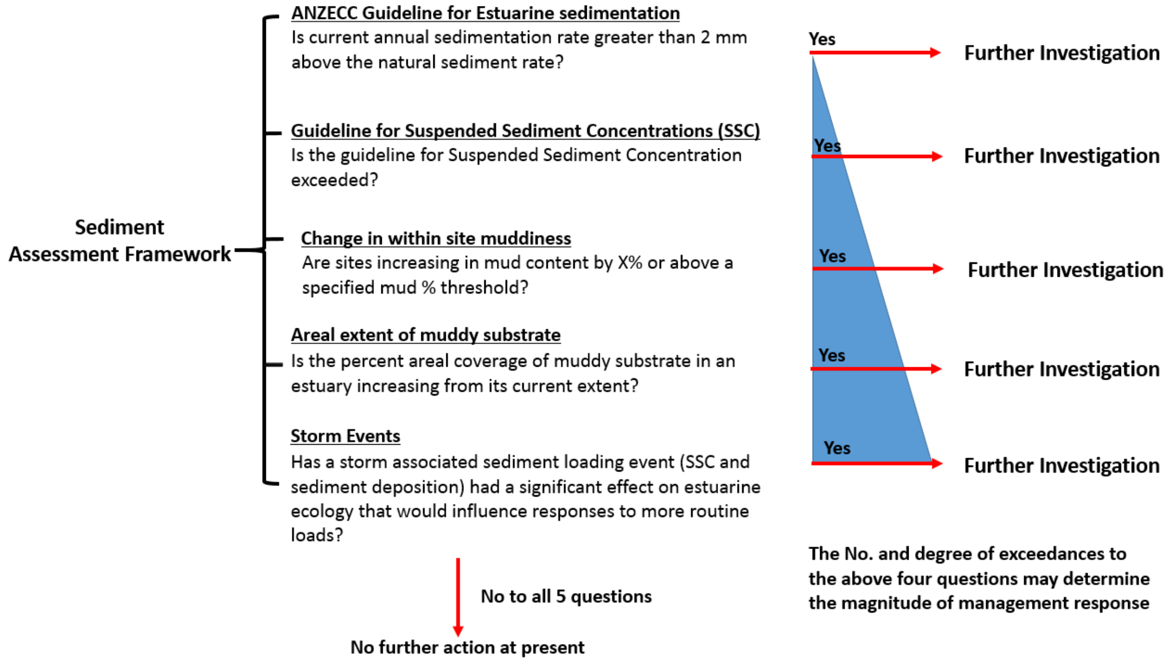


Figure 7: A framework within which the annual sedimentation rate ANZECC guideline should be nested for a more complete assessment of sediment stress. Currently there are no New Zealand developed guidelines for estuarine turbidity. Width of blue band is proportional to the magnitude of management response that is likely to be required.

Managing for a sedimentation rate without specifying a finite time frame implies "indefinite resilience" in the system being managed. This refers to the assumption that the environment can absorb a given amount of a stressor in perpetuity, rather than in a time-bound capacity (Kelly et al. 2015). With a physical material such as sediment that will not dissolve, even a small amount of accumulation on an annual basis will eventually lead to degradation (muddying, infilling, loss of desirable characteristics). Cumulative changes are already being observed in some New Zealand estuaries (Figure 8 and Figure 9). These examples indicate an increase in bed-sediment mud content from roughly 10 to 20% in ten years, a level of change that has been shown to have significant effects[11] on species occurrence, abundance, richness and functional redundancy in New Zealand

[10] Benthic communities are also inherently variable over space and time, yet ecological monitoring has demonstrated how, with an appropriate resolution, seasonal cycles, trends and changes in composition can be observed and related to changes in the environment such as mud content or contamination. See Hewitt et al. (2012) for an overview.

[11] Although a change from 80 to 90% mud in ten years, however, may be scarcely noticeable.

estuaries (Rodil et al. 2013, Townsend et al. 2012). Furthermore, this change would be noticeable under foot[12].

Management guidance is required on acceptable levels of cumulative change in estuarine sedimentary environments. Current scientific understanding indicates that tipping points or threshold changes may occur in response to elevated mud, beyond which the system undergoes significant change (Figure 10). Being able to identify thresholds in ecosystem responses to stressors is critical for environmental protection, yet this knowledge has proved elusive. Research is required on cumulative effects and thresholds, and how the issue of indefinite resilience should be handled in a management context.

Although the focus of the present study has been on the development of a guideline for sedimentation, a complementary guideline for seabed muddiness could be useful. Bed-sediment mud content is relatively simple and cheap to measure, and is already a component of many monitoring programmes. Ecological responses to bed-sediment mud content are also reasonably well understood. Underfoot condition (muddiness) is a key component in human preference and the value people place on marine environments (Batstone and Sinner 2010). A guideline could involve maintaining bed-sediment mud content below a critical value across a specified areal proportion of an estuary. There is a good understanding of how benthic communities and functional health change over mud gradients (Hewitt et al. 2012) and this could be used to derive the guideline. For example, Rodil et al. (2013) demonstrate how functional health changes in relation to mud content (index scores were highest below 10% mud and always low above 60% mud). Nevertheless, converting this information into guidelines for areal extents in estuaries would require a process similar to the one undertaken for sedimentation (e.g., literature review, data mining, workshopping, consultation, peer review).

[12] The measurement of sediment mud content (% of particles <63 um in a sediment sample) is relatively simple, cheap, informative, and widely done in association with estuarine monitoring programmes worldwide.

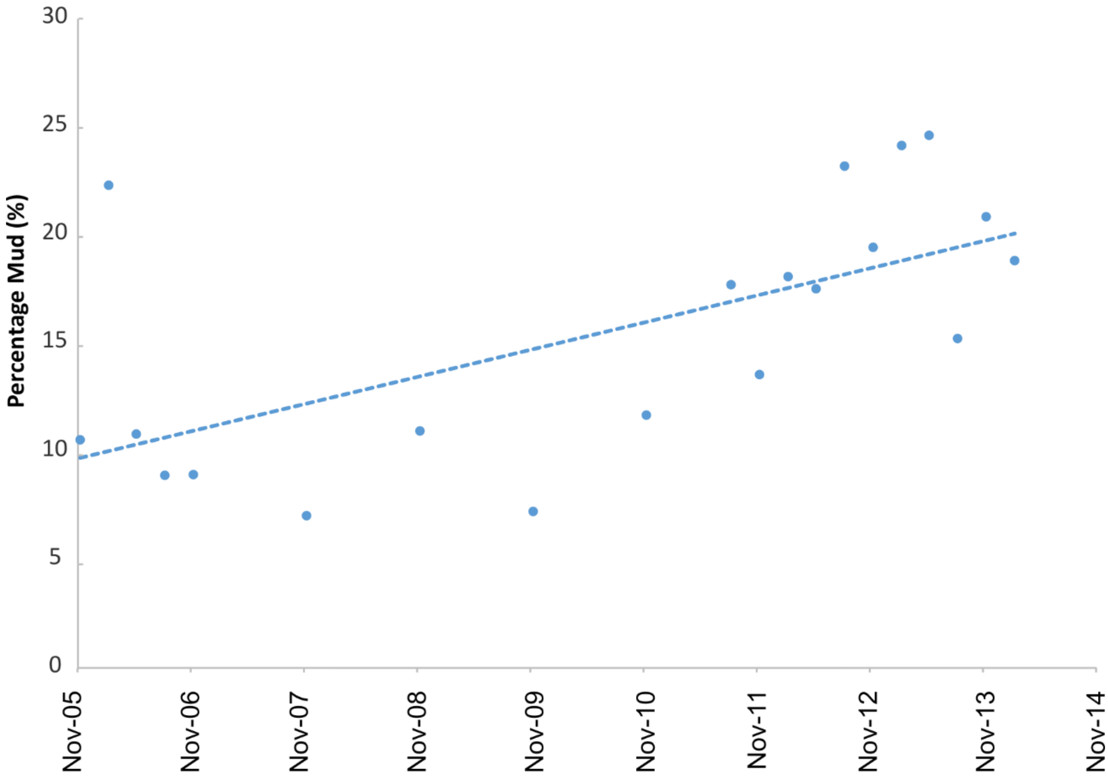


Figure 8: Increase in the percentage mud content of the seabed over time at an ecological monitoring site (HIW) at Herald Island, Upper Waitemata, Auckland. The percentage mud has increased by 1.26% per year over the monitored period, based on simple linear regression (although other interpretations and statistical fits could be applied here).

Figure 9: The apparent change in sediment surface characteristics over time. Evident in the 2015 photo is change from 2007 with surficial mud and the occurrence of mud crab burrows.

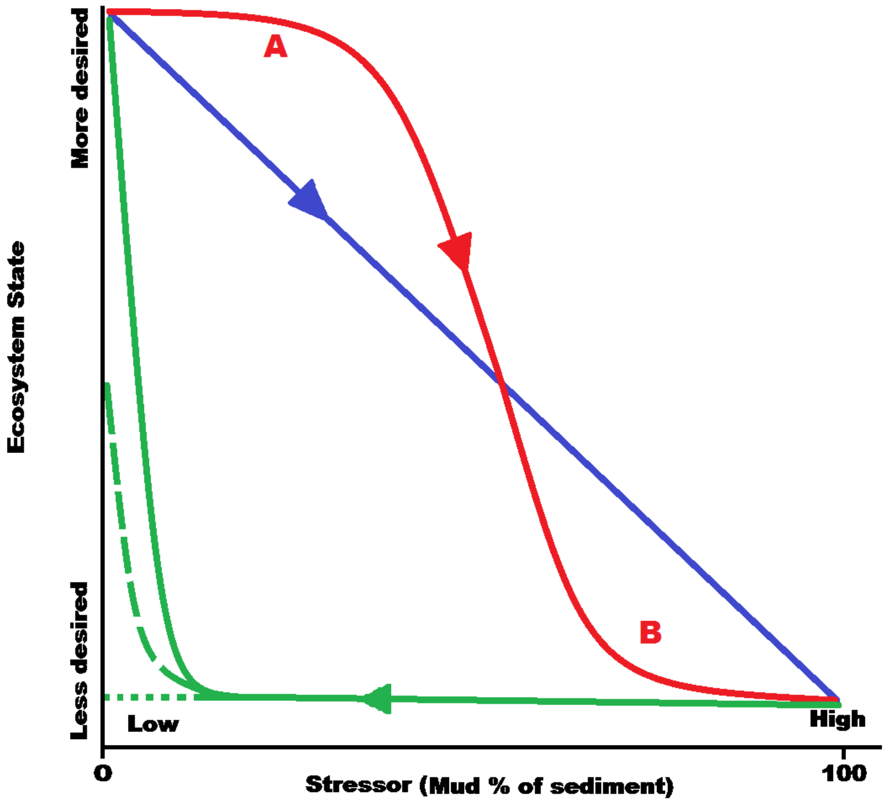


Figure 10: Schematic of the possible linear (blue) and non-linear dynamics (red) between the desired state of an estuary ecosystem and the bed-sediment mud content. We know that threshold changes (non-linear) will occur for estuaries (Thrush et al. 2008) and that the outcome of change in sediment grain-size (addition of mud) will be dependent upon the percentage mud a system/site is already experiencing. Non-linear changes (red) show a sharp decline in the ecosystem state, over a relatively narrow increase in stress (moving from points A to B). Regardless of whether the pathway to degradation is linear or non-linear, the effects may be impossible to reverse, or it could take an extended period of time and a substantial reduction in stress before the system can recover (green, hysteresis).

5 Recommendations

1. We propose for further consideration a Default Guideline Value for sedimentation of 2 mm of sediment accumulation per year above the natural annual sedimentation rate for the estuary, or part of estuary, at hand.

2. The proposed DGV should be refined by further development of relationships between annual sedimentation rate and the health/condition of estuaries. We recommend a more complete evaluation and analysis of the current data, which are limited, before further data are collected.

3. We recommend that a standardised buried-plate methodology be developed, so that fine scale monitoring (monthly or quarterly at particular sites) can be combined with longer term and more spatially widespread monitoring techniques.

4. The ANZECC sedimentation guideline should be nested within a wider framework that considers different modes of impact by sediments (including suspended sediment concentration and seabed muddiness), multiple stressors, cumulative effects, and thresholds. The issue of indefinite resilience also needs to be addressed.

5. Estuarine sedimentation and its effects should be better linked to catchment processes, for example, through an assessment of upstream turbidity and sedimentation interdependence. This will facilitate a clearer understanding of erosion pathways and increase targeted management response.

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Appendix A

Table of availability of metadata based on Hewitt et al. (2014) MEMP and information received from the C-SIG.

Principal Contact / Author	Region	Location	Number of sites/estuaries	Sediment Information	Ecological Information	Frequency of collection	Dataset duration
Auckland Council Megan Carbines Marcus Cameron	Auckland	N. Shore, Whitford embayment	8 estuaries: Puhoi, Orewa, Waiwera, Okura, Waikopua, Mangamangaroa, Turangi, Whangateau Harbour	sediment (grainsize, organics, **accumulation rate**)	epifauna, infauna	bi-annual	> 10 years
	Auckland	Harbours	5 estuaries	sediment (grainsize, organics, chlorophyll-a)	epifauna, infauna	bi-monthly or quarterly	> 10 years
	Auckland	Marine Ecology - Tier II Habitats and Communities	3 estuaries, 2 coastal	soft-sediments, intertidal, subtidal, sediment grainsize	infauna, epifauna, macroalgae, rocky reef,		> 10 years
Environment Canterbury Lesley Bolton-Ritchie	Canterbury	Canterbury	5 estuaries	sediment (nickel, cadmium, redox, ash-free dry weight, grainsize, lead, zinc, chromium, copper, arsenic, organics, mercury)	infauna, epifauna		~5 years
	Canterbury	Avon-Heathcote Estuary	1 estuary	turbidity, suspended solids, sediment (metals, nickel, cadmium, phosphorus, nitrogen, chlorophyll-a, redox, ash-free dry weight, sediment grainsize, lead, zinc, chromium, copper, arsenic),	infauna, epifauna		
James Goff (NIWA)	Canterbury	Lyttelton Harbour	1 harbour	**Historic sedimentation** (over last 400 years)			single sampling
Wybren J. de Vries	Canterbury	Lyttelton Harbour		**bed level monitoring**			short times scale (weeks to months) in 2007
Nick Ward Environment Southland	Southland	Southland	9 estuaries: Waiau Lagoon, Jacobs River Estuary, New River Estuary, Fortrose Estuary, Haldane Estuary, Waikawa Harbour, Fresh Water Estuary (Stewart Island), Awarua Bay and Bluff Harbour	Sediment (nickel, cadmium, phosphorus, nitrogen, redox, ash-free dry, weight, grainsize, lead, zinc, chromium, copper, TP, TN, TOC), **Sedimentation rates (plates and historic)**	infauna, epifauna	variable	>10 years

Principal Contact / Author	Region	Location	Number of sites/estuaries	Sediment Information	Ecological Information	Frequency of collection	Dataset duration
Meridian Energy	Southland	Doubtful Sound (restricted use)	2 estuaries	sediment (grainsize, ash-free dry weight),	Invertebrates, indicator spp. abundances, echinoderm, abundances, infauna, cockles and pipi size frequency.		>10 years
Gisborne District Council	Gisborne	Gisborne, control sites			infauna		>10 years
Greater Wellington Council - Megan Oliver	Wellington	Porirua Harbour, Hutt Estuary, Whareama Estuary, Waikanae Estuary	4 estuaries/harbour	**Sediment accumulation plates** (7 years Porirua, 5 years Hutt Estuary, 7 years Whareama Estuary, 5 years Waikanae Estuary), some contaminants	infauna	annual	~8 years
Hawke's Bay Regional Council	Hawke's Bay	Hawke's Bay	2 estuaries	sediment (nickel, cadmium, phosphorus, nitrogen, chlorophyll-a, redox, ash-free dry weight, grainsize, lead, zinc, chromium, copper, arsenic, organics),	epifauna, infauna		>10 years
Marlborough District Council	Marlborough	Picton Outfall Monitoring Surveys (restricted use)	1 estuary	sediment (grain-size, ash-free dry weight, total organic carbon, total nitrogen, total kjeldahl nitrogen, c and n stable isotope analyses),	infauna		>10 years
Nelson Regional Sewerage Business Unit	Nelson	Bell Island (restricted use)	1 estuary	sediment (metals, ash-free dry weight, chlorophyll-a, grainsize, nutrients {nitrogen, phosphorus}),	infauna, epifauna, macrophytes, heavy metals in shellfish tissue		>10 years
Nelson Regional Sewerage Business Unit	Nelson	Rabbit Island	1 estuary	sediment (nutrients {nitrogen, phosphorus}, grain-size, metals, organics)	shellfish (metal content, faecal indicator bacteria), epifauna, infauna, macrophytes, microalgae		>10 years
NZ Aluminium Smelters Ltd (Cawthron)	Nelson		1 estuary	sediment (grain-size, ash-free dry weight, metals), sediment levels, video survey (sediment type, **sediment accumulation**)	epifauna/ epiflora		~5 years

Principal Contact / Author	Region	Location	Number of sites/estuaries	Sediment Information	Ecological Information	Frequency of collection	Dataset duration
Northland Regional Council	Northland		2 estuaries	sediment (nitrogen, grainsize, lead, zinc, copper, total phosphorus, total organic carbon)			~5 years
Northland Regional Council	Northland		5 estuaries	sediment (nickel, cadmium, phosphorus, nitrogen, redox, ash-free dry weight, grainsize, lead, zinc, chromium, copper)	infauna, epifauna		~10 years
Otago Regional Council	Otago	Dunedin	7 estuaries	sediment (nickel, cadmium, phosphorus, nitrogen, redox, ash-free dry weight, sediment grainsize, lead, zinc, chromium, copper)	infauna, epifauna		~10 years
Pan Pac forest Products Oceans Outfall	Hawke's Bay	Napier (restricted use)	1 coastal	sediment (grainsize, ash-free dry weight, redox depth), photomicroscopy of the sediment cores to identify the presence/absence of pulp mill fibre	infauna		>10 years
Nelson City Council	Nelson	Nelson	1 estuary	sediment (metals, grainsize, organic matter, svocs, organotins, tins),	infauna, epifauna		~5 years
University of Auckland, Nick Shears	N. Shore	Leigh And Mokohinau Islands (restricted use)	2 coastal	**sedimentation rates**	reef benthic communities		>10 years
Tasman District Council	Tasman	Waimea and Moutere Inlets	2 estuaries	**Sediment plates**	infauna,		~8 years
Tasman District Council	Tasman		5 estuaries	sediment (nickel, cadmium, phosphorus, nitrogen, redox, ash-free dry, weight, grainsize, lead, zinc, chromium, copper)	infauna, epifauna		>10 years
Tasman District Council	Tasman	Waimea Inlet	1 estuary	sediment (metals, total nitrogen, total phosphorus, ash-free dry weight, grain-size, chlorophyll-a, redox),	epifauna/infauna, macroalgae		>10 years
Tasman District Council	Tasman	Tasman Bay (restricted use)	1 coastal	sediment (grainsize, nutrients {nitrogen & phosphorus})	epifauna, infauna		>10 years
Bay of Plenty RC (Stephen Park)	Bay of Plenty	No Samples					
Principal	Region	Location	Number of	Sediment Information	Ecological	Frequency of	Dataset

Contact / Author			sites/estuaries		Information	collection	duration
Horizons (Palmerston N) Amy Shears		No Samples					
Waikato Regional Council	Waikato	Firth of Thames: (Kaiaua, Miranda, Thames Gun Club, Kuranui Bay, Te Puru) Raglan Harbour: (Ponganui Creek, Whatitirinui Island, Te Puna Point, Haroto Bay, Okete Bay)	2 coastal	sediment (chlorophyll-a, grainsize), **Sediment accumulation (plates)**	infauna	bi annual	>10 years
NIWA Andrew Swales Coring data	Multiple	Kaipara, Central Waitemata, Auckland East Coast Estuaries, Auckland East coast Bays, Pauatahanui Inlet, Bay of Islands, Whangarei	multiple	**Sedimentation - coring data** (lead-210, Ceasium -137, Beryllium, Pollen/carbon dating		single collection	historic sedimentation rates

Appendix B

Historic measures

Techniques that focus on historic rates of sedimentation involve the collection of long sediment cores from intertidal or subtidal sites. Indicators in the strata are used to determine the time of deposition. Sediment cores are collected in metal or PVC pipes to provide a vertical intact profile. Collection methods vary depending on the study, location of sites, and the duration of dating. In the simplest form, a relatively short core can be pushed into the sediment and retrieved by hand. Other methods involve deployment of coring devices by boat: Swales et al. (2012) used a multi-corer corer to collection 0.9m subtidal cores and a gravity corer (loaded with 60kg weight) at shallow sites to collect 1.7m long cores. Oldman et al. (2009) collected 4m length cores from used a Livingston piston corer from a moored vessel in Mahurangi Harbour. Cores are of varying in size and diameter, but commonly 10 cm in diameter. A good practice is to utilise a bottom cap that swings into position as the core barrel emerges from the sediment to keep the core intact. Following collection, the sediment core is extruded from the core barrel and subsampled at varying depth intervals (typically 1 cm). Each subsample section is aged using one or multiple methods.

Radioisotope Method

Focus: historic sedimentation (10-150 years), small-scale measurement.

Costs: moderate (>$3000, i.e., 2 cores, multiple depths sampled).

Frequency of sampling: one-off / Infrequent.

Strengths / Weaknesses: integrates sedimentation over a long period of time, are less sensitive for contemporary changes, i.e., within the last 5 years, or current.

Certain isotopes are radioactive and release energy over time in the form of radioactive decay. Each radioisotope has a consistent exponential radioactive decay rate (universal law of radioactive decay) which is utilised to date material. The half-life of a radioactive isotope describes the time period taken for half of the isotopes to undergo decay (i.e., a parent radionuclide, transforming into an atom with a nucleus in a different state). The time period of an element's half-life dictates the duration and sensitivity for its use in dating sediment. Caesium-137 has a half-life of 30 years and lead-210 a half-life of 22.3 years, and both are used in combination to date sediment up to seven half-lives old i.e., 100-150 years (Sheffield et al. 1995, Swales et al. 2012). The use of lead-210 in dating is based on excess quantities in the atmosphere which deposits via dry deposition or rainfall and attaches to fine sediment particles. Overtime the lead-210 in the sediment becomes isolated from the surface and so radioactive decay can be used to date the sediment. Caesium-137 is an anthropogenically generated isotope that is the product of the nuclear fission of uranium-235. Nuclear activities, notably the testing and use of atomic bombs, spread caesium-137 rapidly across the globe. Caesium-137 was first detected in New Zealand in 1953 with peak deposition occurring in the mid 1960's (Matthews 1989, Swales et al. 2012). Caesium-137 is found in sediment deposited after the 1950s and is absent from sediment deposited before the 1950s; excluding complicating factors of sediment reworking by bioturbation. The depth to which caesium-137 is found in sediment cores is used to determine the average rate of sediment accumulation since the 1950s (corrected for surface mixing using beryllium-7). The quantities of radioactive isotopes are determined using gamma spectrometry. 40-60g subsamples of sediment from selected depth intervals are analysed and the radioisotope activity expressed in Becquerel per kilogram (Bq Kg^{-1}). Radioisotope profiles are used to determine the time averaged rate sediment accumulation from the regression analysis of natural-log transformed data (Swales et al. 2012). The maximum depth of caesium is used to estimate sedimentation which has occurred since the 1950. A key aspect of this method is for core material to be measured and dissected accurately. Analysis often includes measurement of Beryllium-7 which is a short-lived isotope and provides information on the depth of the surface mixed layer (SML). Beryllium-7 can be used to correct caesium-137 for downward mixing. Using multiple Radio-isotopes increases confidence in the results and increases the time coverage. The cost of core collection is variable depending on method and location. A minimum number of sample (i.e., 6 per cores, 2 cores) are need from different strata to get adequate measurements to produce decay profiles with confidence. The cost of determining lead and caesium is in the region of $250 per sample ($3000 excluding collection, Swales pers. coms.).

Radio Carbon dating

Focus: historic sedimentation (500-70,000 years), small-scale measurement.

Costs: moderate (~$750 per sample based on Accelerator Mass Spectrometry which can date individual small samples, ~$500 standard radio carbon dating).

Frequency of sampling: one-off / infrequent.

Strengths / Weaknesses: unsuitable for material younger than 250-500 years. Measures sedimentation on a decadal scale so of no contemporary use.

Carbon has 3 naturally occurring isotopes C-12, C-13 and C-14, the latter of which is radioactive and as a proportion is $1e^{-10}$ %. Carbon dating uses the radioisotope decay (see above) of carbon-14, which is formed in the upper atmosphere and has a half-life of 5,730 years, to estimate the period of time over which sedimentation has occurred. Stratigraphic layers of known depth are selected and calcium carbonate material ($CaCO_3$) extracted for dating. Mollusc shells e.g., bivalves and gastropods, are commonly used. <10g subsamples of shell material are prepared and analysed using Atomic Mass spectrometry (AMS). From the age of material, the duration over which sedimentation has occurred is known and annual rate is calculated from the depth of sediment above it. Carbon dating is based on the age of shell material, and old shell material can be reworked into younger sediment. To minimise this risk, caution is used when selecting shells for analysis, selecting ones that are whole, disarticulated and un-abraded (i.e., no evidence of transport). It is best practice to replicate cores and samples to increase confidence (Hume and Dahm 1992). Accuracy may be impacted if dated shell material has been relocated from a younger or older time period. This can happen for physical reasons or through biological activity e.g., burrowing bivalves alive today may be buried at depth in older sediment. The University of Waikato Radiocarbon Dating Laboratory has a standard level of precision accurate to +/- 45 to 130 years, which is negligible over the typical period of dating.

Pollen dating

Focus: historic/contemporary, from several years to millennia, small-scale measurements.

Frequency of sampling: one-off / infrequent.

Strengths / Weaknesses: Labour intensive resulting in a high time cost, has largely been superseded by other methods (Compound Specific Stable Isotope Technique).

Land-cover composition, the plants (trees, shrubs, ferns in a catchment/region, influences the types of pollen that are found in an estuary and will be sequestered during the sedimentation process. As a consequence, the type of pollens found within sediment layers are indicative of the type of plants present at the time sedimentation. If there are known changes in land-use over time that have affected the species of plants present these can be used to date a sediment layer and calculate the rates of sedimentation. Sediment layers typically 100 mm apart are selected for analysis. Sediment is treated with 10% hydrochloric acid to remove carbonates, 10% potassium hydroxide to deflocculate and remove humic acids, 40% hydrogen fluoride to dissolve silicates and a chlorine bleach to remove lignin and most organics and mixture of sulphuric acid and acetic anhydride to remove celluossic compounds. The extracted pollen spores, charcoal and lignaceous material are glass slide mounted and examined under microscope. Pollen profiles can be used to date sediment (i.e., the date of the occurrence of introduced pines and grasses, the clearance of certain tree types) and thus the rate of sedimentation since the present. The degree of accuracy and precision is reliant on known changes in land use cover and/or floral species presence. When conducted well, date estimates are within the region of +/- 5 years, although +/- 10 years may be a more typical conservative estimate (Swales et al. 2005). Uncertainty in dating using pollen depends on two factors which can vary: i) the degree of in situ mixing, the efficiency of which declines as sedimentation rates increases and ii) the time lag between initial introduction of a new plant species and the production of sufficient pollen to be detectable in the stratigraphic record (Swales et al. 2005).

Contemporary measures

Contemporary measures describes the techniques that record the rate of sedimentation during/after their deployment. Many of these involve establishing a reference point from which changes in sediment bed height can be measured.

Sediment traps

Focus: sedimentation rate since deployment, small-scale measurement.

Costs: moderate (low equipment/analysis costs, high time requirements).

Frequency of sampling: frequent, monthly or shorter.

Strengths / Weaknesses: Labour intensive. Although of comparative value, there are several issues associated with absolute rate of sedimentation measured from sediment traps. Firstly they do not allow for resuspension, which is a natural process, and it is unclear what proportion of trap material might actually be resuspended rather than forming bed material. Sediment traps fail to include material that travels as bed load transport before contributing to sedimentation. Trapped material may be interfered with by fauna. For examples, traps can be fouled barnacles or filled with mud crabs (pers. obs.) which may alter the quantity of material they contain due to feeding. Traps can be adapted with poison to prevent fouling, but this increases cost of processing and has added logistical issues.

Sediment traps function by collecting material dropping out of suspension that would potentially contribute to the seabed. Based on the volume/weight of sediment that is collected and the period of time over which it is collected, the rates of sedimentation can be determined. Sediment traps have been used in estuarine monitoring programmes in New Zealand (Hewitt and Simpson 2012, Anderson et al. 2004). For example, Auckland Council's programme utilised sediment traps made of plastic pipe, 3.6 cm diameter x 50 cm long, which were dug into the sediment so that 20-25 cm of tube protruded above the sediment surface. These traps collected sediment settling out of suspension from the water column. The amount of sediment collected in sediment traps can be standardised by the number of days deployed and sedimentation presented in units of g cm^{-2} d^{-1}. A common practice is to ensure that sediment traps have an aspect ratio greater than 5:1, to prevent resuspension (White 1990, Anderson et al. 2004). Appropriate deployment duration is important to make sure traps do not overfill, which is dependent on the relative rates of sedimentation of a specific estuary/site. The cost of equipment is very cheap, however given the frequency of sampling (fortnightly-monthly), there is a higher time cost involved, in both field collection and deployment and also is processing of samples (extracting sediments from trap barrels, drying, weighing etc.).

Disturbance rods

Focus: sedimentation rate since deployment, small-scale measurement.

Costs: moderate (low equipment costs, moderate time requirement).

Frequency of sampling: frequent, monthly.

Strengths / Weaknesses: Subject to artefact. The criticisms of this methods are comparable to those of sediment plates below, but even less reliable. Any marker protruding from the sediment surface has the potential for scour as it interrupts the flow environment. This can result in erosion around the base of the rod. Additionally, movement of the peg further into or out of the sediment (natural slippage, tampering etc.,) affects the measured rate of sedimentation.

Sedimentation is measured by driving a rod firmly into the sediment and measuring the distance of a marked point on the rod away from the sediment surface (Turner and Riddle 2001, Anderson et al. 2004). Clifton (1969) did this by driving iron rods into the sediment so 20cm protruded from the sediment surface at the time of initiation, with further changes of exposed rod length measured over time (the height of the rod indicative of net sedimentation/erosion). This method is only really viable in sheltered locations where scour is not an issue.

Buried plates

Focus: sedimentation rate since deployment, small-scale measurement.

Costs: moderate (low equipment/analysis costs, moderate time costs depending on sampling frequency).

Frequency of sampling: As frequently as possible (studies have sampled from monthly to annually).

Strengths / Weaknesses: Sedimentation plates buried in very soft sediments may be impacted by process of sampling, however the degree of influence is largely unknown. Scour from pegs marking plates demonstrates the importance of best practise and that the validity/reliability of each individual situation must be assessed.

The buried plate techniques is one of the most common for measuring contemporary rates of sedimentation (Robertson and Stevens 2013, Hewitt and Gibbs 2012, Hewitt and Simpson 2012, Hewitt et al. 2015). Sedimentation is measured from the monthly/annual accumulation of sediment on top of buried 'plates', commonly made of concrete. Sedimentation (or erosion) over time is measured as the difference in sediment height above the plate from a baseline measurement. This is typically measured by inserting probes (metal or plastic rods) into the sediment until the plate is reached. Normally, replicate plates and replicate measurements are taken, to average over irregular surface feature that are common on the sediment surface. Multiple plates are often used across an estuary to reflect a range of depository or active environments. Plates should be buried to a depth where they are stable in the sediment strata (usual around 30cm). Adaptations have used strong mesh rather than concrete to prevent sinking (of heavy plates) and allow sediment exchange processes. Care must be taken not to puncture or push mesh deeper in act of measuring sediment depth. A systematic approach and care is needed to demarcate the location of sediment plates so they can be repeatedly sampled over time. However, reference markers need to be far enough away so that they do not influence the area where sediment is being monitoring. The best practice is for marker pegs to be separated by a significant distance (i.e., ~5m). Modifications in the setup of plates includes additional anchorage, similar to a drogue, to minimise tipping or movement of plates. Immediately after burial plates are usually left to 'bed in' for a period of time (~months-year) before measurements are taken. These methods are most effective in environments with high rates of sedimentation >> 30 mm per year, or for comparative studies. Sedimentation plates buried in very soft sediments may be impacted by process of sampling, if repeated visitation results in deep footprints throughout the sampling area (particularly if sampling is frequent, e.g., monthly). Equipment costs are generally minimal (<$1000) depending on the number or sites and replicates. Time costs are medium to high. Initial setup incurs the greatest time costs (excavating sediments and burying plates in often challenging environments). Accuracy and precision are dependent on multiple factors including biological and physical activity (affecting signal to noise strength) and ability to measure sediment depth with care.

Transect surveys

Focus: sedimentation rate is calculated over the period between surveys. This method can provide moderate coverage (depending on the number of transects). Information is collected across an estuary rather than a point source.

Frequency of sampling: multiple surveys required, time interval variable.

Strengths / Weaknesses: Rather than a single point of information, as with plate and rod methods, transect surveys cover a broader area so provide great spatial information.

A transect across an intertidal flat is conducted with periodic measures of the distance between the seabed and a known reference point in the vertical plane. Changes in elevation over time to identify periods of erosion or sediment deposition. This method uses equipment such as Electronic Distance Meters (EDMs) that measure distances and elevation.

Bathymetric surveys and LIDAR

Focus: Sedimentation rate calculated for the period between surveys. Broad-scale.

Costs: Variable, but typically very high when using vessels/planes.

Frequency of sampling: Multiple surveys required, time interval variable.

Strengths / Weaknesses: The main strengths are the capacity to survey across broad areas of seabed. The main weakness is that accuracy has been low in the past. Recent surveys by professional surveyors can achieve a good level of accuracy.

This technique uses vertical and horizontal (latitude and longitude) position to determine the distance a vessel is from the seabed. From this changes in seabed height over time can be calculated and the rate of sedimentation. Bathymetric surveys can utilise RTK GPS (real time kinematics global position system), allowing fine-scale positioning accuracy. Importantly this provides vertical as well as horizontal position and can factor out issues such as tidal state and wind fluctuations from its calculations. Light detection and ranging (LIDAR) use the principle of RADAR where light is transmitted to a target and the degree of reflection and scattering is indicative of distance away. Airborne LIDAR Hydrography (ALH) became more commonplace in the 1990s after its development in the 1960s. The use is more common for subtidal surveying, but is possible for intertidal surveying at high water (See all reference for Appendix B in Appendix C below).

Appendix C

Appendix References:

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