Kaipara Harbour Sediment Mitigation Study

Harbour benthic ecology narrative

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Contents

Tables

Figures

Executive summary

Northland Regional Council with support from Auckland Council and Ministry for the Environment have contracted a consortium led by Streamlined Environmental Ltd and consisting of Streamlined Environmental, Landcare Research, NIWA and the University of Otago, to conduct the Kaipara Harbour Sediment Mitigation Study.

The first aim of the Study is to develop a catchment economic model for use in assessing the economic costs and environmental benefits of a range of scenarios for mitigating sediment losses to rivers and estuaries within the Kaipara Harbour catchment. The second aim of the Study is to develop a management tool for use in formulating consistent farm-scale sediment mitigation plans. The tool will be easily usable by land management advisors in the field to identify appropriate actions to mitigate critical source areas of sediment under different land uses at the farm scale.

This report provides a narrative assessment of how changes in annual average sedimentation rate (AASR) in the harbour, in response to management actions taken in the catchment, will translate into changes in harbour ecosystem health and functioning.

Daigneault et al. (2017) used the NZFARM spatially explicit integrated catchment economic model to predict catchment sediment runoff and associated AASR under each of 12 scenarios (various combinations of landuse change and sediment mitigation applied in the catchment). Predictions of AASR were made for 9 depositional basins in the harbour.

The analysis required information on sedimentation thresholds sufficient to cause ecological harm. A default guideline value of 2 mm/y above the total natural sedimentation rate in each depositional zone (i.e., total AASR predicted under conditions of full native forest cover and intact wetlands) was used for this purpose.

Key results are:

- Sedimentation rates under the baseline scenario (current land-use and no mitigation) exceeded the default guideline value by at least 1 mm/year in three depositional zones: the Kakarai (KAIF), the Makarau (MAIF) and the Kaipara (KPIF) intertidal flats, all within the southern part of the harbour.
- Reducing AASR to the guideline value in KAIF, MAIF and KPIF will alleviate sediment stress and improve ecosystem health and functioning, although relatively large percentage reductions from baseline sedimentation rates would be required to achieve this (28%, 31% and 55% reductions at KAIF, MAIF and KPIF, respectively).
- At KAIF, two of the management scenarios would lessen AASR to a point close to the default guideline value, whilst full afforestation to pine (scenario 10) was the only management scenario option at KAIF that appeared to reduce AASR significantly below the default guideline value.
- At MAIF, the modelling suggested a low natural sedimentation rate of 0.9 mm/y. None of the scenarios were able to reduce AASR to a level less than 2.9 mm/y (the default guideline value for this zone).
- At KPIF, the baseline AASR was the highest of the nine depositional zones investigated (7.0 mm/y). Several of the scenarios at KPIF had AASR values ≥6 mm/y, exceeding the

default guideline value by >3 mm. It is likely that a reduction of AASR from 6 mm/y to 3 mm/y would increase the taxonomic richness of sediment-dwelling organisms by as much as 30%, and would enhance the abundance of functionally important bivalves such as cockles and wedge shells.

- In five of the depositional zones within the northern part of the harbour, baseline sedimentation is within a fraction of a millimetre per year higher or lower than the guideline. These basins will be experiencing some level of sediment stress and will benefit from management interventions to reduce catchment sediment runoff. In addition to the two afforestation scenarios, scenario 5 (stock exclusions + All HEL plans) is predicted to reduce AASR by more than 1 mm/year in all five zones.

- It is important to recognise that the modelled variable "AASR" is a spatially averaged, temporally averaged, value, and that the models used to predict AASR do not resolve small scale bathymetric and hydrodynamic features, for example, stagnant areas behind oyster reefs and date mussel beds that are known to accumulate fine sediments. Thus field observations from particular sites may not always match well with basin-wide AASR predictions.

- AASR, as a management metric, does not fully address the full complexity of sediment as an environmental stressor. When attempting to evaluate the efficacy of the different management scenarios, the starting condition of the habitat, particularly bed sediment muddiness, should be considered. Bed sediment muddiness is negatively correlated with ecological health and macrofaunal abundance and richness. Suspended fine sediment concentrations in the water column are also known to have adverse effects on benthic plants and animals.

- Ecological health may improve slowly with reductions in AASR at sites with greater than 20% mud, as it may take years for existing bed sediment muddiness to reduce to the 2-10% range. Some areas in the Kaipara Harbour, such as MAIF and KPIF may fall into this category.

1 Introduction

Northland Regional Council (NRC) with support from Auckland Council (AC) and Ministry for the Environment have contracted a consortium led by Streamlined Environmental Ltd and consisting of Streamlined Environmental, Landcare Research, NIWA and the University of Otago, to conduct the Kaipara Harbour Sediment Mitigation Study.

The first aim of the Study is to develop a **catchment economic model** for use in assessing the economic costs and environmental benefits of a range of scenarios for mitigating sediment losses to rivers and estuaries within the Kaipara Harbour catchment.

Sediment mitigation applied in the catchment reduces sediment runoff, which translates into changes in "sediment attributes" such as suspended-sediment concentration, water clarity and euphotic depth in freshwater, and sedimentation rate and seabed muddiness in the harbour. Changes in sediment attributes in turn may translate into changes in ecosystem health and functioning and certain values derived by humans from the use of water, for example, kaimoana gathering and swimming.

The catchment economic model will estimate the cost of applying sediment mitigation in the catchment and the reduction in sediment runoff and the associated changes in sediment attributes that will result from the application of the mitigation.

Model predictions will assist NRC and AC with making decisions about managing sediment losses to waters in Kaipara Harbour and its catchment.

The second aim of the Study is to develop a **management tool** for use in formulating consistent farm-scale sediment mitigation plans. The tool will be easily usable by land management advisors in the field to identify appropriate actions to mitigate critical source areas of sediment under different landuses at the farm scale.

1.1 Study overview

The NZFARM (New Zealand Forest and Agricultural Regional Model) catchment economic model (Daigneault et al. 2017) was used to assess the economic costs and environmental benefits of a range of scenarios for reducing catchment sediment losses.

Eleven scenarios were investigated. Nine scenarios involved applying specific sediment-mitigation options and the other two involved landuse change (afforestation). A baseline scenario was established for comparison with the other scenarios.

For each scenario, annual-average load of catchment sediment delivered to both freshwater and the harbour was predicted.

The sediment load under each scenario was transformed into estimates of three freshwater sediment attributes:

- suspended-sediment concentration
- visual clarity
- euphotic depth

and one harbour sediment attribute:

- annual average sedimentation rate (AASR).

Environmental and amenity benefits were inferred from the set of sediment attributes.

Costs associated with each scenario were estimated by NZFARM.

1.2 This report

Sedimentation was thought to be very low prior to the arrival of Polynesians about 700 years ago. By the early 1900s, with increased European settlement, most of the land suitable for pastoral agriculture had been cleared. Annual average sedimentation rates (AASR) for the harbour over the last 50-100 years have been estimated to be on the order of 4 to 6 mm/y (Swales et al. 2016). The purpose of this report is to provide a narrative assessment of how changes in AASR in the harbour, in response to management actions taken in the catchment, will translate into changes in harbour ecosystem health and functioning.

2 Background

2.1 Kaipara Harbour

Kaipara Harbour is the largest harbour in New Zealand (612 km perimeter, 947 km^2 total surface area, and 409 km^2 total intertidal area; Department of Conservation 1992; Heath 1975 & 1976) and spans the jurisdictions of Auckland Council and Northland Regional Council. Both authorities are concerned about the effects of historical and present day land-based activities on the ecological functioning and health of Kaipara Harbour. Data on benthic habitat types and benthic macrofaunal organisms present in the southern Kaipara Harbour are available from Hewitt & Funnell (2005) and time-series data on benthic macrofauna and sediment characteristics have been collected at 4 to 6 sites in the southern Kaipara since 2009 (Hailes and Carter 2016). Northland Regional Council collected data using the Estuary Monitoring Protocol of Robertson et al. (2002) at two sites in the Arapaoa in 2009, 2010, 2011, and 2013 and at 41 sites across the northern Kaipara Harbour in 2014 (Griffiths 2014). Thus, there is relatively up to date information on the current status and recent trends in benthic ecological health and habitat types throughout the Kaipara Harbour.

2.2 Model predictions of annual average sedimentation rate (AASR)

Daigneault et al. (2017) developed the spatially explicit integrated catchment economic NZFARM model during the Kaipara Harbour Sediment Mitigation Study, in order to better understand the effects of present day land-based activities and various existing and proposed catchment management actions on sediment loading to Kaipara Harbour and the freshwater streams and rivers in the surrounding catchment. NZFARM incorporated data and estimates from economic and land use databases and biophysical models. Annual sediment loads from 21 subcatchments (reporting zones) were estimated using the SedNetNZ model.

Green et al. (2017) developed a method for predicting AASR and seabed muddiness in the harbour given catchment sediment runoff, although the method for predicting seabed muddiness was not able to be implemented because of insufficient data. Land-based mitigation costs and effectiveness in reducing sediment were obtained from a range of sources.

The model for predicting AASR was implemented for each of the nine depositional basins shown in Figure 1 and Table 1.

Figure 1: The nine depositional basins of Kaipara Harbour where changes in AASR in response to changes in catchment sediment runoff are predicted. See Table 1 and Figure 2 for more information.

Table 1: A listing of depositional basin numbers, names and code abbreviations. Code abbreviations, rather than basin names or numbers, are used in the text hereafter. Column four gives baseline (no mitigation) annual average sedimentation rates (AASR, units of mm/y) calculated for each deposition zone, with the degree of confidence in each rate estimate given in the brackets. The fifth column, Z, is the proportion of present day AASR that is due to marine sand and shell as opposed to catchment material. The information comes from Green et al. (2017).

Basin number	Basin name	Basin code	Baseline AASR (confidence in estimate)	Z
1	Wairoa	WAIF	3.0 (medium)	0.2 (shell)
2	Arapaoa	ARIF	2.0 (very high)	0.1 (shell)
3	Otamatea	OTIF	3.0 (low)	0.2 (shell)
4	Tinopai	TNSF	1.5 (very low)	0.8 (marine sand + shell)
5	Whakaki	WHIF	2.0 (low)	0.1 (shell)
6	Oruawharo	ORIF	3.0 (low)	0.2 (shell)
7	Kakarai	KAIF	6.5 (very high)	0.4 (marine sand)
8	Makarau	MAIF	4.0 (medium)	0.1 (marine sand)
9	Kaipara	KPIF	7.0 (high)	0.0

Figure 2 shows in graphic form the present-day AASR and how AASR is broken down by catchment sources of sediment and marine sources of sediment. Marine sources of sediment include sand washed in through the mouth of the harbour and shell material that is produced in situ.

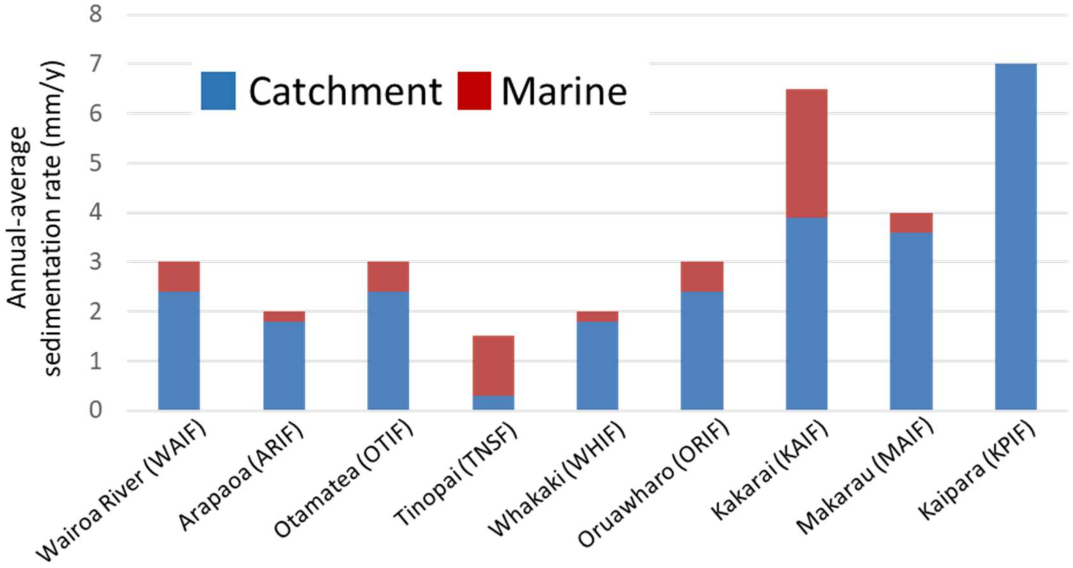

Figure 2: Present-day AASR for each of the 9 depositional basins. The blue bar shows the proportion of the sedimentation due to catchment sediment and the red bar shows the proportion due to marine sources of sediment (marine sands plus shell hash).

The model accounts for the fact that sediment deposited at any given location in the harbour may originate from any of numerous river catchments that drain into the harbour. For instance, sediment that deposits on the intertidal flats at the mouth of the Hoteo River may primarily originate from the catchment of the Hoteo River, but some might also originate from further afield, for instance, from the catchment of the Kaipara River or the catchment of the Wairoa River. This is an important consideration, since mitigation may not be applied uniformly across the whole catchment of the Kaipara Harbour, which has to be accounted for.

The model also accounts for the fact that, in addition to the catchment sediment that deposits in the harbour, sediments of marine origin, washed in from the coastal ocean and dispersed and deposited by waves and currents, and shell hash that is produced in situ, may also deposit in any given depositional basin. The partitioning between catchment and marine sources of sediment will affect the sensitivity of AASR to reductions in catchment sediment load. For instance, AASR in Kaipara (KPIF) depositional basin will be more sensitive to reductions in catchment sediment load due to mitigation since sedimentation in that basin is entirely due to catchment sediment. AASR in Tinopai (TNSF) will be least sensitive, since a large proportion of the sedimentation at that location is due to marine sources of sediment, which are not affected by mitigation in the catchment.

2.3 Scenarios

Nine sediment-mitigation scenarios and two landuse-change scenarios were investigated using NZFARM (Table 2).

- There were nine **sediment-mitigation scenarios**.
    - Five were practice-based, such as fencing all streams for stock exclusion, and four were outcome-based, for instance, reducing the catchment sediment load at each of the

freshwater nodes by a certain percentage. None of these scenarios addressed landuse change, only mitigation.

- Two additional **landuse-change scenarios** were investigated.
  - Both of these involved afforestation, which were designed to establish the minimum feasible catchment sediment loads and best possible attribute states.

All scenarios were designed so that attributes would always be maintained or improved.

Table 2: The scenarios investigated using NZFARM.

Scenario number	Scenario name	Scenario description
Baseline Scenario		
0	Baseline	Current landuse with no mitigation practices to match same assumption as SedNetNZ erosion model.
Sediment-Mitigation Scenarios		
Practice-based		
1	Current Mitigation	Current landuse with likely proportion of mitigation practices implemented today. Assumes 80% of streams and rivers on dairy farms and 30% of streams and rivers on other pastoral land are fenced to exclude livestock (dairy cattle, dairy support cattle, beef cattle and deer) and 10% of pastoral land area with 1.0 t/ha/yr or higher erosion rates (i.e., highly erodible land, HEL) has soil conservation measures.
2	Farm Management Plan, All HEL	Current landuse with farm management plans (predominately promoting soil conservation by planting poplar or willow poles) implemented on all HEL.
3	Stock Exclusion Rules	Current landuse with riparian fencing of REC or larger permanent streams for stock exclusion on all pastoral land meeting the NZ Government's proposed stock exclusion regulations (2017).
4	Stock Exclusion Rules + Riparian Planting	Current landuse with riparian fencing for stock exclusion on all pastoral land meeting the NZ Government's (2017) proposed stock exclusion regulations on REC2 or larger permanent streams, but also with 5 m stream buffer with planted vegetation.
5	Stock Exclusion Rules + All HEL Plans	Combination of scenarios 2 and 3.
Outcome-based		
6	Freshwater Node 10%	Annual catchment sediment load at all seven freshwater nodes reduced by 10%.
7	Freshwater Node 30%	Annual catchment sediment load at all seven freshwater nodes reduced by 30%.
8	Marine Deposition 15%	Annual catchment sediment load in all nine harbour depositional basins reduced by 15%.
9	Marine AASR 2 mm Above 'Natural' State	Average annual sedimentation rate (AASR) from catchment-based erosion is no more than 2 mm greater than AASR under 'natural' land conditions (scenario 11).
Landuse-Change Scenarios		
Afforestation		
10	Full Afforestation (Pine)	All non-forest land (e.g., pasture, arable, lifestyle blocks) is planted with radiata pine. Used to estimate maximum attainable mitigation while maintaining a 'productive' land use.
11	Full Afforestation (Native) + Wetland Restoration	All non-forest land is planted with native bush and likely extent of pre-human wetlands are restored. Used to estimate 'natural' erosion loads in the catchment and thus maximum attainable mitigation.

Notes on scenarios

1. Scenario 0, the *Baseline* scenario, against which the other scenarios are compared, comprises the 2014 catchment sediment loads predicted by SedNetNZ, assuming no mitigation in the catchment, and the present-day harbour AASR shown in Table 1 and Figure 2.
2. Scenario 9 (relating to marine deposition) is the one scenario that seeks to achieve a target AASR, which it does as follows:

   Scenario 9 constrains the AASR to the component of the *Baseline* AASR that is due to marine sediment **plus** the smaller of (a) the catchment-sediment component of the *Baseline* AASR **or** (b) the catchment-sediment component of the "natural" AASR predicted under Scenario 11 (all non-forest land planted with native bush and pre-human settlement wetlands restored) **plus** 2 mm/year.

   Referring to Table 3 (below):

   - For depositional basins ARIF, TNSF and WHIF, (a) is smaller than (b) and hence no reduction in catchment sediment runoff is required to meet the Scenario 9 target AASR.
   - For all the other depositional basins, (a) is greater than (b) and hence reduction in catchment sediment runoff is required to meet the Scenario 9 target AASR.
   - Basins KAIF, MAIF and KPIF require the greatest reduction in catchment sediment (relative to the Baseline scenario) to meet the Scenario 9 target AASR.

Table 3: Percentage reductions in catchment sediment (relative to Baseline scenario) required to meet Scenario 8 target AASR (see text for explanation).

	Baseline			**Scenario 11 "natural"**			**9 Scenario 8**			
Harbour depositional basin	AASR (mm/y)	Marine sediment component (mm/y)	Catchment sediment component (mm/y)	AASR (mm/y)	Marine sediment component (mm/y)	Catchment sediment component (mm/y)	Marine sediment component (mm/y)	Catchment sediment component (mm/y)	AASR (mm/y)	% reduction in catchment sediment component (relative to *Baseline)* required to achieve AASR
WAIF	3	0.6	2.4	0.89	0.6	0.29	0.60	2.29	2.89	-5%
ARIF	2	0.2	1.8	0.36	0.2	0.16	0.20	1.80	2.00	0%
OTIF	3	0.6	2.4	0.78	0.6	0.18	0.60	2.18	2.78	-9%
TNSF	1.5	1.2	0.3	1.24	1.2	0.04	1.20	0.30	1.50	0%
WHIF	2	0.2	1.8	0.32	0.2	0.12	0.20	1.80	2.00	0%
ORIF	3	0.6	2.4	0.88	0.6	0.28	0.60	2.28	2.88	-5%
KAIF	6.5	2.6	3.9	3.41	2.6	0.81	2.60	2.81	5.41	-28%
MAIF	4	0.4	3.6	0.90	0.4	0.50	0.40	2.50	2.90	-31%
KPIF	7	0	7	1.18	0	1.18	0.00	3.18	3.18	-55%

3 Guidance for linking AASR to ecological effects

To understand what the resultant AASR values mean for the ecology of the harbour, and whether reductions in AASR from particular management interventions are low enough to prevent ecological harm, guidelines on the levels of AASR that are sufficient to cause ecological harm are required.

In 2015, fifteen researchers from a broad cross section of New Zealand institutions attended a workshop to develop suitable guidelines for managing chronic sedimentation effects. A default guideline value of 2 mm of sediment accumulation per year above the natural annual sedimentation rate for an estuary, or part of estuary, was agreed. Lohrer et al. (2004) studied the effects of differing thicknesses of sedimentation in experiments designed to mimic the immediate aftermath of storm events and found that 3 mm of sediment was the minimum thickness capable of producing significant shifts in macrobenthic community structure. These effects were observed at one of two experimental sites in the Whitford Embayment when 3 mm of terrigenous sediment was applied to experimental plots in the field every month for six months. Workshop participants had little information on the effects of lesser amounts of sediment that gradually accumulate, but agreed that any guideline value would need to be below the 3 mm threshold identified by Lohrer et al. (2004). After some discussion, 2 mm/y was selected as a reasonable and conservative default guideline value.

The "natural sedimentation rate" that was factored into the default guideline value was defined as the rate under native-forested catchment prior to human occupation. The natural sedimentation rate may vary between different estuaries and within different parts of an individual estuary. The default guideline value is 2 mm/y on top of the natural sedimentation rate. It was set as such because, otherwise, parts of estuaries with natural sedimentation rates >2 mm/y would never dip below the recommended guideline value, regardless of the extent of management intervention (including complete native reforestation).

The default guideline framework mentioned above is able to be applied to the Kaipara Harbour system because Daigneault et al. (2017) has estimated the "natural sedimentation rate" in the nine depositional zones using a land cover scenario of full native forest cover and intact wetland areas. Table 4 gives the natural sedimentation rate and the resultant default guideline values. The default guidelines values have been overlain on Figure 3 to facilitate a visual interpretation of the efficacy of the different management intervention scenarios in each of the 9 depositional environments in Kaipara Harbour.

Although both marine and terrigenous sediments contribute to AASR in some depositional zones, the analysis undertaken here is based entirely on total AASR. Steps were taken to exclude the marine-originated sediments from the analysis (Table 4b), as catchment sediments (rather than marine sediments) are generally considered to be the primary drivers of adverse effects. However, information on how the proportional contribution of marine and terrigenous sediments to AASR varied across scenarios was not available. The proportion of marine sediment contributing to AASR has likely decreased since pre-human times because of increased catchment sediment loads. Thus, total AASR was deemed to be better for calculating default guideline values and for analysing management intervention effectiveness and was more conservative (Table 4).

Major sedimentation 'events' in the immediate aftermath of storms, increases in bed sediment mud content, and elevated suspended sediment concentrations can all significantly affect estuarine soft-sediment benthos (Thrush et al. 2004). Note that the analysis of AASR undertaken here did not consider the ecological implications of these other potential sources of sediment stress, which is a potential limitation, given the potential for interactive and cumulative effects.

4 Results

Modelling results presented in Figure 3 show that baseline sedimentation rates (scenario 0) exceed the default guideline value by at least 1 mm/year in three depositional zones: KAIF, MAIF and KPIF, all within the southern part of the harbour. In five of the six depositional zones within the northern part of the harbour (not Tinopai, TNSF), baseline sedimentation is within a fraction of a millimetre per year higher or lower than the guideline.

Based on the above, areas where management is most needed to reduce sedimentation rates to at least the default guideline value are KAIF, MAIF and KPIF. Relatively large percentage reductions in sedimentation rate would be required to meet the default guideline values in these three zones (-28%, -31% and-55% for KAIF, MAIF and KPIF, respectively; Table 3) which is simulated in Scenario 9 of Daigneault et al. (2017). By reducing AASR to the guideline value, scenario 9 will alleviate sediment stress and improve ecosystem health and functioning; however, Scenario 9 has much higher costs than the other outcome-based scenarios and would require mitigation over larger areas.

4.1 Basins currently close to the default guideline value.

The five depositional zones in the northern part of the harbour where AASR is close to the default value (ARIF, WHIF, WAIF, OTIF, ORIF) will be experiencing some level of sediment stress and will benefit from management interventions to reduce catchment sediment runoff. In addition to the two afforestation scenarios, scenario 5 (stock exclusions + All HEL plans) is predicted to reduce AASR by more than 1 mm/year in all five zones, and scenario 4 (stock exclusion rules + riparian planting) is predicted to reduce AASR by more than 1 mm/year in four of the five zones.

Table 4: Selected data from Appendix 5 (Table 12) of Daigneault et al. (2017). Table data are estimates of AASR (mm/y) under a number of different catchment management scenarios in three depositional basins of interest. Default guideline values (far right column) are calculated as scenario 11 AASR + 2 mm. Scenario 11 itself is not considered to be a management option. All values in (a), including default guideline values, are for total AASR. All values in (b) are for catchment-originated sediment only, with the proportion of catchment-originated sediment relative to the total AASR in each basin given in the far left hand column. Bold numbers indicate AASR values that are greater than their respective recommended default guideline values. Default guideline values in (a) were used for the analysis (see text).

(a)

	0	1	2	3	4	5	6	7	8	9	10	11*	*
Deposition Basin	Baseline	Current Mitigation	Soil Cons Plan - All HEL	Stock Exclusion Rules	Stock Exclusion Rules + Planting	Stock Exclusion + All HEL Plans	Freshwater Node 10%	Freshwater Node 30%	Marine Deposition 15%	Marine 2mm above 'natural'	Full Afforestation (Pine)	Full Afforestation (Native) +Wetlands	Default Guideline Value
WAIF	**3.0**	2.7	2.3	2.7	2.2	2.0	2.9	2.6	2.6	2.9	1.4	0.9	2.9
ARIF	2.0	1.8	1.4	1.8	1.5	1.3	2.0	1.9	1.7	1.8	0.7	0.4	2.4
OTIF	**3.0**	2.8	2.1	2.8	1.9	1.9	**3.0**	**2.9**	2.6	2.8	1.3	0.8	2.8
TNSF	1.5	1.5	1.4	1.5	1.4	1.4	1.5	1.4	1.5	1.5	1.3	1.2	3.2
WHIF	2.0	1.8	1.3	1.9	1.0	1.2	1.9	1.8	1.7	1.4	0.7	0.3	2.3
ORIF	**3.0**	2.8	2.2	2.8	2.5	2.0	**3.0**	2.9	2.6	2.9	1.3	0.9	2.9
KAIF	**6.5**	**6.1**	**5.9**	**6.1**	**5.8**	**5.5**	**6.2**	**5.5**	**5.9**	5.1	4.1	3.4	5.4
MAIF	**4.0**	**3.9**	**3.8**	**3.9**	**3.0**	**3.7**	**4.0**	**3.9**	**3.5**	2.9	2.9	0.9	2.9
KPIF	**7.0**	**6.0**	**6.7**	**5.1**	**4.1**	**4.8**	**6.3**	**5.0**	**6.0**	3.2	1.9	1.2	3.2

Table 4: (continued)

(b)

	0	1	2	3	4	5	6	7	8	9	10	11*	*
Deposition Basin	**Baseline**	**Current Mitigation**	**Soil Cons Plan - All HEL**	**Stock Exclusion Rules**	**Stock Exclusion Rules + Planting**	**Stock Exclusion + All HEL Plans**	**Freshwater Node 10%**	**Freshwater Node 30%**	**Marine Deposition 15%**	**Marine 2mm above 'natural'**	**Full Afforestation (Pine)**	**Full Afforestation (Native) +Wetlands**	**Default Guideline Value**
WAIF	**2.4**	2.1	1.7	2.1	1.6	1.4	2.3	2.0	2.0	2.3	0.8	0.3	2.3
ARIF	1.8	1.6	1.2	1.6	1.3	1.1	1.8	1.7	1.5	1.6	0.5	0.2	2.2
OTIF	**2.4**	2.2	1.5	2.2	1.3	1.3	**2.4**	**2.3**	2.0	2.2	0.7	0.2	2.2
TNSF	0.3	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.3	0.3	0.1	0.0	2.0
WHIF	1.8	1.6	1.1	1.7	0.8	1.0	1.7	1.6	1.5	1.2	0.5	0.1	2.1
ORIF	**2.4**	2.2	1.6	2.2	1.9	1.4	**2.4**	2.3	2.0	2.3	0.7	0.3	2.3
KAIF	**3.9**	**3.5**	**3.3**	**3.5**	**3.2**	**2.9**	**3.6**	**2.9**	**3.3**	2.5	1.5	0.8	2.8
MAIF	**3.6**	**3.5**	**3.4**	**3.5**	**2.6**	**3.3**	**3.6**	**3.5**	**3.1**	2.5	2.5	0.5	2.5
KPIF	**7.0**	**6.0**	**6.7**	**5.1**	**4.1**	**4.8**	**6.3**	**5.0**	**6.0**	3.2	1.9	1.2	3.2

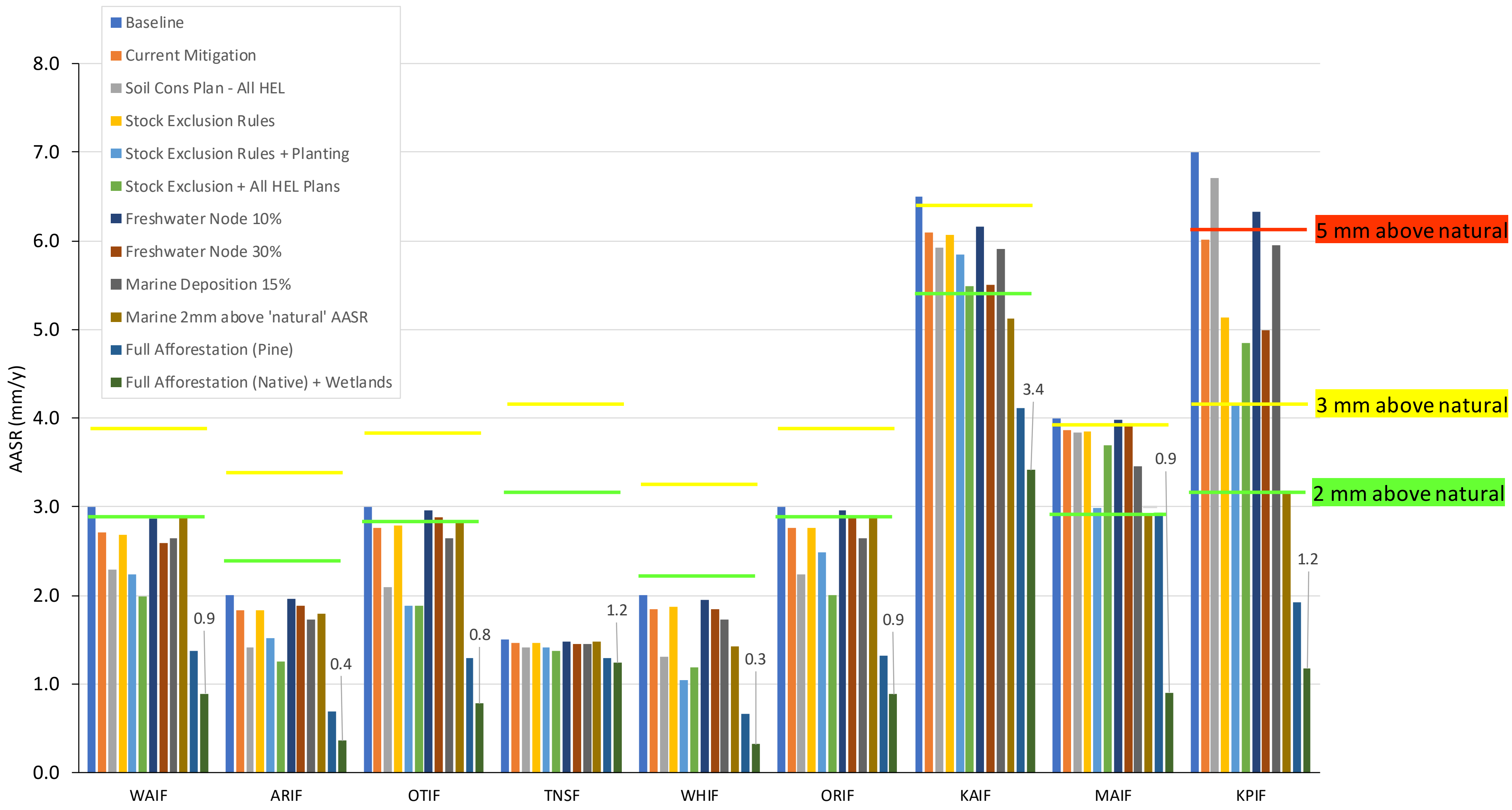

Figure 3: (Figure ES.2 of Daigneault et al. 2017). Marine Annual-Average Sedimentation Rate (AASR) by Scenario and Deposition Area. Areas include: Wairoa intertidal flats (WAIF), Arapaoa intertidal flats (ARIF), Otamatea intertidal flats (OTIF), Tinopai subtidal flats (TNSF), Whakaki intertidal flats (WHIF), Oruawharo intertidal flats (ORIF), Kakarai intertidal flats (KAIF), Makarau intertidal flats (MAIF), Kaipara intertidal flats (KPIF). Deposition rates of 2 mm, 3 mm and 5 mm above the natural sedimentation rate of each depositional basin are overlain atop the figure in green, yellow and red, respectively. 2 mm above natural AASR was agreed to be a suitable default guideline value or threshold beyond which ecological effects may begin to be detected.

4.2 Basins currently above the default guideline value

AASRs were predicted to be above default guidelines under most of the scenarios modelled at KAIF, MAIF, and KPIF (Figure 3). The number of scenarios predicted to exceed default guideline values was relatively similar in these three zones. There were some notable differences at these sites, however, so they are discussed individually below.

4.2.1 Kakarai intertidal flats (KAIF)

The AASR of the baseline “no intervention” scenario at KAIF was predicted to be 6.5 mm/y (Table 4a), which is >1 mm above the default guideline value at this site (5.4 mm/y), and >3 mm above the natural sedimentation rate in pre-human times (3.4 mm/y). The modelling shows KAIF to have the highest natural sedimentation rate of the nine zones (3 to 10 fold higher than the other sites; >2 mm greater than the next highest sites, TNSF and KPIF). Thus, while AASR is predicted to be relatively high under most of the scenarios at KAIF, the default guideline value is also high in this naturally heavily depositional area.

Two of the management scenarios at KAIF would lessen the AASR to a point close to the default guideline value, with scenario 5 (stock exclusions + All HEL plans) and scenario 7 (freshwater node 30%) both having predicted AASR values of 5.5 mm/y (Figure 3). Therefore, if bed sediments within this depositional zone are still relatively sandy (<10% mud content), these intervention scenarios would generate very slight but detectable improvements to the ecology. The improvements may be manifest as elevated densities of common species (e.g., polychaetes, amphipods and small bivalves) and an average of approximately 1 additional species per core (where 20-25 species per core is the norm) (Lohrer et al. 2004). Full afforestation to pine (scenario 10) is the only management scenario option at KAIF that appears to reduce the AASR significantly below the default guideline value of 5.4 mm/y (AASR at KAIF under scenario 10 is 4.1 mm/y). This management intervention would clearly be the best in terms of providing a buffer for uncertainty and as a precautionary approach, given that we are not considering potentially simultaneous effects of elevated suspended sediment concentrations (SSC) or gradual increases in bed sediment mud content, both of which are known to have impacts on the ecology (discussed below).

As to the degree of muddiness of the sediments at KAIF at present, Swales et al. (2011) sampled a single core (KAI-16) at the mouth of the Hoteo River and estimated bed sediment mud content at roughly 50% throughout the last 70 years. However, the degree of sediment muddiness changes with distance from the riverine source, and extensive sandy flats have been documented relatively close to the KAIF depositional zone depicted in Figure 1 (e.g., see Hailes and Carter 2016). Auckland Council’s benthic ecological monitoring site closest to this basin is characterised by firm wave-rippled sand with low densities of tube worms, a variety of gastropods, and some seagrass (Figure 4).

Other work in this area of the harbour has also documented extensive seagrass beds (e.g., around Moturemu Island), plus populations of the key suspension feeding bivalve *Austrovenus stutchburyi* (cockles). Cockles live 0-5 cm below the sediment surface when the tide is out, moving up to filter particles from the overlying seawater when the tide is in. They provide an important recreational and cultural food source for humans, and are also an important prey item for birds, rays and other fish. They are functionally important, affecting water column and sediment food supply and the release of nutrients from sediment pore water (Sandwell 2006, Thrush et al. 2006). Cockles are known to be sensitive to terrestrial sedimentation and increases in suspended sediment concentrations (Norkko et al. 2002, Thrush et al. 2005, Hewitt and Norkko 2007, Hewitt and Gibbs 2010). Thus, management interventions to reduce bed sediment muddiness, sediment deposition and suspended sediment concentrations would likely boost cockle populations and the ecosystem functions and services that they deliver.

Figure 4: Photos of KAIF. (A) looking east across the Auckland Council ecological monitoring site KKF, near to the KAIF depositional basin, (B) characteristic rippled sediment topography with sparse *Zostera muelleri* (0.25 m^2 quadrat), and (C) characteristic rippled sediment topography. (Figure from Hailes and Carter 2016).

4.2.2 Makarau intertidal flats (MAIF)

When comparing like-with-like scenarios, the ASSRs predicted for MAIF were always lower than those predicted at KAIF or KPIF (Figure 3, Table 4a). This included the natural sedimentation rate in pre-human times, which was just 0.9 mm/y at MAIF. The best of the modelled catchment interventions at MAIF in terms of reducing AASR were scenarios 4 (stock exclusion rules and planting) and 10 (pine forest on all pastoral, arable and life-style block land). These two scenarios each reduced AASR to a value approximately equal to MAIF's default guideline value of 2.9 mm/y. It appears that even the most stringent of mitigation measures (scenario 10) will not reduce AASR significantly below the default guideline value at this site.

Auckland Council has an ecological monitoring site called NPC that is in the general vicinity of MAIF, located on the sandflat south of the outlet of Ngapuke Creek (Hailes and Carter 2016). The monitored site is consistently firm and sandy with ripples ranging from 1-10 mm wave height and 10-50 mm wave length (Figure 5). Bivalve shell hash is present on the sediment surface, consisting mainly of *Macomona, Austrovenus* and *Cyclomactra* shells. A surficial muddy layer is occasionally observed at this site, generally less than 10 mm thickness, except in April 2014 when it was observed to reach 30 mm depth. Other parts of the MAIF depositional zone may be considerably muddy now, although the relatively low pre-human AASR suggests that the area may once have been sandier.

Site NPC has been mainly polychaete dominated, with *Heteromastus filiformis* and *Magelona dakini* generally the numerical dominants. The most abundant bivalve species present at this site is *Hiatula siliquens*, followed by the wedge shell *Macomona liliana*. Although cockles (*Austrovenus stutchburyi*) are present at NPC, they are consistently low in number. Management interventions to reduce bed sediment muddiness may have positive effects on the densities of these shellfish species.

Figure 5: Photos of MAIF. (A) looking south east across the Auckland Council ecological monitoring site called NPC, near to the MAIF depositional basin, (B) characteristic rippled sediment topography with *Arcuatula senhousia* remnants (0.25 m^2 quadrat), and (C) muddy surficial sediment layer.

4.2.3 Kaipara intertidal flats (KPIF)

The KPIF depositional zone is where management intervention may have the greatest influence on AASR (Figure 3; Table 4a). 100% of the material contributing to the AASR in the KPIF depositional zone comes from the catchment, with no contribution from marine sand or shell. Terrigenous sediment loads can be reduced by management intervention, whereas sediments of marine origin cannot. Therefore, management interventions designed to reduce AASR in the KPIF depositional zone will be operating at maximum efficiency. However, the current baseline AASR for KPIF is the highest of the nine depositional zones investigated (7.0 mm/y) and the degree of confidence in this estimate was deemed to be high.

The natural sedimentation rate with intact native forest and wetlands is estimated to be 1.2 mm/y, which puts the default guideline value for KPIF at 3.2 mm/y. It follows that a reduction in AASR of nearly 4 mm/y (from the baseline AASR of 7.0 mm/y) is required to meet the recommended guideline. The only management intervention scenario that achieves this target is full afforestation (scenario 10). The next best scenario in terms of AASR reduction is scenario 4 (stock exclusion and planting), however, the resultant AASR under scenario 4 would remain more than 1 mm above the default guideline value. Thus, there would likely be detectable improvements in the ecology if scenario 10 were adopted in favour of scenario 4.

Several of the scenarios at KPIF have resultant AASR values ≥ 6 mm/yr (Table 4a). This is more than 3 mm higher than the recommended default guideline value for KPIF. It is likely that a reduction of AASR from 6 mm/y to 3 mm/y in a relatively sandy area of the KPIF zone (bed sediment <10% mud content) would increase the taxonomic richness of sediment-dwelling organisms by as much as 30% (from a typical value of 12-18 species to approximately 16-24 species, judging from Lohrer et al. 2004). The abundances of common species with a preference for sandy intertidal habitat is also predicted to increase with this level of reduction in AASR. This may include functionally important bivalves (cockles, *Austrovenus stutchburyi*, pipi, *Paphies australis*, and wedge shells, *Macomona liliana*) as well as various other macrofauna (the cumacean *Colurostylis*, the anemone *Anthopleura aureoradiata*, the amphipod *Waitangi bervirostris*, the polychaete *Aonides oxycephala* and the gastropods *Notoacmea scapha* and *Cominella glandiformis*) (Norkko et al. 2001; Anderson et al. 2008; Hewitt and Gibbs 2010).

The KPIF depositional zone may contain both muddy and sandy habitats. However, per Hailes and Carter (2016), the ecological monitoring site inside KPIF appears to be mud-influenced (Figure 6), with evidence of terrigenous sediment deposits observed on ~50% of the sampling occasions since 2009, ranging from 10-100% in areal coverage across the 9000 m^2 site. The monitoring site in the KPIF depositional zone has had a bed sediment mud content varying between 5.9% and 31.2%, and has medium to high densities of functionally important shellfish such as *Macomona liliana*. *Macomona* lives ~7-10 cm below the sediment surface and feeds on particulate matter located on the sediment surface using a long siphon. Similar to cockles, this relatively long-lived species (5 years) is an important prey item for birds, rays and other fish and has been demonstrated to affect seafloor productivity and nutrient recycling (Thrush et al. 2006). It is also known to be sensitive to terrestrial sedimentation and increases in suspended sediment concentrations (Norkko et al. 2002, Thrush et al. 2005, Hewitt and Norkko 2007, Hewitt and Gibbs 2010, Townsend et al. 2014), thus its populations and associated functions would be predicted to increase following reductions in AASR.

Figure 6: Photos of KPIF. (A) looking east across the Auckland Council ecological monitoring site KaiB, in the KPIF depositional zone site (B) characteristic sediment topography with attached *Gracilaria* spp. (0.25 m^2 quadrat), and (C) evidence of the muddy surficial sediment layer. (Figure from Hailes and Carter 2016).

5 Discussion

5.1 Why sediment loading is a concern

Sediment loading from catchments to estuaries has two primary effects: it increases the rate of deposition of sediments to the seafloor, and it increases the concentrations of fine sediments suspended in the water column. Although the deposition of sediments generally only occurs in locations where wave action and current speeds are relatively weak, high suspended sediment concentrations (SSC) can occur more broadly. While the scope and focus of this report was AASR, it is important to recognise that the ecological effects of sediment loading from coastal catchments can occur by various means. A general review of potential effects in estuaries stemming from deposited and suspended sediments is provided below.

5.1.1 Deposited sediments

The deposition of sediment on the seabed, particularly terrigenous sediment that has washed out of coastal catchments, is widely recognised as a stressor to coastal marine fauna (Thrush et al. 2004), and the response of coastal soft-sediment macrofaunal communities to sediment deposition has been shown to be dose-dependent. Sudden deposits of terrigenous material >100 mm thickness are generally considered to be 'catastrophic', in that they smother and kill practically all of the underlying benthic organisms. Only the largest, most mobile, and best burrowing species (for example, mud crabs) are able to survive events of this magnitude. However, previous observations and modelling results suggest that such events are relatively infrequent and limited in spatial extent (for example, coming after saturating rains cause landslips and massive exports of sediment to local tidal flats).

Much more common and pervasive are smaller events resulting in <10 mm of terrestrial sediment deposition. Experiments conducted in North Island estuaries suggest that as little as 3 mm of the terrigenous material is sufficient to significantly alter macrobenthic community structure (measured after 10 d, relative to 0 mm controls), though this amount of deposition is not likely to cause complete defaunation of the underlying sediments (Lohrer et al. 2004, 2006a). With this level of deposition, the number of individuals and taxa per area will decline, as will the densities of the common 'key' species (such as cockles and wedge shells), but the effects will likely be restricted to small juvenile bivalves and other small surface-oriented taxa. With repeated deposition events (e.g., 3 mm thickness, monthly, over a 6 month period), the sandflat sediments will gradually become muddier, and macrofaunal community composition will progressively change. While 1 mm of terrigenous sediment deposition is not likely to kill many macrofauna, work by Woodin et al. (2012) in New Zealand suggests that it may interrupt feeding and alter behaviours.

One of the concerns with frequent low-level loading and deposition is the gradual 'muddying' of estuarine benthic habitats (shifts from predominantly sandy to predominantly muddy sediments). This is one of the reasons for the focus on AASR, as presumably it correlates with more pervasive problems such as the gradual muddying of particular intertidal sites and the gradual spatial expansion of muddy (e.g., >25% mud) areas. Relatively small increases in sandflat mud content can dramatically alter macrofaunal community composition and the abundances of many macrofaunal species. Numbers of macrofaunal individuals and taxa per area are both negatively correlated with bed sediment mud content, and several key estuarine bivalves (cockles, pipis, wedge shells) prefer sandy substrates with <40% mud content (Thrush et al. 2003).

Another consequence of increasingly muddy sediments is the potential to alter ecosystem rates and processes. Some of this is purely physical, as elevated mud content reduces sediment pore spaces and sediment permeability, thus restricting aerobic processes and the exchange of solutes across the sediment-water interface (Billerbeck et al. 2007, Huettel and Rusch, 2000). However, the loss of large bioturbating fauna in sediments with 20-40% mud content is another contributing factor, with reductions in sediment oxygen demand and nutrient regeneration apparently linked to changes in the abundances of the bioturbators (Pratt et al. 2013). The Pratt et al. study (2013) involved an analysis of data from nine North Island estuaries incorporating a sand-to-mud gradient. It indicated that muddier sediments were significantly less likely to have high rates of benthic gross primary productivity and nutrient regeneration than sandier sediments during daytime inundation periods. Cockles, which were more abundant in sand than mud, contributed to microphytobenthic primary production through bioturbation and ammonium release. It appears that a transition from clean sandy substrate to a muddier habitat type can dramatically alter biotic interactions and reduce the system's capacity for primary production and nutrient recycling.

5.1.2 Suspended sediments

The loading of sediments from the land tends to increase the ratio of inorganic to organic particles in the seston (suspended particulate matter), thereby reducing the nutritional quality of the food available to suspension feeders. Even when the bulk organic content per volume of water is unchanged, a higher ratio of inorganic to organic sediment particles is likely to increase feeding costs (as nutritious particles must be sorted from the inorganic ones). High suspended sediment concentrations (SSC) also have the potential to overwhelm filter feeders that cannot process particles efficiently enough. This may result in the clogging of the filtering apparatus or, in the case of bivalves, induce them to close their valves and wait until conditions become more favourable again.

Ecologically and culturally important bivalve species such as horse mussels (*Atrina zealandica*) and pipi (*Paphies australis*) are particularly sensitive to SCC, with SSC >80-100 mg l^{-1} causing significant reductions in filtration rates with adverse effects on their condition and growth (Ellis et al. 2002, Hewitt and Pilditch, 2004). Other coastal benthic species are known to be much less sensitive to high SSC (e.g., oysters), but there are some that are likely more sensitive (e.g., sponges, ascidians, bryozoans, cnidarians). Rankings of the sensitivities of various coastal benthic macrofaunal species present in the Auckland Region have been reported on by Gibbs and Hewitt 2004, Norkko et al. 2001, and Anderson et al. 2008.

The impact of SSC on bivalve condition becomes increasingly pronounced with increased length of exposure (Hewitt and Norkko, 2007). This is likely because some of the coping mechanisms (i.e., the closing of the bivalve shells) can only be maintained for relatively short periods, after which the animals will begin to starve or suffocate. Moreover, for a given SSC, increasing length of exposure results in a greater overall dose of sediment. Thus, consistently high loadings of sediment from rivers and high frequencies of storm-driven SSC events (elevated riverine loadings coupled with high winds that keep particles in suspension and transport them far afield) will have the greatest impacts.

There is evidence that the responses to SSC are somewhat dependent on environmental context, including background SSC concentrations and history of prior exposure to SSC (Hewitt and Pilditch 2004, Lohrer et al. 2006b). Large suspension feeders that are accustomed to living in clear marine waters appear to be more sensitive to elevated SSC, relative to individuals from the same species (horse mussels, golf ball sponges, solitary tunicates) that have been collected from turbid waters (Lohrer et al. 2006b). This implies that far-field transport of sediments to areas that are normally relatively clear could be problematic, whilst elevated turbidity in areas that are already turbid may have lesser effects.

Another direct effect of increased SSC is a reduction in the penetration of incident ambient sunlight downward through the water column. This means that the depth to which there is sufficient light for photosynthesis will be reduced with increasing SSC. Many of New Zealand's estuarine systems, including the Kaipara Harbour, are dominated by very shallow waters and extensive intertidal flats, so a reduction in light may be a relatively minor problem. However, in shallow soft-sediment habitats such as these, benthic microphytes and seagrass meadows make a much larger contribution to overall system productivity than phytoplankton do (Kang et al. 2003, Middelburg et al. 2000), and experimental increases in SSC have been shown to reduce benthic net and gross primary productivity and photosynthetic efficiency (Pratt et al. 2014). The Pratt et al. study (2014) also indicated that with the reduction in benthic primary production, there was less efficient trapping of ammonium (NH_4^+) and thus a greater efflux of ammonium from the sediment to the overlying water (Pratt et al. 2014). This suggests that the problem of nutrient overloading into estuaries may be exacerbated if coupled with inputs of suspended sediments, and that the effects of nutrient enrichment may extend further offshore after the sediments have settled out of solution. NIWA research demonstrating the effects of turbidity on seagrass primary productivity are in their final stages of analysis and will soon be submitted to peer reviewed journals.

5.2 Interpreting AASR model results from a marine ecology perspective

Limiting the loadings of terrigenous sediments to Kaipara Harbour is a necessary first step towards improving the Harbour's ecological health. This is likely to be true even in the six depositional basins where the model indicates that AASR is presently below the default guideline values. This is because AASR, as a management metric, does not fully address the issue of sediment as a stressor; not in the specific basins discussed here, nor in the Harbour as a whole. Sediment stress is a multi-faceted, multiplicative combination of rare but catastrophic sedimentation events, the gradual muddying of the seabed, the areal expansion of muddy habitats, and increases in suspended sediment concentrations. Thus, although reducing sediment loadings through better catchment management practices will likely have multiple benefits to the ecology of Kaipara Harbour, demonstrating the benefits of AASR reduction itself is challenging. The main benefit of this modelling exercise may be for identifying the basins that are most at risk at present and for exploring the cost effectiveness and relative benefits of alternative future management actions.

It is also important to recognise that the modelled variable "AASR" is a spatially averaged, temporally averaged, statistic. It is quite conceivable that, in reality, there are areas within each depositional basin that have substantially higher AASR (where ecological conditions look significantly worse), and areas that have substantially lower AASR (where ecological conditions look significantly better). The Green et al. (2017) harbour model does not resolve small scale bathymetric and hydrodynamic features, for example, stagnant areas behind oyster reefs and date mussel beds that are known to accumulate fine sediments (Richie Griffiths, NRC, personal observations). Thus, field observations in particular areas in the Kaipara Harbour (including regularly visited sampling sites that may be several hundred meters in extent) may not necessarily match the conditions predicted by modelled AASR at the scale of a depositional basin (several square kilometres).

Ecological impacts in Kaipara Harbour due to the accumulation of fine sediments over the last 180 years are widely acknowledged. The legacy of sediment accumulation, which has not affected all parts of the harbour equally, may affect the efficacy of management actions. Bed sediment muddiness, for example, is likely to be a key determinant of recovery trajectory. After years of elevated AASR resulting from human activities on land, benthic habitats in the depositional zones are likely to have become muddier. The muddying of the habitat would have altered the suitability of the habitat for many macrofaunal species. Interventions to reduce AASR may not immediately generate positive ecological responses; legacies of muddy sediments and associated resuspended fine sediments (elevated SSC) may impinge on the ecology for years to decades after management interventions are initiated.

There appear to be some general thresholds for sediment mud content that are pertinent for benthic macrofauna (Rodil et al. 2011). A traits-based index of ecological health formulated from the taxonomic richness of benthic macrofauna in 7 particular trait categories, the TBI, has been calculated at hundreds of sites in the Auckland Region. TBI scores are noticeably higher when mud content is less than 10%, with scores ranging mostly between 0.3 and 0.6 on a scale of 0.0 to 1.0 (1.0 being highest; Figure 7). At sediment mud content >20%, TBI scores are commonly in the low 0.1–0.3 'poor' range. Beyond 60% mud, TBI scores are predominantly in the 0.1-0.3 'poor' range and rarely exceed 0.4. The relationship between TBI and sediment mud content is consistent with what is known about the effects of sediment mud on the occurrence and abundance of individual species, and community variables such as total abundance and species richness (Thrush et al. 2003, 2005; Anderson et al. 2008).

Based on the characteristics of the ecological monitoring site in the KPIF depositional zone, this area may have a considerable legacy of sediment loading that has elevated sediment mud content and likely has higher SSC as well. The Daigneault et al. (2017) model suggests that relatively dramatic and potentially costly management intervention will be required to improve the ecology at this site; the possibility of legacy effects may hinder improvements and lengthen the recovery process. The same may be true of MAIF, which may also contain areas that have become significantly muddy.

The degree of change from the natural ecological state that has occurred at KAIF may be smaller than that which has occurred at MAIF and KPIF. Whilst we cannot go back in time to sample the ecology, the modelling of Daigneault et al. (2017) suggests that KAIF is a zone of naturally high fine sediment deposition. With a naturally higher rate of sediment deposition and bed sediment mud content, KAIF has likely always suited mud tolerant species more than highly mud sensitive ones. Thus, even though AASR has increased by approximately similar magnitudes at KAIF and MAIF, the degree of ecological impacts due to human activities in the catchments over the years may have been less at KAIF. It stands to reason that the rate of recovery back to the natural state would be faster at KAIF also.

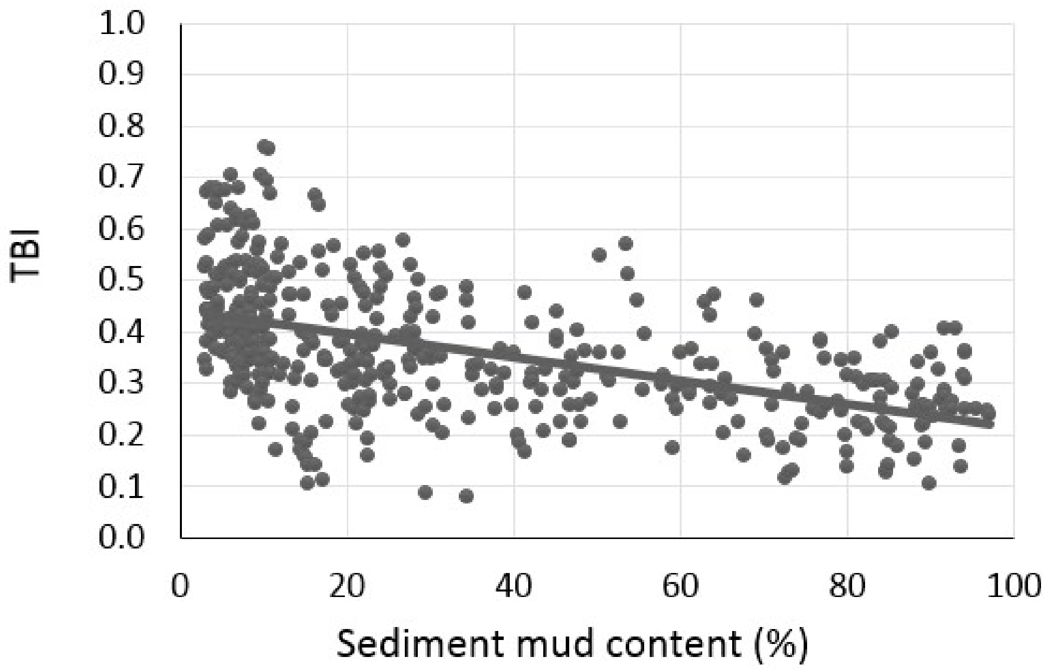

Figure 7: Relationship between bed sediment mud content and a macrofaunal traits based index of health (TBI). Higher TBI scores are indicative of better ecological health and functional redundancy.

5.3 Research needs and final thoughts

This was the first attempt in New Zealand to investigate the ecological implications of AASR relative to a specified default guideline value. The default guideline was proposed by well qualified ecological experts and backed by literature values, however, the default guideline value requires further testing and refinement. Specifically, empirical data on the relationships between AASR and the health/condition of estuaries are required. A more complete evaluation and analysis of the existing data should be undertaken before further data are collected.

Several councils and research providers have been using buried-plate methodologies to empirically measure AASR. A best-practice standard methodology needs to be discussed and universally applied, so that fine scale monitoring (monthly or quarterly at particular sites) can be combined with longer term and more spatially widespread monitoring techniques.

Although AASR may be the simplest parameter to model (relative to increases in mud content, areal expansion of muddy habitats, and elevated of SSC), the use of AASR and AASR-based management guidelines needs to be nested within a wider framework that considers different modes of impact (for example, muddying of the seabed, adverse effects due to increased suspended sediment, reductions in visual clarity, etc.) by sediments.

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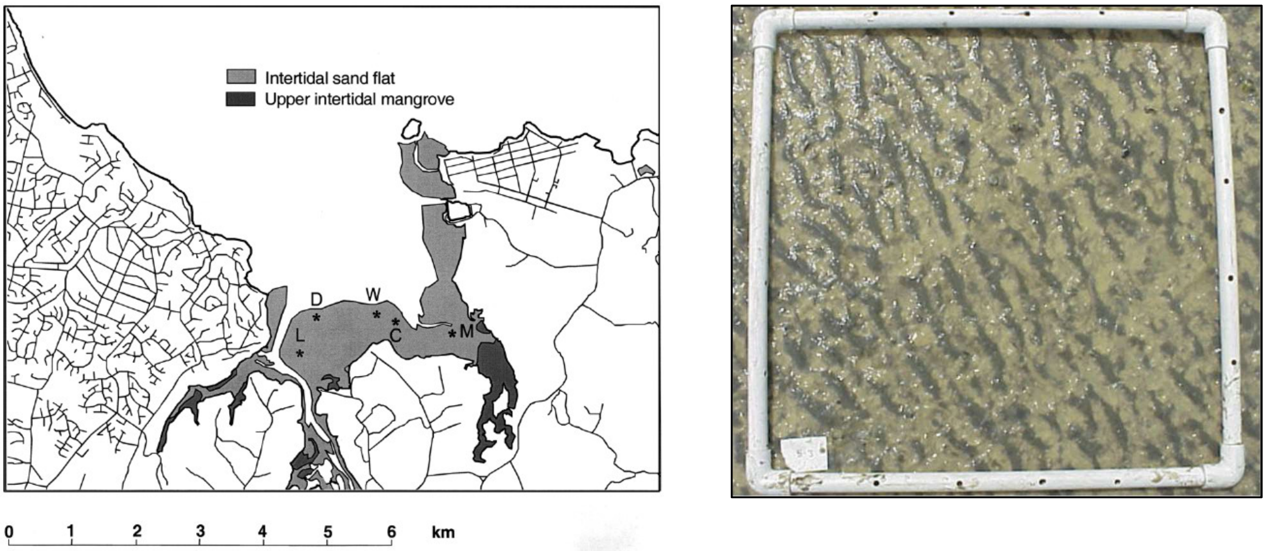
7 Appendix 1. Summary of Lohrer et al. 2004.

Lohrer, A.M., Thrush, S.F., Hewitt, J.E., Berkenbusch, K., Ahrens, M., Cummings, V.J. (2004) Terrestrially derived sediment: response of marine macrobenthic communities to thin terrigenous deposits. *Marine Ecology Progress Series,* 273: 121-138.

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 in Appendix Figure 1) 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.



Appendix Figure 1. Map of Whitford Embayment and sites examined by Lohrer et al. (2004)(left panel). A treatment plot following the experimental application of terrigenous sediment (right panel); quadrat size: 50 cm x 50 cm (0.25 m^2).