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Regional Estuary Monitoring Programme (REMP) intertidal sedimentation measurements, results and review of methodologies

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Table of Contents

1 Introduction 1

1.1 Estuarine and sedimentation processes 1

2 Methodology 4

2.1 Sediment plate methodology 4

2.1.1 Firth of Thames 4

2.1.2 Whaingaroa (Raglan) Harbour 5

2.2 Calculation of sediment accumulation rate 8

2.3 Plate elevation and water depths 8

2.4 Plate material and condition 8

3 Results 9

3.1 Firth of Thames 9

3.2 Whaingaroa (Raglan) Harbour 17

4 Discussion 27

4.1 Sedimentation trends 27

4.1.1 Firth of Thames 27

4.1.2 Whaingaroa (Raglan) Harbour 36

4.2 Effectiveness of methodology for measuring sedimentation. 37

4.2.1 Plate subsidence 37

4.2.2 Plate material 37

4.2.3 Measurement technique 37

4.2.4 Temporal scale of measurements 38

4.2.5 Spatial configuration and coverage 44

5 Conclusions and recommendations. 46

5.1 Plate setup. 46

5.2 Plate positioning 46

5.3 Temporal frequency of measurements 47

5.4 Measurement method 47

6 References 48

Appendix A. Heights of plates from LiDAR and tide gauge data 52

Appendix B. Wave model 55

Figures

Figure 1: Locations of the REMP sites, Tararu tide gauge and wave hindcast model in the Firth of Thames. 6
Figure 2: Locations of the REMP sites in Whaingaroa (Raglan) Harbour. 7
Figure 3: Sedimentation recorded in the Firth of Thames over the Kaiaua Plates. 11
Figure 4: Sedimentation recorded in the Firth of Thames over the Miranda Plates. 12
Figure 5: Sedimentation recorded in the Firth of Thames over the Gun Club Plates. 13
Figure 6: Sedimentation recorded in the Firth of Thames over the Kuranui Bay Plates. 14
Figure 7: Seabed level relative to mean sea level and SAR. 15
Figure 8: Sedimentation recorded over the Haroto Bay Plates. 18
Figure 9: Sedimentation recorded over the Whatitirinui Island Plates. 19
Figure 10: Sedimentation recorded over the Te Puna Point Plates. 20
Figure 11: Sedimentation recorded over the Okete Bay Plates. 21
Figure 12: Sedimentation recorded over the Ponganui Creek Plates. 22
Figure 13: Seabed depth relative to mean sea level and associated SAR. 23
Figure 14: Distribution of wave events from the MetOcean View hindcast model plotted as the percentage occurrence of Tp and Hs (see Figure 1 for hindcast model location). 30
Figure 15. Wave rose showing distribution of wave events from the MetOcean View hindcast model plotted as the percentage occurrence of Hs and the associated wave direction 30
Figure 16: Wave rose showing distribution of wave events from the MetOcean View hindcast model plotted as the percentage occurrence of Tp and the associated wave direction. 31
Figure 17: Wind rose summarising the wind record at Tararu tide gauge between 1st January 2003 and 1st January 2015 (see Figure 1 for tide gauge location. 31
Figure 18: Modelled τw for a 100 km fetch (solid coloured lines) and a 25 km fetch (dashed coloured lines) for water depths ranging between 0 and 4 m and wind speeds ranging between 0 and 6 m/s. 35
Figure 19: Frequency of occurrence of bed level change between monthly samples expressed as a percentage occurrence for Kaiaua (blue line), Miranda (red line), Gun Club (yellow line) and Kuranui Bay (purple line). 39
Figure 20: SAR determined from analysis of the full record and a sub-sampled annual record for the Firth of Thames. 41
Figure 21. SAR determined from analysis of the full record and a sub-sampled annual record for Whaingaroa (Raglan) Harbour. 42
Figure 22. Summary of values of R2 from data comparison in Figures 20 and 21. 43

Tables

Table 1: Summary of SAR (mm/yr) at each plate in the Firth of Thames. 10
Table 2: Summary of plate condition in the Firth of Thames on the 14/06/2018. 16
Table 3: Summary of SAR (mm/yr) at each plate in Whaingaroa (Raglan) Harbour. 17
Table 4: Summary of plate condition in Whaingaroa (Raglan) Harbour on the 31/08/2016 (Haroto Bay and Te Puna Point) and 10/04/2017 (Whatitirinui Island, Ponganui Creek and Okete Bay). 24

Abstract

Sedimentation within estuaries is a natural process but excessive sedimentation can lead to poor ecological health, with current guidance suggesting that sediment accumulation rates (SAR) should not exceed 2 mm/yr above pre-catchment disturbance SAR. To track patterns of contemporary intertidal sedimentation WRC has been monitoring SAR in the Firth of Thames and Whaingaroa (Raglan) Harbour since 2003 as part of an estuarine State of the Environment (SoE) monitoring programme. The programme measures sediment depth above plates (concrete pavers) buried in the intertidal flats. The purpose of these measurements is to track SAR in each estuary and to pair the measured SAR with monitoring of ecological health. This report analyses the WRC SAR monitoring to assess the suitability of the methodology including spatial distribution of plates, temporal distribution of measurements and longevity of the plates. Sedimentation rates at each monitoring site have also been derived from the measurements. This purpose of this analysis is to determine if the sedimentation monitoring programme has been effective and to establish principles around which a standardised sedimentation monitoring programme can be designed in the future, for the purposes of both SoE monitoring and for implementation of monitoring set out in Sea Change 2016 (a spatial plan for the Hauraki Gulf). The analysis found that sedimentation rates are highly variable, with areas of both erosion and accretion ranging between -11.52 (erosion) and 5.59 (accretion) mm/yr in the Firth of Thames and -3.98 (erosion) and 7.04 (accretion) mm/yr in Whaingaroa (Raglan) Harbour. This spatial variation in SAR can be tentatively related to the spatial distribution of hydrodynamics in each estuary including the presence or absence of wind waves, the patterns of residual circulation and magnitude of sediment supply. Sedimentation plates are effective at measuring annual rates of SAR providing the plates are set out with an appropriate spatial array that take into account the spatial distribution of hydrodynamics and are measured annually at regular intervals for at least ten years. Simple guidelines for installing the plates and a standardised methodology are also outlined in this report.

1 Introduction

Waikato Regional Council's Regional Estuary Monitoring Programme (REMP) was initiated in April 2001 to determine the state of selected estuaries in the region and monitor changes over time (Turner, 2000). REMP has recorded macrofauna and sediment characteristics in Whaingaroa (Raglan) Harbour, Firth of Thames and Tairua Estuary, with the aim of relating changes in benthic community structure and ecological health to changes in the physical environment. Measurement of intertidal sediment accumulation rates (SAR) began in Whaingaroa (Raglan) Harbour and Firth of Thames in 2003 using a series of buried sediment plates, measurements have not been made at Tairua. The purpose of this report is as follows:

1. Analyse the trends of intertidal sedimentation measured in the programme.
2. Review the effectiveness of the sediment plate methodology as a monitoring technique in the context of REMP and WRC monitoring requirements.
3. Propose an updated, scientifically robust and effective intertidal sedimentation monitoring plan for future use.

This report discusses intertidal sedimentation only, as the measurement of subtidal sedimentation requires a different approach and methodology and therefore will be addressed in forthcoming work.

1.1 Estuarine and sedimentation processes

WRC measures sedimentation because of the potential negative impacts on the marine environment (Thrush et al. 2004). Although sedimentation is a natural process, there are many human activities that can accelerate sedimentation in the coastal environment. Elevated SAR, suspended sediment and changes in seabed sediment composition have a range of effects on the marine ecology including changes in species composition, loss of sensitive species, decline in diversity, and modification of animal behaviours (Lohrer et al. 2004, Norkko et al. 2002, see review in: Townsend and Lohrer, 2015). ANZECC Guidelines now recommend a maximum SAR threshold of 2 mm/yr above background levels, as the available evidence indicates that environmental degradation can occur at rates above this threshold (Townsend and Lohrer, 2015).

Sea Change has produced a Marine Spatial Plan that aims to direct future management across the Hauraki Gulf Marine Park area (an area encompassing the Hauraki Gulf and the Coastal Marine Area (CMA) of the eastern Coromandel) and outlines a series of objectives which require supporting evidence from monitoring. The ANZECC guidelines have been adopted by Sea Change and objective WQ1 states (Sea Change, 2017): *"Sedimentation rate across the Gulf to be no more than 2 mm per year above the baseline rate by 2050."* Although this guidance is based on our best understanding, SAR and resultant ecological impacts are known to be poorly characterised, with most evidence of ecological harm based on short-term deposition 'events' (Townsend and Lohrer, 2015). This may differ to the characteristics of sediment accumulation occurring within an estuarine system, which could occur over a range of temporal scales, either as: (i) gradual incremental sedimentation, (ii) a discrete depositional event sediment following land clearance or a storm event, (iii) as a result of successive accretional and erosional episodes or due to a combination of the above.

The reality is that patterns of estuarine sedimentation are complex and do not follow straight-forward or predictable relationships e.g., between the magnitude of sediment supply (rivers and/or open ocean), the amount of suspended sediment in an estuary and the resultant sedimentation patterns and SAR within the estuary basin. In general terms the deposition of sediment is controlled by complex interactions of freshwater flow (e.g. McKergow et al., 2010) and oceanographic processes such as tidal flow (e.g. Brown and Davies, 2010), waves (e.g. Green et al., 1997), residual circulation (e.g. Bolle at al., 2010) and intertidal drainage (e.g. Fagherazzi et al., 2008). These processes all contribute to an uneven distribution of sediment across the estuarine basin and therefore modify the basin morphology. This further changes the hydrodynamics through mechanisms such as distortion of tidal patterns and tidal asymmetry and flow (Friedrichs and Aubrey, 1988) or wave dissipation and fetch length (Fagherazzi et al., 2006, Hunt et al., 2015) and these hydrodynamic processes in turn affect the subsequent patterns of sediment deposition. Therefore the hydrodynamics, sediment supply and morphology are all interlinked in a complex non-linear fashion, meaning that sedimentation is difficult to predict and that, even under a scenario of consistent sediment supply, the rate and patterns of sedimentation would not be consistent over time.

Furthermore, the sediment type and particle sizes can change over time (e.g. Hume and Dahm, 1992) due to changes in land use, catchment management and natural variability from erosion. Different sediment types will have different properties that affect their transport and subsequent deposition (Soulsby, 1997; Whitehouse et al. 2000). Sediment particles mobilise when the bed shear stress due to currents or waves exceeds a critical value, with this critical value varying depending on the sediment properties. Finer sediments in general require less hydrodynamic energy to mobilise and disperse compared to coarser sands and gravels, but are more prone to processes of flocculation and cohesion which can also increase the bed shear stress required to remobilise the sediment. Fine sediments tend to travel as suspended load throughout the water column whereas coarser sands and gravels tend to travel as bedload. All of these factors that influence sediment transport will further complicate patterns of sedimentation as the sediment type changes over time.

Finally the re-suspension and deposition of sediment is episodic and therefore a measurement of the long-term SAR only captures a fraction of the total volume of sediment deposited (Bentley et al., 2014). During a hydrodynamically calm period sediment is deposited on the seabed and then a proportion of the sediment is resuspended during a following hydrodynamically active period. The timescale of this period could be over an ebb/flood cycle, a spring/neap cycle or between wave events of a given return period. A thorough understanding of the timescales are required to monitor sedimentation at an appropriate scale.

In general intertidal areas exposed to tidal processes tend to accrete (Friedrichs, 2011; Hunt et al., 2015); this is due to:

1. Settling of fine sediment onto the intertidal during slack water at high tide
2. Transport of coarse sediment in a landward direction due to flood-dominant currents over intertidal areas. This can be enhanced in an estuary with a progressive tidal wave.
3. A spatial gradient of suspended sediment from the channel to the intertidal, which means that flood currents bring sediment laden water shoreward. This gradient occurs because the tidal currents (and therefore higher bed shear stresses) are stronger in the channel relative to the intertidal.

In contrast intertidal areas exposed to wave processes tend to erode (Friedrichs, 2011; Hunt et al., 2015); this is due to:

1. The inhibition of fine sediment settling onto the intertidal during slack water at high tide due to wave stirring (wave energy tends to be larger at high tide because of the larger fetch).
2. A spatial gradient of suspended sediment from the intertidal to the channel, which means the ebbing currents bring sediment-laden water seaward. This gradient occurs due to greater orbital velocities from waves over the shallower intertidal and therefore higher bed shear stresses in the intertidal relative to the channel. Although there is a net spatial gradient between the intertidal and the subtidal the relationship between depth and orbital velocities from waves is non-monotonic (Fagherazzi et al., 2006) as follows:
    a. In water that is very shallow, shorter period waves are dissipated by bottom friction and orbital velocities from the waves are minimal leading to conditions favouring deposition.
    b. In deep water, orbital velocities are attenuated also leading to conditions favouring deposition of sediments. Shorter period waves are attenuated more rapidly than longer period waves meaning that orbital velocities from longer period waves can influence bed sediments in deeper water than those from shorter period waves.
    c. In intermediate water depths, the waves are not dissipated and the orbital velocities are not attenuated leading to conditions favouring erosion.

The spatial variations in hydrodynamic processes means that some intertidal areas will accrete and some will erode even in estuaries that are subject to high levels of sediment supply. Therefore the positioning of plates will influence the SAR recorded.

2 Methodology

2.1 Sediment plate methodology

WRC has been monitoring estuarine intertidal sedimentation using a series of buried sediment plates. Plates are buried beneath the sediment surface and depth measurements are periodically taken between the sediment surface and the top of the plate. Changes over time in the thickness of this measured layer determine the rate at which sediment is accumulating or eroding. The sediment plates used at all locations are square concrete tiles, measuring 30 x 30 cm with a thickness of 4 cm. The sediment thickness above each plate is measured by inserted a metal rod (a knitting needle 3.75 mm by 330mm in length) through the mud until the plate is reached. If the rod encounters hard material between the sediment surface and the plate (such as shells) the true depth of the sediment may not be measured correctly. To minimise incorrect measurements, ten rods are used simultaneously to give replicate measurements. Any large deviations, in the order of cms, can be rapidly identified and repeated within the same location to check if the measurement is correct. This process also ensures that the measurements are distributed across the plate to allow for any variations in sediment level e.g., due to bedforms or bioturbation. The distribution of the replicate measurements over the surface of the plate is not prescribed but effort is made to distribute the measurements across the surface of the plate as widely as possible by first finding the edges of the plate and working inwards towards the centre with the needles. All needles are left in place until all of the replicates are positioned and this allows a final visual check on the distribution of the measurements.

2.1.1 Firth of Thames

The plate methodology was first developed as part of a WRC student project (Collins, 2003) and permanent monitoring locations have been established at four REMP sites in the Firth of Thames (Figure 1). Plates were buried in February 2003 to a depth of ~20 cm and levelled horizontally with a spirit level along the widths and diagonals of the plate. The plates were buried along a shore-perpendicular transect (shallow to deep water, Figure 1f) with the REMP site situated at the centre. A total of six plates were used at each site: three seaward and three landward of the monitored area (Figures 1b – 1e). The plates are numbered sequentially with plate 1 closest to the land (shallowest water depth) and plate 6 located at the seaward end of the transect (deepest water depth). Plates were not buried in the centre of the biological monitoring plot as localised sediment disturbance, during the collection of sediment and macrobenthic samples, could have potentially influenced measurements of sediment thickness. The plates extend a total of ~100 m seaward and ~100 m landward of the biological monitoring plot with a ~50 m gap between each plate (Figures 1b – 1f). Four location marker pegs were placed around each plate. Sediment depth measurements above each plate were taken initially at 1-month intervals and the sampling frequency was then dropped to quarterly in 2009 although there are some inconsistencies around these sampling frequencies. The inconsistent sample frequency was due to a combination of factors including: changes in staff availability; the requirement for low spring tides to access the plates; and occasional poor weather that prevented sampling at scheduled times.

2.1.2 Whaingaroa (Raglan) Harbour

Intertidal sedimentation monitoring was established at five REMP sites in Whaingaroa (Raglan) Harbour in 2003 (Figure 2). Here sediment plates were installed in a different configuration to that used in the Firth of Thames (the rationale for change in approach is unclear). Four plates were used at each sampling site: two plates clustered on the seaward side of the biological monitoring plot and two plates on the landward side with the exception of Okete Bay which only has a seaward cluster of plates (Figures 2b – 2g). There is a distance of ~4 m between each plate within a cluster and a distance of ~100-200 m between each cluster. The two plates in the seaward cluster are named plates A and B, the two plates in the landward cluster are named plates C and D. Sediment depth measurements have generally been biannual or quarterly but the sampling frequency has been inconsistent. The inconsistent sample frequency was due to a combination of factors including: changes in the personnel used for carrying out the sampling, the requirement for low spring tides to access the plates, and occasional poor weather that prevented boat access and sampling at scheduled times.

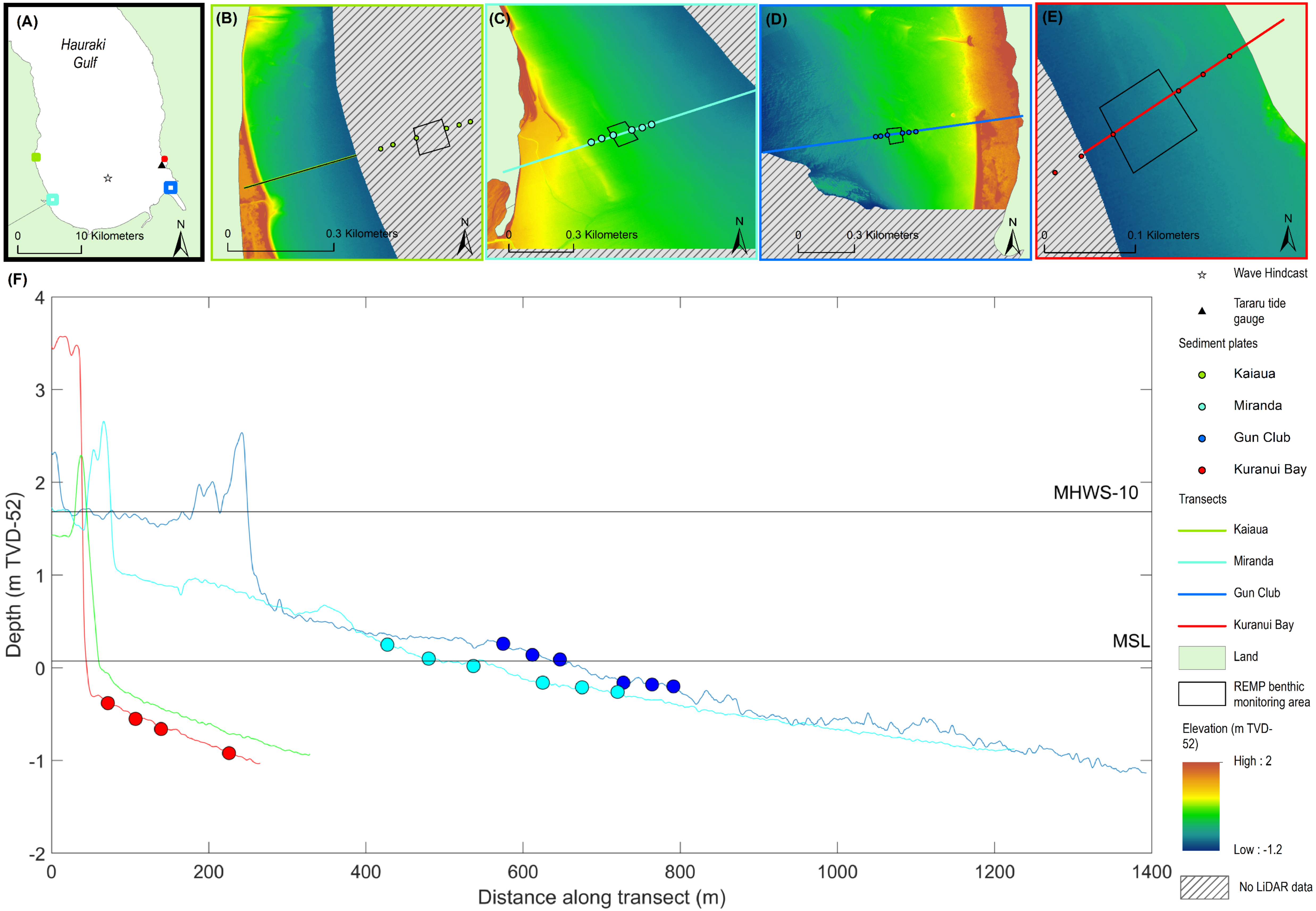

Figure 1: Locations of the REMP sites, Tararu tide gauge and wave hindcast model in the Firth of Thames.
(A). Detailed locations of the plates, the biological monitoring plot, elevations and transects are shown at Kaiaua (B), Miranda (C), Gun Club (D) and Kuranui Bay (E). Elevations along each cross shore transect are shown for each monitoring plot (F). All elevation data is from WRC LiDAR collected in 2007/2008.

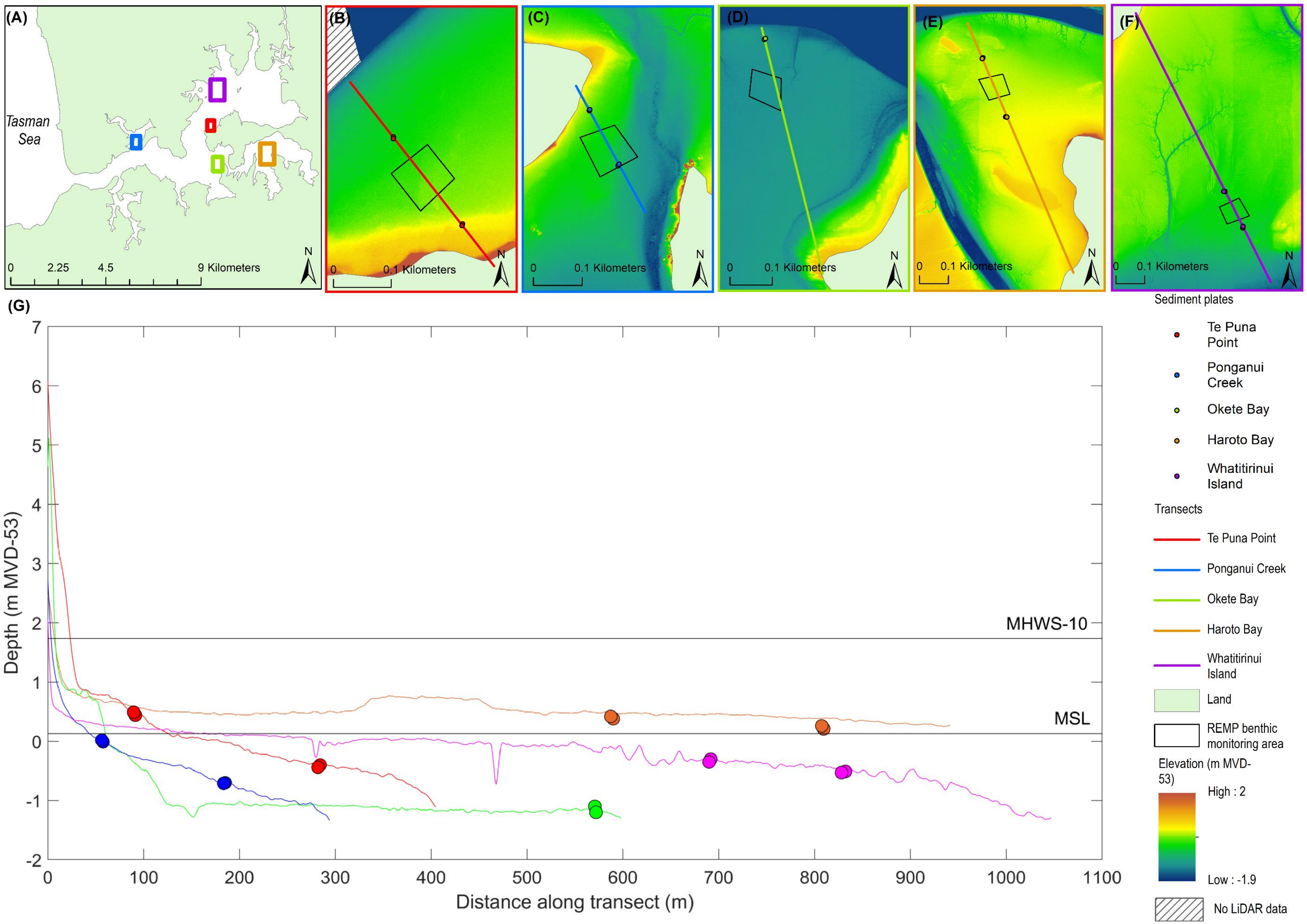

Figure 2: Locations of the REMP sites in Whaingaroa (Raglan) Harbour.
(A). Detailed locations of the plates, the biological monitoring plot, elevations and transects are shown at Te Puna Point (B), Ponganui Creek (C), Okete Bay (D), Haroto Bay (E) and Whatitirinui Island (F). Elevations along each cross shore transect are shown for each monitoring plot (F). All elevation data is from WRC LiDAR collected in 2010**.**

2.2 Calculation of sediment accumulation rate

To calculate sediment accumulation over the entire monitoring period (2003 to 2015) the ten replicates were averaged for each plate, for each sampling occasion, and a linear trend was fitted to the data. The overall rate of sediment accumulation was calculated in mm/yr from the slope of the linear trend line.

2.3 Plate elevation and water depths

The plates are situated at a range of different intertidal elevations and consequently experience differing inundation durations, water depths and hydrodynamic conditions. To assess the variability in water depths over the plate sites, the elevation of the intertidal flat above each plate was determined from LiDAR and the depth of water was calculated using water level records from the Tararu tide gauge for the Firth of Thames (see Figure 1 for location of tide gauge) and the Kawhia tide gauge for Whaingaroa (Raglan) Harbour (see Appendix A for details). LiDAR data was not available for Kaiaua (Figure 1b) and for plates 5 and 6 at Kuranui Bay (Figure 1e).

2.4 Plate material and condition

For the plate methodology to be viable, the long-term integrity of the plates is paramount. Plates were assessed for degradation and orientation in Whaingaroa (Raglan) Harbour in 2016-17 and the Firth of Thames in 2018: in each case the sediment depth above the plate was recorded and then carefully uncovered, visually checked for any deterioration of the concrete and a spirit level used to check the level. The plate was reburied and the sediment depth measured again. In the Firth of Thames, two plates from the Gun Club site and two plates from Miranda site were assessed. At Gun Club, plate 3 landward and plate 4 seaward of the REMP site were uncovered. Plate 3 had been previously exposed due to sediment erosion. At Miranda plate 2 landward and plate 5 seaward of the REMP site were assessed. In Whaingaroa (Raglan) Harbour, one plate from each cluster was uncovered at each of the 5 REMP sites.

3 Results

3.1 Firth of Thames

Bed levels are summarised for each monitoring site in Figures 3-6 and the SAR, calculated from linear fit, shown in Table 1. Miranda to the west (Figure 4) and Gun Club to the east (Figure 5) showed similar behaviour in sedimentation, with erosion occurring at plates landward of the REMP site (shallower, plates 1-3) and accreting seaward of the REMP site (deeper, plates 4-6, with the exception of Miranda plate 4). At Kaiaua (Figure 3), which is more seaward than Miranda to the west, a similar rate of sediment deposition was recorded for all plates (Figure 3 and Table 1). At Kuranui Bay (Figure 6) accretion was recorded at the most landward plates (plates 1 and 2) and erosion at the seaward plates (plates 3-6). The relationship between water depth and SAR for Miranda, Gun Club and Kuranui Bay is shown in Figure 7. This Figure shows that plates at bed levels higher than -0.24 mMSL are eroding and plates at bed levels lower than -0.24 mMSL and above -0.62 mMSL are accreting. Below – 0.62 mMSL the plates at Kuranui Bay are eroding. Because the Miranda and Gun Club transects span similar bed elevations it is possible to plot lines of best fit demonstrating that the SAR over the plates at both Gun Club and Miranda behave similarly at equivalent elevations. Plates at Kuranui Bay are deeper than those at Miranda and Gun club and show increasing SAR over the shallower plates (plates 1 and 2), increasing erosion rates over the intermediate plates (plates 3 and 4)and then a reduction in erosion over the two deepest plates (plates 5 and 6). Plates 5 and 6 are not plotted on Figure 7 as the water was covering these plates during the LIDAR collection. The variation in SAR between the plates and the overall magnitude of bed change at Kuranui Bay is less than those recorded at Gun Club and Miranda. If all plate data at each site is aggregated to calculate a single SAR for each transect, accretion is recorded at Kaiaua and erosion is recorded at Miranda, Gun Club and Kuranui Bay (Table 1).

Inspection found Plate 4 at Gun club and Plate 2 at Miranda to be level and in good condition (Table 2). Plate 5 at Miranda could not be visually inspected due to groundwater but felt level and in good condition. Plate 3 at Gun Club had been previously exposed due to bed erosion and the plate felt unevenly orientated. Records show that this plate was uncovered once in 2008 and once in 2009 (vertical dashed lines in Figure 5) which would likely have led to scour and differential settlement of the plate.

The magnitude of variation in sediment thickness between the replicate sediment depths taken before uncovering and after burial, a proxy for plate unevenness/tilting, also indicated that Plate 3 at Gun Club was not level (Table 2). Prior to uncovering, sediment thicknesses varied by 35 mm across the 10 replicates whereas Plate 4 at Gun Club and Plate 2 and Plate 5 at Miranda varied by only 12, 11 and 21 mm. Post burial, after the bedforms had been smoothed the differences in sediment thickness were even more marked between Plate 3 at Gun Club and the other plates. Sediment thicknesses at Plate 3 at Gun Club varied by 38 mm whereas Plate 4 at Gun Club and Plates 2 and 5 at Miranda varied by only 4, 5 and 7 mm respectively.

Table 1: Summary of SAR (mm/yr) at each plate in the Firth of Thames.

	Kaiaua	Miranda	Gun Club	Kuranui Bay
Plate 1	2.34	-11.23	-0.33	1.89
Plate 2	3.50	-10.21	-11.52	0.03
Plate 3	3.38	-6.95	-9.94	-3.04
Plate 4	1.58	-0.92	3.83	-4.67
Plate 5	2.63	1.96	5.59	-2.37
Plate 6	3.19	4.29	4.63	-0.66
All plates	2.75	-3.86	-1.51	-1.70

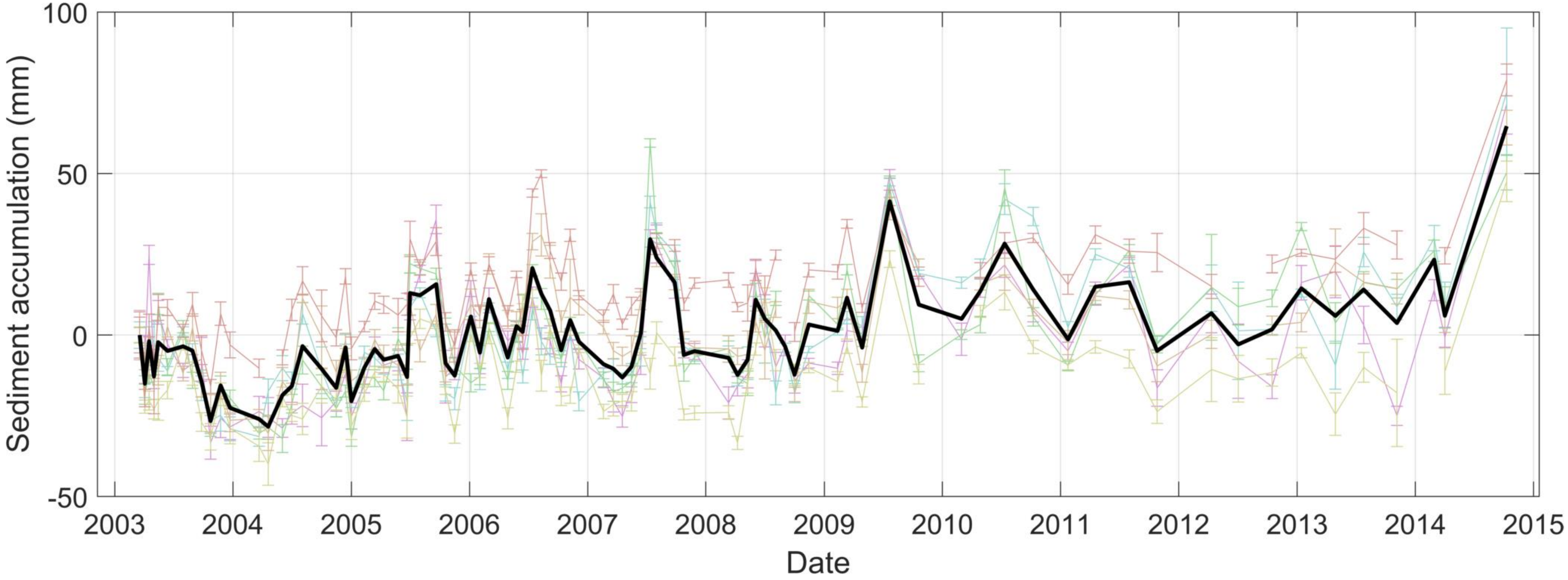

Figure 3: Sedimentation recorded in the Firth of Thames over the Kaiaua Plates.
Averages for the ten replicates at Plate 1 (pink line), Plate 2 (blue line), Plate 3 (green line), Plate 4 (yellow line), Plate 5 (orange line) and Plate 6 (red line) are shown and error bars show the standard deviation around this average. The average of all plates is shown by the thick black line. Plate 1 is landward and Plate 6 is seaward.

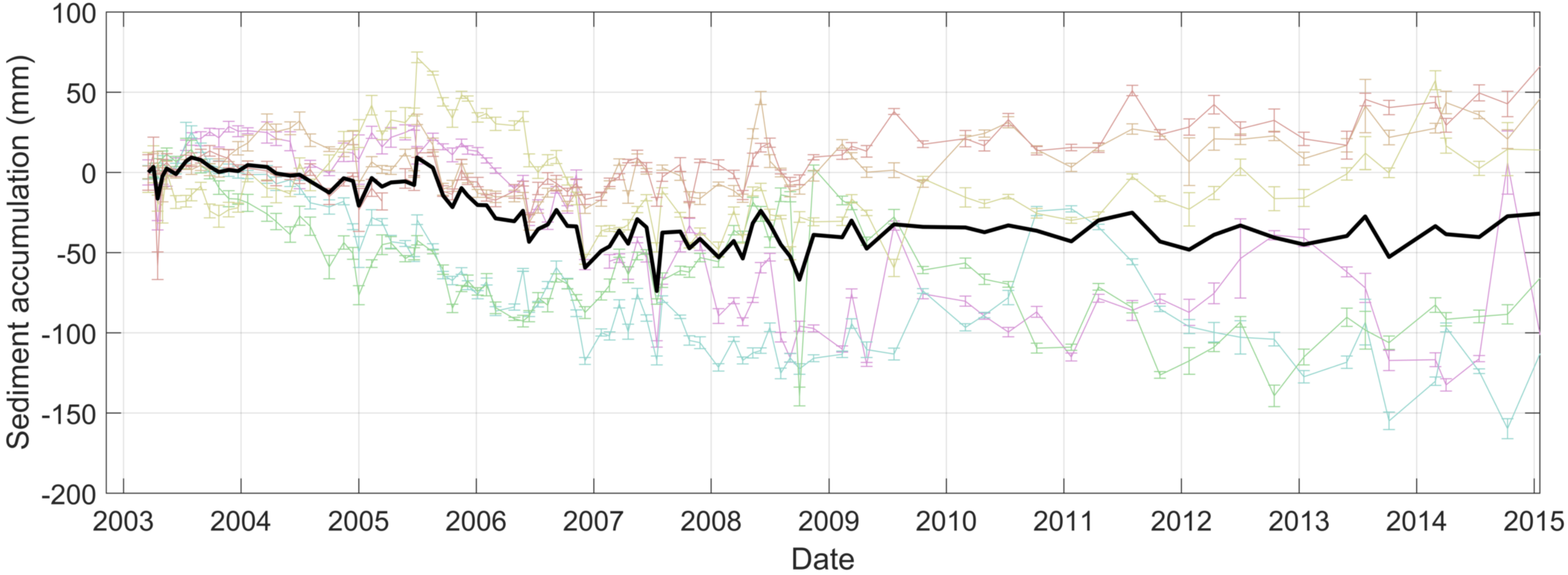

Figure 4: Sedimentation recorded in the Firth of Thames over the Miranda Plates.
Averages for the ten replicates at Plate 1 (pink line), Plate 2 (blue line), Plate 3 (green line), Plate 4 (yellow line), Plate 5 (orange line) and Plate 6 (red line) are shown and error bars show the standard deviation around this average. The average of all plates is shown by the thick black line. Plate 1 is landward and Plate 6 is seaward.

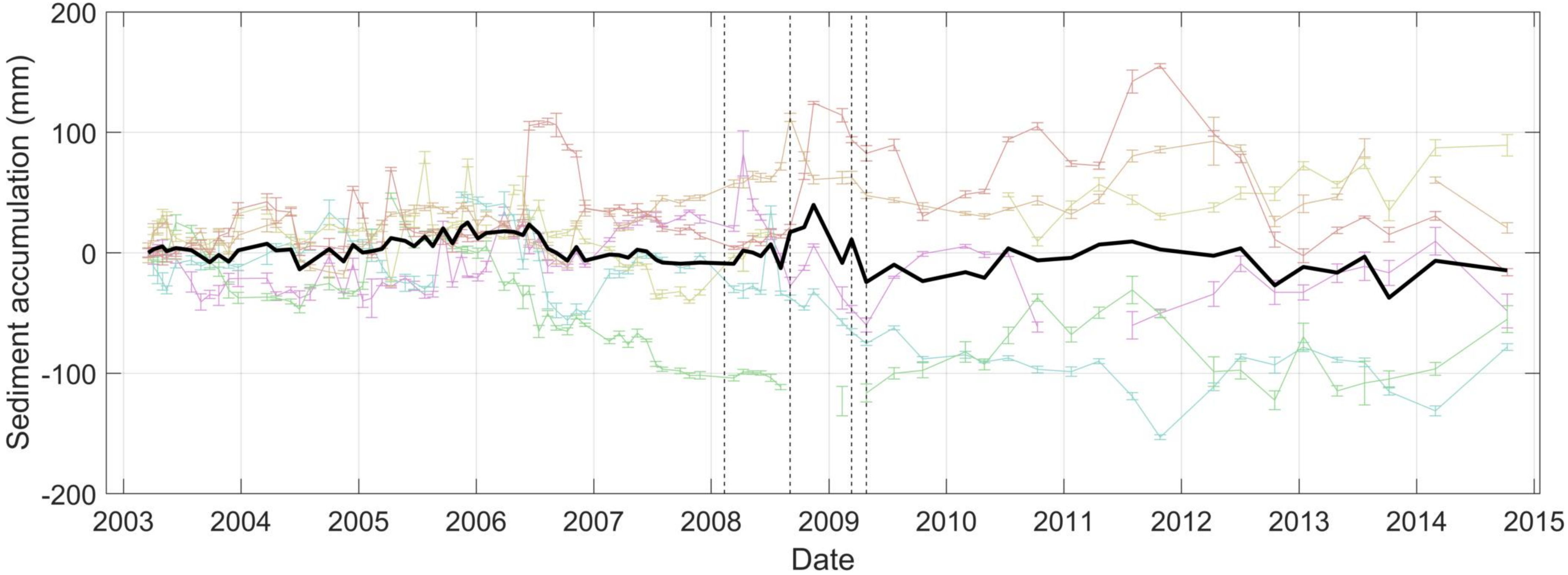

Figure 5: Sedimentation recorded in the Firth of Thames over the Gun Club Plates.
Averages for the ten replicates at Plate 1 (pink line), Plate 2 (blue line), Plate 3 (green line), Plate 4 (yellow line), Plate 5 (orange line) and Plate 6 (red line) are shown and error bars show the standard deviation around this average. The average of all plates is shown by the thick black line. The two periods during which plate 3 was uncovered at the Gun Club site are shown between the pairs of dashed black lines. Plate 1 is landward and Plate 6 is seaward.

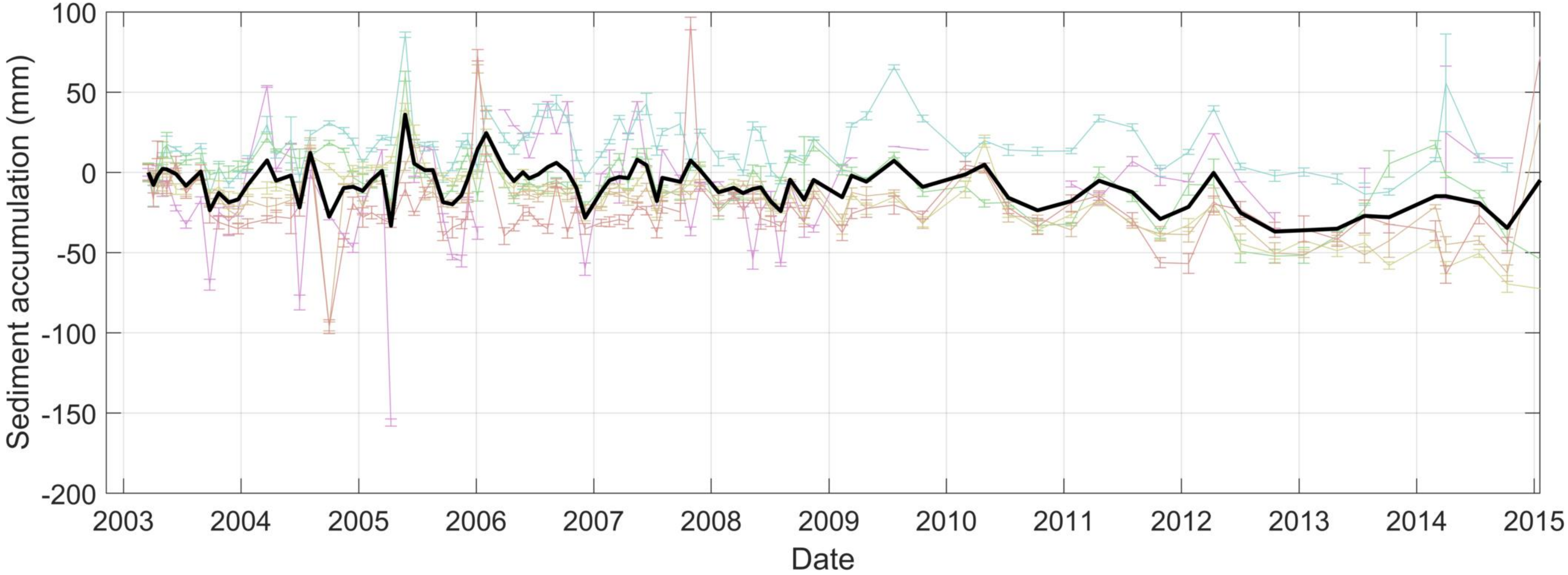

Figure 6: Sedimentation recorded in the Firth of Thames over the Kuranui Bay Plates.
Averages for the ten replicates at Plate 1 (pink line), Plate 2 (blue line), Plate 3 (green line), Plate 4 (yellow line), Plate 5 (orange line) and Plate 6 (red line) are shown and error bars show the standard deviation around this average. The average of all plates is shown by the thick black line. Plate 1 is landward and Plate 6 is seaward**.**

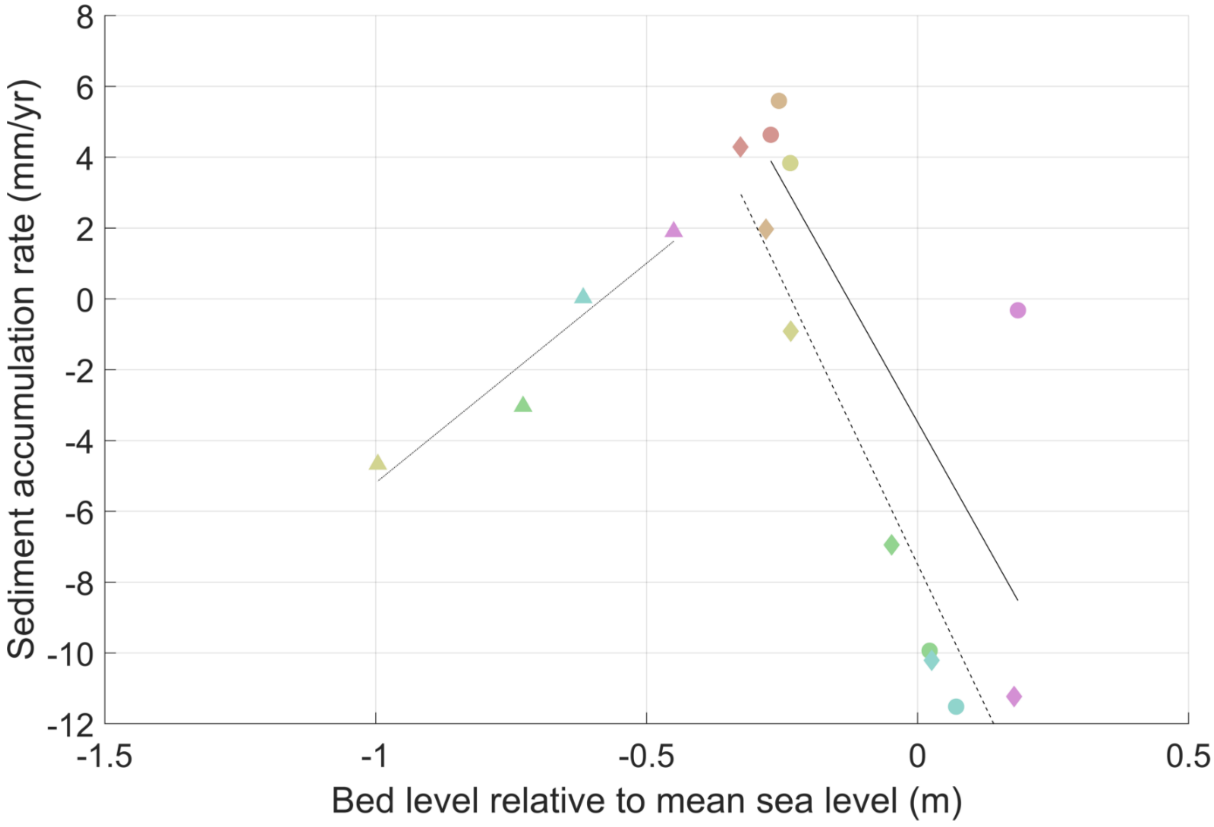

Figure 7: Seabed level relative to mean sea level and SAR.
Data from the Gun Club (circles), Kuranui Bay (triangles) and Miranda (diamonds). The colour of each symbol denotes the plate number, Plate 1 (pink symbol), Plate 2 (blue symbol), Plate 3 (green symbol), Plate 4 (yellow symbol), Plate 5 (orange symbol) and Plate 6 (red symbol). Note that LiDAR data were not available for Plates 5 and 6 at Kuranui Bay and all plates at Kaiaua and these plates are not plotted. The solid black, dashed black and dotted black lines show fit using linear regression for the Gun Club, Miranda and Kuranui Bay data, respectively**.**

Table 2: Summary of plate condition in the Firth of Thames on the 14/06/2018.

REMP site	Plate ID	Photo	Maximum variation in sediment thickness over 10 replicate measurements (mm)		Notes
			Before uncovering	After burial	
Gun Club	4		12	4	Spirit level showed that plate was level. Plate felt to be in good condition but could not be seen due to groundwater.
	3		35	38	Has been exposed before due to fluctuations in bed level. Hard to see the plate due to groundwater but the plate felt like it was sloping, the variations in sediment depth measurements over the plate seem to confirm this.
Miranda	2		11	5	Spirit level showed that plate was level. Plate felt to be in good condition but could not be seen due to groundwater.
	5		21	7	Plate feels level. Too much water to see (no photo taken). Does not feel pitted or eroded and is in good condition

3.2 Whaingaroa (Raglan) Harbour

Between 2003 and 2015, monitoring found net sediment accumulation at Haroto Bay (Figure 8 and Table 3) in the smaller southern sub-estuary, and Okete Bay (Figure 11 and Table 3), and net erosion at Whatitirinui Island (Figure 9 and Table 3) and Te Puna Point (Figure 10 and Table 3), both in the larger, northern sub-estuary. Both erosion and accretion have occurred at Ponganui Creek (Figure 12 and Table 3), which is seaward closer to the main entrance, over the monitoring period but the changes have been small and the seabed elevation is largely stable. Although there was variability between individual plates, the variability has not been systematic. The relationship between water depth and SAR shows no clear relationship between different monitoring sites (Figure 13) but clusters of plates tended to show similar behaviour. If all plate data at each site is aggregated to calculate a single SAR for each transect, accretion is recorded at Haroto Bay and Okete Bay, erosion is recorded at Whatitirinui Island and Te Puna Point, and Ponganui Creek can be considered largely stable (Table 3).

Inspection found that plates were intact, level and in good condition (Table 4), although at Haroto Bay and for Whatitirinui Island, Plate D, full assessments were not possible. However, for these the condition was checked by feeling for pitting along the top, edges and corners of the plates and all were in good condition. There was no indication of plates tilting, with relatively small magnitudes of variation in sediment depth across replicates for individual plates (Table 4). One exception was recorded for Plate D Whatitirinui Island with a post burial variability of 39 mm. This was likely to be due to uneven sediment infilling above the plate and will be checked during the next routine monitoring visit.

Table 3: Summary of SAR (mm/yr) at each plate in Whaingaroa (Raglan) Harbour.

	Haroto Bay	Whatitirinui Island	Te Puna Point	Okete Bay	Ponganui Creek
Plate A	1.67	-2.98	-1.64	4.05	0.30
Plate B	0.86	-3.05	-3.56	7.04	1.32
Plate C	2.83	-3.98	-1.01		-0.43
Plate D	2.86	-2.37	-0.73		-1.18
All plates	2.02	-3.14	-1.73	7.36	-0.02

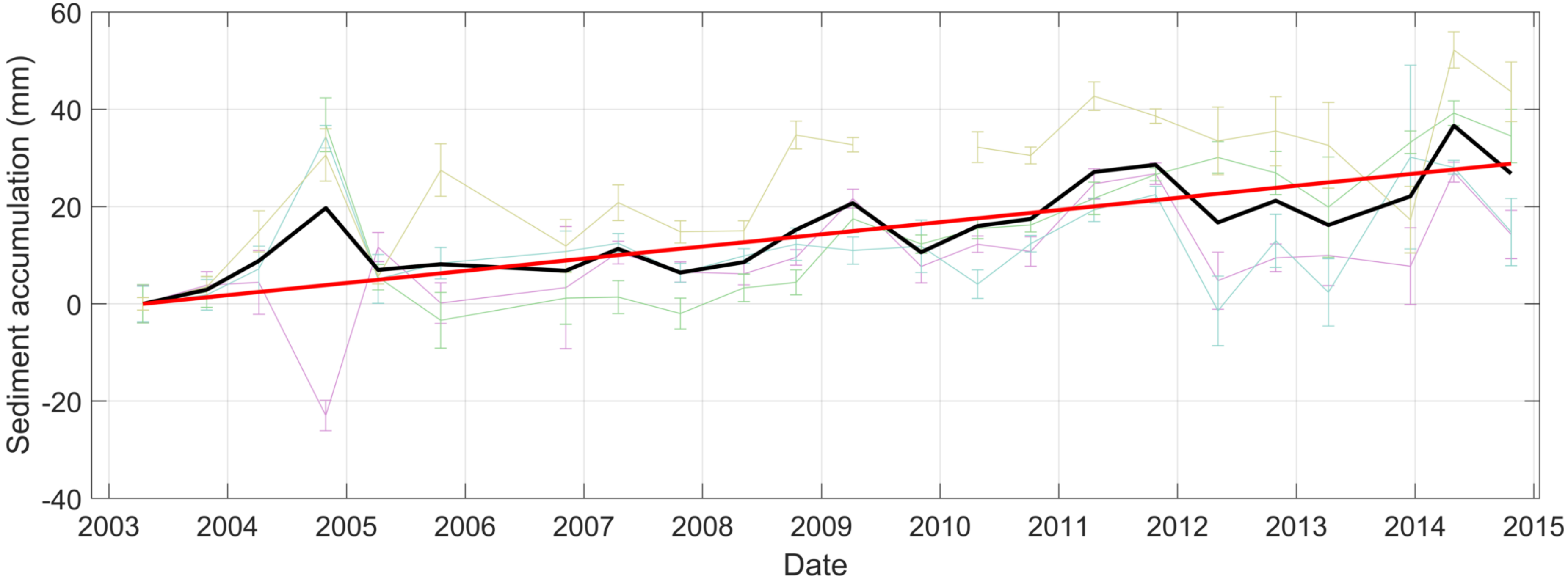

Figure 8: Sedimentation recorded over the Haroto Bay Plates.
Averages for the ten replicates at Plate A (pink line), Plate B (blue line), Plate C (green line) and Plate D (yellow line) are shown and error bars show the standard deviation around the average. The average of all plates is shown by the thick black line. Plates C and D are landward, plates A and B are seaward. Linear accretion rates from the analysis of sediment cores (Swales et al., 2005) are shown as a thick red line.

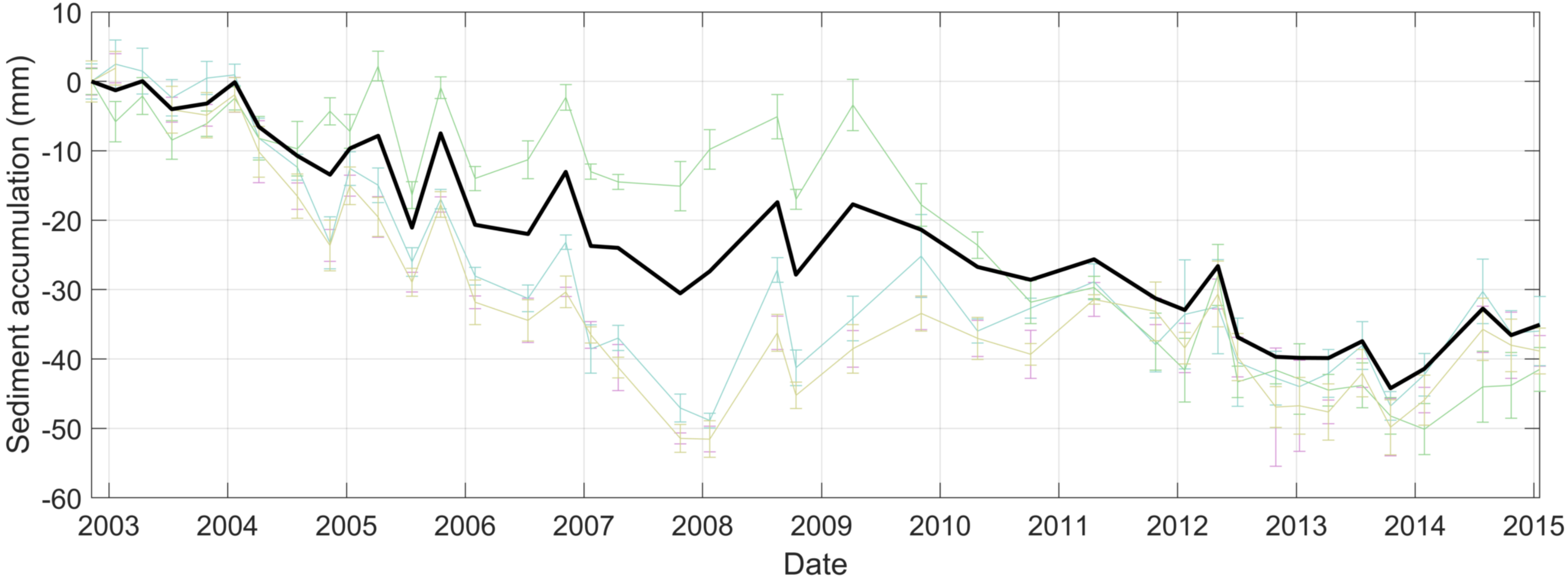

Figure 9: Sedimentation recorded over the Whatitirinui Island Plates.
Averages for the ten replicates at Plate A (pink line), Plate B (blue line), Plate C (green line) and Plate D (yellow line) are shown and error bars show the standard deviation around the average. The average of all plates is shown by the thick black line. Plates C and D are landward, plates A and B are seaward.

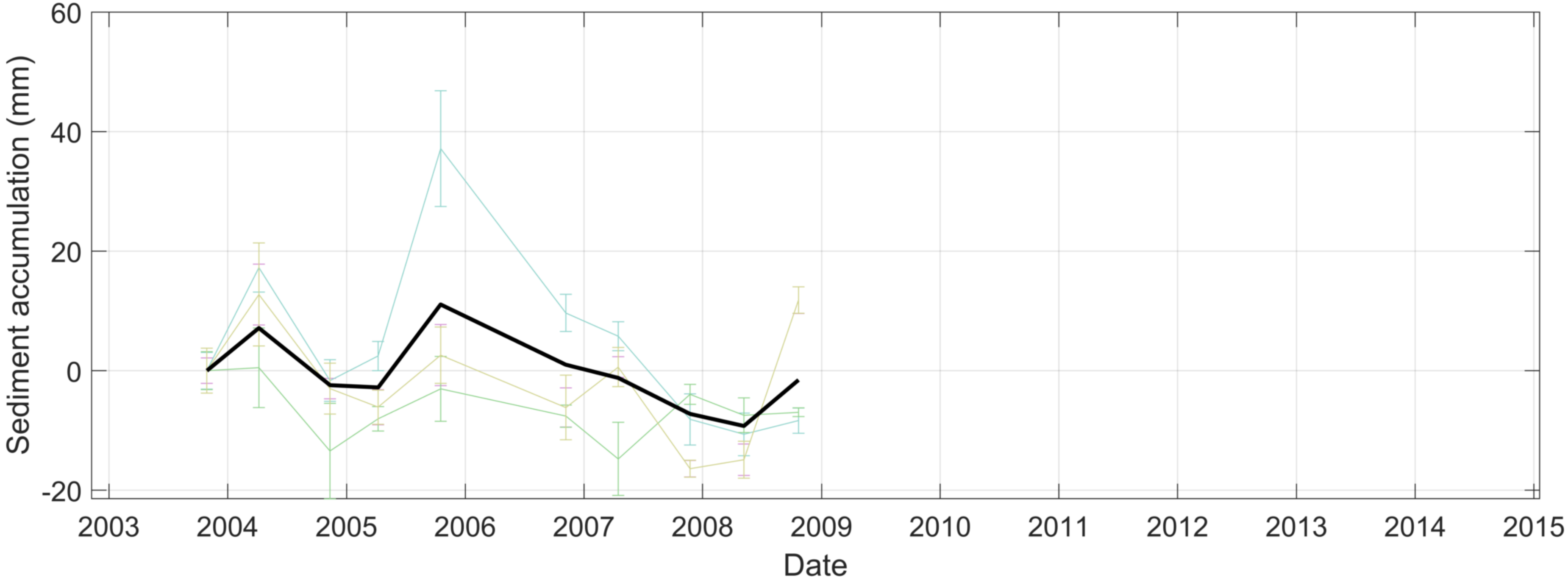

Figure 10: Sedimentation recorded over the Te Puna Point Plates.

Averages for the ten replicates at Plate A (pink line), Plate B (blue line), Plate C (green line) and Plate D (yellow line) are shown and error bars show the standard deviation around the average. The average of all plates is shown by the thick black line. Plates C and D are landward, plates A and B are seaward.

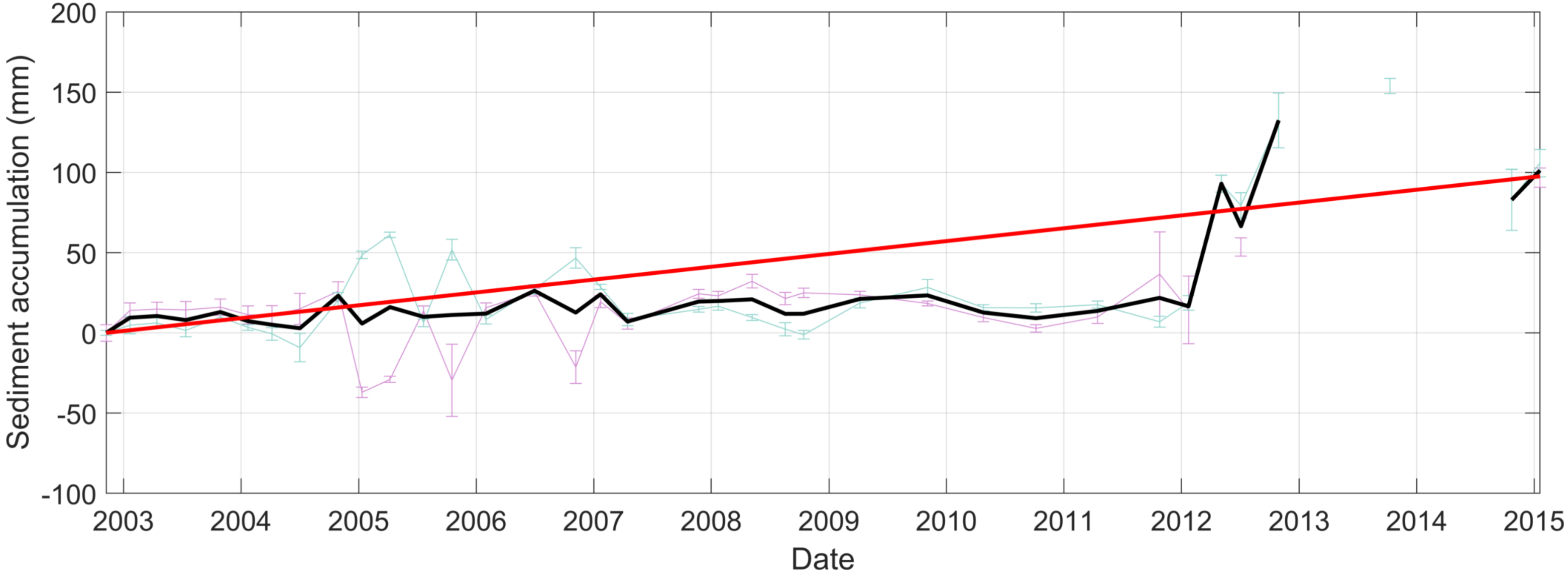

Figure 11: Sedimentation recorded over the Okete Bay Plates.

Averages for the ten replicates at Plate A (pink line) and Plate B (blue line) are shown and error bars show the standard deviation around the average. The average of all plates is shown by the thick black line. Plates A and B are seaward of the benthic monitoring plot. Linear accretion rates from the analysis of sediment cores (Swales et al., 2005) are shown as a thick red line.

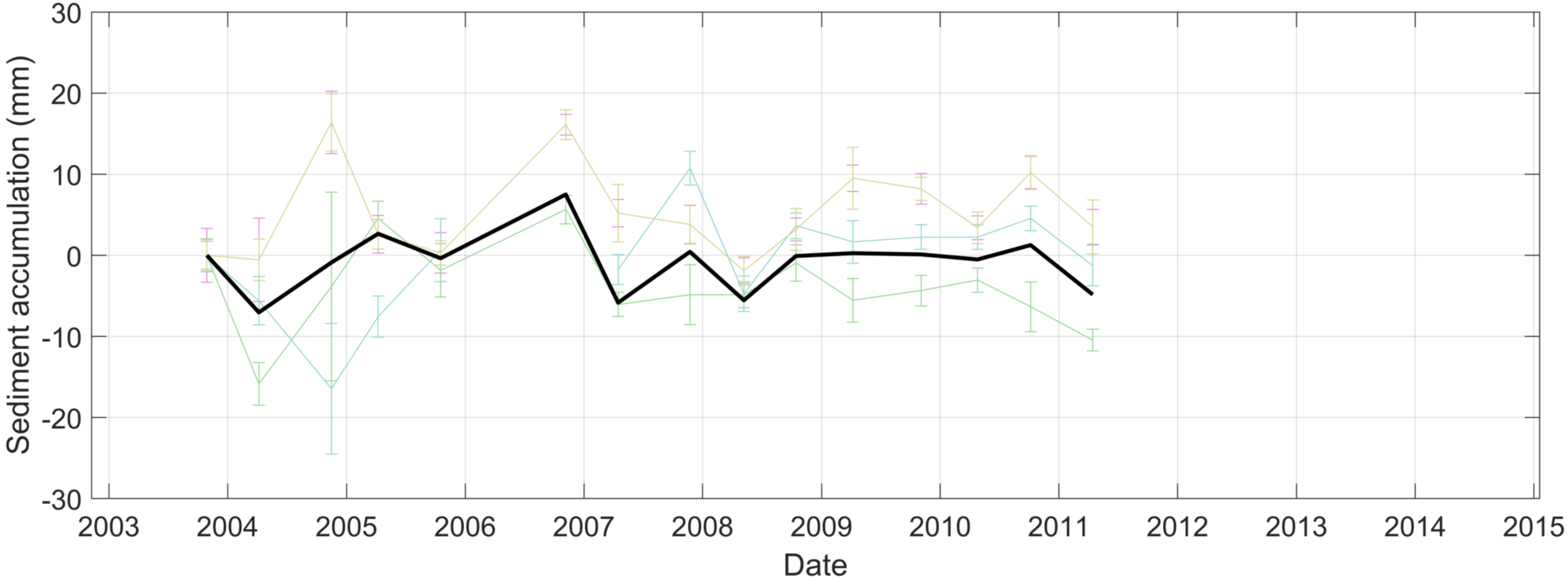

Figure 12: Sedimentation recorded over the Ponganui Creek Plates.

Averages for the ten replicates at Plate A (pink line), Plate B (blue line), Plate C (green line) and Plate D (yellow line) are shown and error bars show the standard deviation around the average. The average of all plates is shown by the thick black line. Plates C and D are landward, plates A and B are seaward.

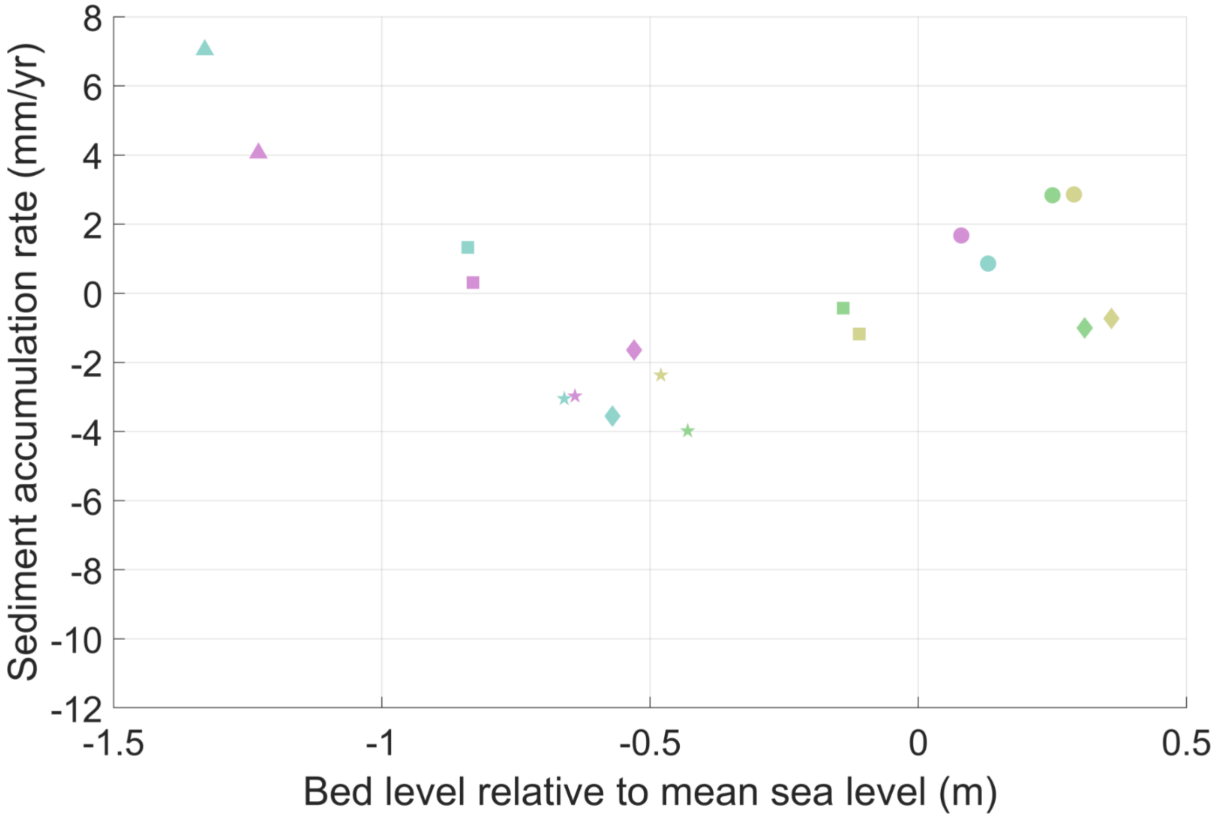

Figure 13: Seabed depth relative to mean sea level and associated SAR.
Data from the Haroto Bay site (southern arm) are shown as circles, Okete Bay is shown as triangles, Te Puna Point (northern arm) is shown as diamonds, Whatitirinui Island (northern arm) is shown as stars and Ponganui Creek is shown as squares. The colour of each symbol denotes the plate number, Plate A (pink symbol), Plate B (blue symbol), Plate C (green symbol) and Plate D (yellow symbol).

Table 4: Summary of plate condition in Whaingaroa (Raglan) Harbour on the 31/08/2016 (Haroto Bay and Te Puna Point) and 10/04/2017 (Whatitirinui Island, Ponganui Creek and Okete Bay).

REMP site	Plate ID	Photo	Maximum variation in sediment thickness over 10 replicate measurements (mm)		Notes
			Before uncovering	After burial	
Haroto Bay (Waitetuna arm)	B		7	4	No photo and level could not be checked due to groundwater. Plate not visible but felt in good condition.
	C		6	11	No photo due to groundwater. It was noted that the plate felt uneven but this could not be assessed due to groundwater. Plate not visible but felt in good condition.
Te Puna Point (Waingaro arm)	A	 	17	17	Plate was level and in good condition.

	C	 	6	12	Plate was almost level and in good condition
Whatitirinui Island (Waingaro arm)	B		8	9	Plate is level and in good condition
	D		8	39	No photo due to groundwater. Plate not visible but felt in good condition
Ponganui Creek	A		7	8	Plate is level and in good condition

	C	 	12	7	Plate is level and in good condition
Okete Bay	A		10	13	Spirit level showed that plate is not level, the plate is in good condition.

4 Discussion

4.1 Sedimentation trends

4.1.1 Firth of Thames

The distinction in patterns of sedimentation across the transects at Kuranui Bay (Figure 6) and Kaiaua (Figure 3) relative to the similar patterns of sedimentation at the southern Firth of Thames sites (Figures 4 and 5) (i.e. Miranda and Gun Club) can be attributed to site specific changes in elevation or due to other differences in the morphological and hydrodynamic environment. As the range of plate elevations at the southern Firth of Thames sites and Kuranui Bay sites are different and do not overlap (Figure 7), it is impossible to establish if similar sedimentation patterns at similar depths would occur at the southern Firth of Thames sites and the Kuranui Bay sites. The intertidal elevation at Kaiaua are not known but the LiDAR survey, the extent of which ends landward of plate 1 (Figure 1b), suggests that the plates are lower than all the other sites. This lower elevation is confirmed by technical staff at WRC who are only able to access this site at tides predicted at 0.4 m LAT.

Other studies have measured sedimentation within the mangrove forest (Swales et al., 2019) and adjacent intertidal flat (Zeldis et al., 2015) in the southern part of the Firth of Thames situated between the Gun Club and Miranda sites. Measurements of sediment accumulation over buried tiles in the mangrove forest show contemporary SAR of ~13 – 47 mm/yr between 2009 and 2016 with SAR increasing towards the seaward fringe of the mangroves. Analysis of ^{210}PB within sediment cores show SAR ranging between 26 – 43 mm/yr between c. 1990 – 2006. The SAR over the intertidal areas are again greatest adjacent to the seaward edge of the mangrove forest and reduce to a constant level averaging ~26 mm/yr in the area 600 – 1000 m from the seaward edge of the mangrove forest in 2006. The lower SAR presented here indicate that the large SAR recorded in the mangrove forest (Swales et al., 2019) and over the adjacent intertidal flats (Zeldis et al., 2015) in the southern Firth of Thames are atypical and represent a preferential sink for fine sediment. It is possible that the sink of sediment in the southern Firth of Thames removes large proportions of fine sediment from the Firth and therefore helps prevent sedimentation elsewhere. Given the large SAR identified in the southern Firth of Thames (Swales et al., 2019; Zeldis et al., 2015) the relatively low rates of accretion and / or erosion identified here are unexpected, this section discusses the possible reasons for the observed spatial patterns of sedimentation over the plate sites.

The Firth of Thames is a mesotidal system (Dyer, 1997) with a mean spring tidal range of 3.3 m and a mean neap tidal range of 2.1 m (LINZ, 2017a). The patterns of sediment erosion in the upper intertidal over the southern Firth of Thames sites do not reflect a typical tidally dominated environment where deposition and accretion might be expected over the shallower intertidal areas. Instead the relationship between increasing water depth and sediment accumulation is indicative of a wave dominated environment where the intertidal is responding to the differing influence of wave attenuation or dissipation has on bed sediment transport with changing water depths (Fagherazzi et al., 2006, 2007; Mariotti and Fagherazzi, 2013a, 2013b; Hunt et al., 2015, 2016, 2017). The sediment erosion over the upper intertidal areas may also be indicative of the intertidal flat tending towards a concave-up wave dominated shape along the cross-shore profile (Friedrichs and Aubrey, 1996; Bearman et al., 2010; Friedrichs, 2011; Zhou et al, 2015; Hunt et al., 2015, 2016). This concave-up cross-shore profile is a theoretical equilibrium intertidal shape that occurs when the spatial distribution of bed shear stresses due to waves and therefore suspended sediment concentrations, are in equilibrium across the intertidal profile resulting in no net transport of suspended sediment (Friedrichs and Aubrey, 1996).

Good quality long-term wave records are not available for the Firth of Thames. The tide gauge at Tararu was setup with the intention of recording wave conditions but previous analysis of the data to estimate wave heights highlighted concerns over the quality of the wave record (NIWA, 2015). It is possible that the shape of the structure, on which the tide gauge is situated, interferes with the propagation of waves and is not suitable for wave collection. Furthermore the instrument and sampling schedule is not optimised for collecting wave data and therefore the dataset requires validation with an independent instrument. This structure needs to be replaced within the next few years and this could offer an opportunity to optimise the instrumentation and structure for wave data collection. To provide a comparison dataset and to help further characterise the wave climate within the Firth of Thames a wave sensor is being deployed by WRC in 2019 as part of the Firth of Thames water quality buoy.

In the absence of wave data, modelled hindcast wave data can be used to infer the wave climate in the Firth. Hindcast information from MetOcean View (https://metoceanview.com/) extracted at the centre of the study area (see Figure 1 for hindcast model location) at a water depth of ~4m below LAT (LINZ, 2017b) indicates that the most common waves have a small peak period (*Tp*) with waves between 2 and 4 s accounting for 43.5% of the hindcast record (Figures 14 and 15). These small period waves are associated with small waves with significant wave heights (*Hs*) ranging between 0 and 1 m (Figure 14). Most waves have a *Tp* of 2–3 s (Figure 15) and an *Hs* of between 0–0.5 m accounting for 25% of the record alone (Figure 16). The small short period waves come from a variety of directions but the majority of waves come from the north (Figures 15 and 16). The total amount of waves from the northerly sector amounts to 71% of the total record with waves between 2 and 4 s from the north accounting for 21.4% of the total record (Figure 16). Wind conditions measured at the Tararu tide gauge between 2003-2015 (see Figure 1 for location of tide gauge) show that the most common wind speeds range between 0 and 10 m/s and account for 93% of the record (Figure 17). The majority of winds have speeds of less than 6 m/s accounting for 70% of the record (Figure 17). The most common wind direction is from the north (345 - 15˚) accounting for 15.5% of the record and the north-northwest (315 - 345˚) accounting for 13.4% of the record (Figure 17). Within these common directions, the most frequent wind speeds are in the 0 – 6 m/s bin (18.5% of the record) and the 6 – 10 m/s bin (8.2% of the record) (Figure 17). Wind from these directions have a maximum fetch of ~100 km terminating at the area around Little Barrier and Great Barrier Islands. When the wind is blowing from the edges of these northerly sectors (345˚ and 15˚) the fetch is shorter and measures ~25 km.

Overall, the wind record and wave hindcast data indicate that the sites in the Firth of Thames are exposed to both occasional long-period waves that propagate into the Firth and more common shorter period waves that are generated along the large fetch coincident with the prevailing northerly wind direction. The sedimentation record at Miranda and Gun Club is indicative of a typical short wave period dominated sedimentation pattern with accretion over the deeper plates and erosion over the shallower plates and therefore also a possible increase in concavity of the intertidal profile. The initiation of erosion could potentially arise from changes in forcing conditions such as a reduction in sediment supply relative to wave forcing or a change in the wave climate. A further possibility is that the erosion is part of a cyclical feedback between intertidal height and hydrodynamics whereby intertidal levels accrete to a level where orbital velocities from waves can begin to erode the intertidal. There is not enough evidence to confirm either of these hypothesises and will be the subject of ongoing investigations and further monitoring.

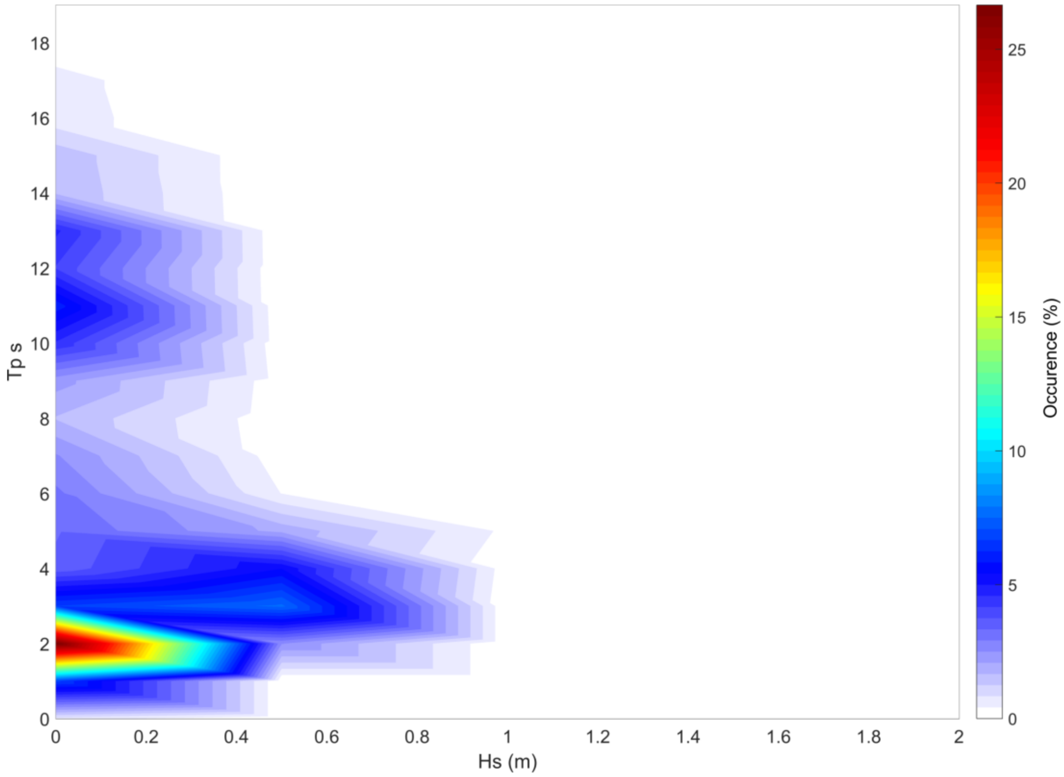

Figure 14: Distribution of wave events from the MetOcean View hindcast model plotted as the percentage occurrence of Tp and Hs (see Figure 1 for hindcast model location).

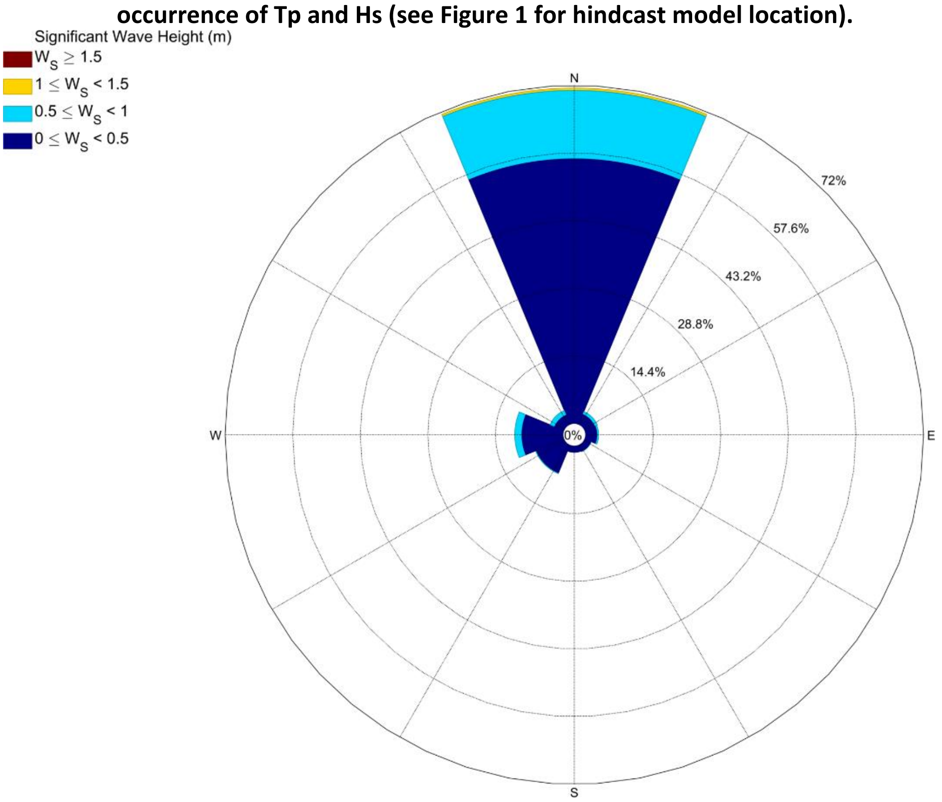

Figure 15. Wave rose showing distribution of wave events from the MetOcean View hindcast model plotted as the percentage occurrence of Hs and the associated wave direction

The data was extracted at 37.148S 175.426E (see Figure 1 for hindcast model location).

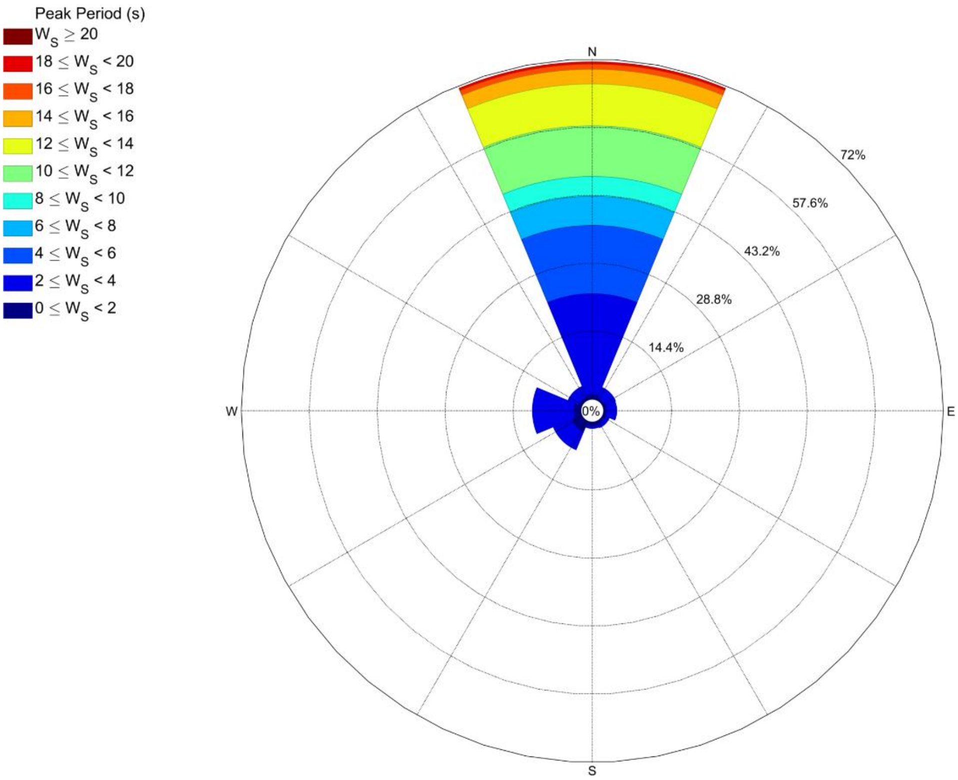

Figure 16: Wave rose showing distribution of wave events from the MetOcean View hindcast model plotted as the percentage occurrence of Tp and the associated wave direction.
The data was extracted at 37.148S 175.426E (see Figure 1 for hindcast model location).

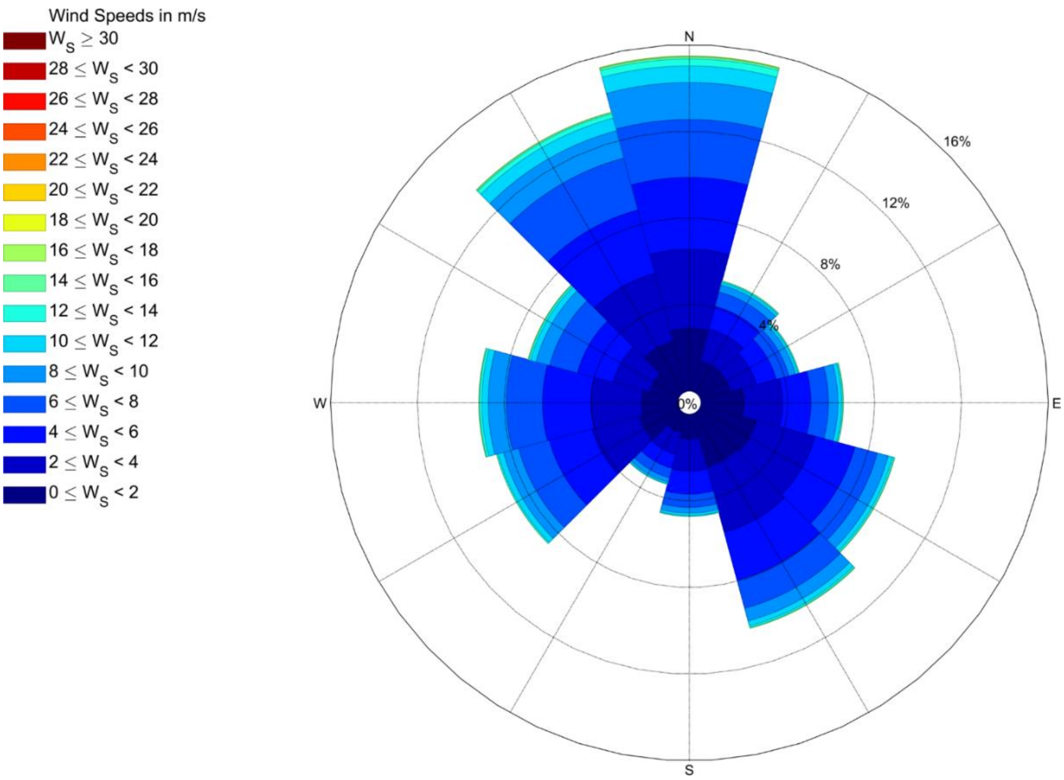

Figure 17: Wind rose summarising the wind record at Tararu tide gauge between 1st January 2003 and 1st January 2015 (see Figure 1 for tide gauge location.

To test the hypothesis that waves are driving patterns of erosion and accretion across the intertidal profiles at each site, a simple model was written in Matlab to calculate the typical bed shear stress from locally generated short period waves (τ_w) for different water depths, wind speeds and fetch lengths using empirical equations (e.g. Hunt et al., 2017; see Appendix B for details of model setup). The model was run with wind scenarios ranging between 0 and 6 m/s. These wind speeds were run over a fetch lengths of 100 km representing the maximum available fetch and 25 km representing a smaller cross basin fetch and water depths ranging between 0 and 20 m (Figure 18).

With a fetch length of 100 km and using the same depth as at the location of the hindcast model point (~7.8 m at Mean High Water Springs (MHWS) (LINZ, 2017a)) the *Tp* predicted by the model ranged between 0 and 3.4 s and *Hs* ranged between 0 and 0.7 m. With a fetch length of 25 km and the same water depth the *Tp* predicted by the model ranged between 0 and 2.7 s and *Hs* ranged between 0 and 0.46 m. These modelled *Hs* and *Tp* comprise 61% and 51 % of the hindcast wave model record and therefore represent the envelope of most common wave types and indicate that the model is replicating the relevant wave climate at a simple monochromatic level.

To assess the likelihood of sediment erosion or accretion the modelled values of τ_w can be compared to the critical bed shear stress (τ_{crit}) required to initiate sediment movement. The range of potential τ_{crit} are calculated based on sediment characteristics at each site (see Appendix B for details) and are plotted as horizontal black lines on Figure 18 showing an upper, average and lower τ_{crit}. When $\tau_w > \tau_{crit}$ then erosion is likely, when $\tau_w < \tau_{crit}$ then accretion is likely. To show how these modelled patterns of τ_w relative to τ_{crit} relate to measured trends of sedimentation or accretion each tile has been plotted relative to its depth at MHWS (see Appendix A for calculation of water levels) and the measured SAR (Table 1) at each plate over the entire monitoring record (Figure 18). The model indicates that for a fetch of 100 km, waves generated by a wind speed of ~4 m/s cause erosion of sediment over the upper (shallower) plates and accretion of sediment over the lower (deeper) plates consistent with the monitoring data (Figure 18) at Miranda and Gun Club. For a smaller fetch of 25 km a slightly larger wind speed of ~ 5 m/s is required to initiate a similar pattern of erosion and accretion (Figure 18) at Miranda and Gun Club. Erosion rates are greater over the shallower plates and this is likely to be due to the non-monotonic shape of the τ_w curves which peak in shallower water depths (Figure 18). In addition the sediment overlying the upper (shallow) plates only requires small waves and consequently low wind speeds (> ~ 3m/s) to erode and these smaller wind speeds are slightly more common than higher wind speeds (Figure 17) so these wave events would occur more often. Wind speeds greater than the thresholds of ~4 m/s and 5 m/s will cause erosion of the sediment over the lower (deeper) plates, the greater the wind speed the more lower (deeper) plates experience erosion (Figure 18). This occasional erosion due to larger wind speeds will account for the periodic erosion of sediment identified in the monitoring record and the relatively small rates of net accretion over the lower (deeper) plates at Gun Club and Miranda (Figures 4 and 5).

The model results (Figure 18) indicate that the increased erosion with depth at Kuranui Bay does not fit the expected patterns of erosion and accretion from short period locally generated waves and therefore it is probable that different hydrodynamic processes are driving the sedimentation patterns observed at Kuranui Bay compared to Gun Club and Miranda. Importantly this distinction between the processes driving sedimentation at Kuranui Bay compared to Gun Club and Miranda means that the patterns of sedimentation shown in Figure 7 should not be grouped and viewed across a constant depth continuum. Instead Kuranui Bay should be treated as a separate hydrodynamic and sedimentary environment subject to different physical processes to those experienced at Gun Club and Miranda.

It is important to emphasise that this model is only a basic representation of the hydrodynamic environment. The model has not been calibrated or validated and the modelled magnitude τ_w is extremely sensitive to the calculations used, the chosen boundary conditions and the assumptions made during its formulation (see Appendix B for details of modelling assumptions and approach). Furthermore, the sediment plate depths are plotted at a static water level at MHWS (see Appendix A for water level definition), in reality the modelled magnitude of τ_w at each plate will change greatly during the tidal cycle due to the changing water depths as the tide ebbs and floods and switches between spring and neap states. These changes in water levels will complicate the processes of erosion and accretion considerably especially considering that the fetch in the Firth of Thames will be long, and therefore the wave climate could be well-developed, even at low water. This is in contrast to an estuary like Raglan when the fetch varies greatly during a tidal cycle (Hunt et al., 2015; 2016) and between spring and neap tides (Hunt et al., 2016; 2017). Further data collection is required to reduce these critical assumptions. Overall the model results support the interpretation that waves drive patterns of sedimentation over Gun Club and Miranda but not at Kuranui Bay but further data needs to be collected to support this hypothesis.

The reason for erosion at greater water depths at Kuranui Bay is not known but further investigation is underway to investigate the physical processes driving these distinct patterns of bed change. It is possible that the patterns of erosion in deeper water at Kuranui Bay could be in response to occasional long period waves that propagate into the study area from the Pacific Ocean. It is also possible that Kuaraui Bay is exposed to strong tidal currents, subject to tidal asymmetry, alongshore wave driven transport or wind driven estuarine circulation all of which could prevent sediment accumulation. Published hydrodynamic modelling results and data within the Firth of Thames (Proctor and Greig, 1989; Black et al., 2000) indicate that residual tidal circulation is weak and does not appear to be orientated in a systematic direction (Proctor and Greig, 1989) that could explain the observed erosion at Kuranui Bay. It has been hypothesised that as tidal currents would deflect to the left in the Firth of Thames, flood tides would be stronger along the eastern side of the Firth and ebb tides would be stronger along the western side of the Firth creating a clockwise tidal circulation pattern (Zeldis et al., 2015). This clockwise pattern of circulation could feasibly supply oceanic water with low suspended sediment concentrations to the eastern side of the Firth (i.e. Kuranui Bay) during the flooding tide and estuarine water with higher concentrations of suspended sediment to the western side of the Firth (i.e. Kaiaua) during the ebbing tide but there is no known published evidence to support this hypothesised clockwise tidal circulation.

Modelling studies indicate that both the residual circulation (Proctor and Greig, 1989) and patterns of sediment deposition (Zeldis et al., 2015) are modified by wind. Modelled wind speeds of 15 m/s from the northeast could feasibly enhance a clockwise residual rotation within the Firth of Thames (Proctor and Grieg, 1989) although these wind conditions appear to be rare (Figure 17). Instead, wind records at Tararu show that the prevailing wind directions during the sediment plate monitoring are from the north, the northwest and the southeast. Under modelled southeasterly winds of 15 m/s residual currents are strengthened towards the western side of the Firth and are therefore consistent with the deposition patterns recorded in the plate data over Kaiaua (Proctor and Greig, 1989). Under modelled northwesterly winds of 15 m/s residuals are enhanced in a direction away from the western side of the Firth of Thames (i.e. Kaiaua) and towards the south but importantly residual currents under both the prevailing southeasterly and northwesterly winds are not enhanced in a direction towards the eastern side of the Firth of Thames (i.e. Kuranui Bay) (Proctor and Greig, 1989; Black et al., 2000). These modelled patterns of wind enhanced residual currents indicate that under prevailing wind conditions circulation is not directed towards the western side of the Firth of Thames and the Kuranui Bay site and therefore these circulation patterns could contribute to the observed erosion along much of the plates at Kuranui Bay. Overall the published modelled data in the Firth of Thames offers limited insight into the measured patterns of sedimentation and erosion at the plate sites due to the limited hydrodynamic data collected and the limited wind speed and direction scenarios modelled. Furthermore, wind scenarios of 15 m/s and greater are uncommon amounting to < ~ 0.5 % of the wind record and therefore do not represent the diversity of actual wind scenarios experienced in the Firth of Thames (Figure 17).

Any sedimentation trends are further complicated by the overall subsidence of the Firth of Thames basin. Measurements of subsidence at the Tararu tide gauge and within the Mangrove forest along the southern margin of the Firth by WRC, NIWA and the University of Otago (Swales et al., 2016) have shown evidence of deep subsidence within the Firth of Thames basin. Within the Mangrove forest, subsidence ranges between 7.7 ± 0.5 to 9.4 ± 0.5 mm/yr and at the Tararu tide gauge subsidence rates of 3.6 ± 0.7 mm/yr were measured. These rates of subsidence were attributed mainly to sediment compaction with a smaller contribution from vertical land movement (Swales et al., 2016). Based on these subsidence measurements the Firth could have potentially sunk by between 58 and 150 mm between 2000 and 2016. A drop in bed height would increase water depths which in turn attenuates orbital velocities and increases sediment accommodation space. In general subsidence of the basin and increases in water depth should increase SAR but the effects are likely to be more complex and should become more apparent with further monitoring.

Based on the available data, it appears that the similar patterns of erosion in shallower water depths and accretion over deeper water depths at Gun Club and Miranda are controlled by the relative strength of orbital velocities from locally generated short period waves. Similarly the trend of deposition at the deeper Kaiaua site is likely due to attenuation of orbital velocities in deep water, although the actual depth of this site is not known. In contrast the trend of erosion over the deeper (relative to Miranda and Gun Club) Kuranui Bay sites could be a result of weak tidal and wind driven circulation patterns and therefore a reduced supply of fine sediment to this area but processes at the Kuranui Bay site are poorly understood. Deployment of the plates over a similar range of water depths at each site would have made comparison of the datasets simpler and further reduced uncertainty regarding the processes controlling sedimentation at each site. Further targeted hydrodynamic data collection will help understand basic patterns of circulation and wave distribution in the Firth of Thames.

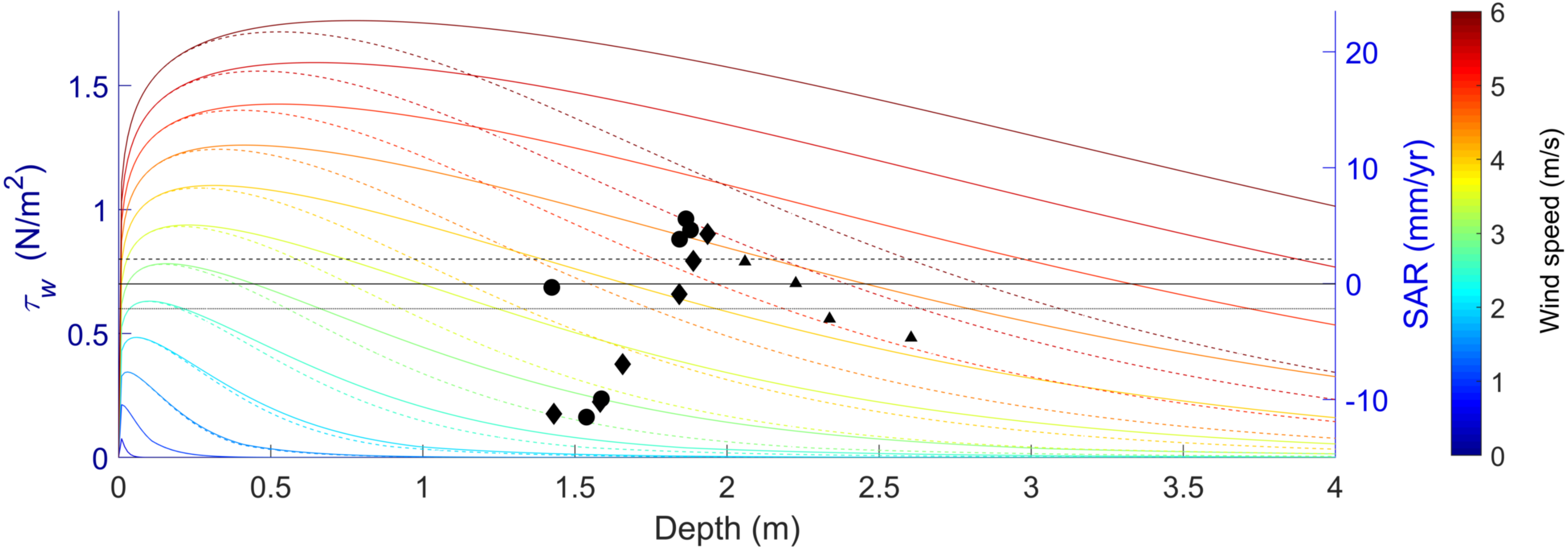

Figure 18: Modelled τw for a 100 km fetch (solid coloured lines) and a 25 km fetch (dashed coloured lines) for water depths ranging between 0 and 4 m and wind speeds ranging between 0 and 6 m/s.

SAR at each plate are plotted against the range of expected water depths at high tide. The symbols are plotted at MHWS10 (see Appendix A for details). Data from Gun Club are shown as circles, Kuranui Bay is shown as triangles and Miranda is shown as diamonds.

4.1.2 Whaingaroa (Raglan) Harbour

The sediment plate data collected in Whaingaroa (Raglan) Harbour show distinct sedimentary environments in each part of the harbour, with stability at the Ponganui plates (Figure 12), erosion at Whatitirinui Island (Figure 9) and Te Puna Point (Figure 10) in the northern arm and accretion at Haroto Bay (Figure 8) and Okete Bay (Figure 11) in the southern arm. The plates at Whatitirinui Island (Figure 9), Haroto Bay (Figure 8) and Okete Bay (Figure 11) are located in the same position as the sediment cores collected and analysed for SAR on behalf of WRC (Swales et al., 2005) and a comparison of the contemporary SAR recorded in the cores and the plates show a high level of similarity (red line in Figures 8 and 11). A quantitative comparison was not possible at Whatitirinui Island (Figure 9) because a sediment core cannot record a rate of erosion, only an absence of sedimentation but the sediment plates and the core are consistent.

The spatial distribution of sedimentation patterns can be related to the variability of hydrodynamic processes (Hunt et al., 2015; Hunt et al., 2016) and sediment supply in the different parts of the estuary, reflecting the dendritic shape. Whaingaroa (Raglan) Harbour splits into a series of sub-systems, each with a distinct hydrodynamic and morphological regime. Compared to the Firth of Thames, Whaingaroa (Raglan) Harbour data show less variability in SAR between the plates at each site, although this can be partly attributed to the smaller spacing between the clustered plates relative to transects. Consequently this may reduce the spatial variability in hydrodynamics across plates at a specific site and therefore rates of erosion or accretion. The accretion recorded at Haroto Bay in the Waitetuna (southern) arm of the estuary can be attributed to sheltering from the prevailing wind direction at this site (Swales, et al., 2005; Hunt et al., 2015; Hunt et al., 2016, Hunt et al. 2017) and the supply of fine sediment from the Waitetuna River and catchment (McKergow et al., 2010). Similarly the accretion recorded at Okete is likely to be due to the fine sediment input into the estuary and the sheltered nature of the site relative to the prevailing wind direction. The Ponganui site is generally stable despite being sheltered from the prevailing south westerly winds. The reason for the lack of sediment deposition could be due to the proximity of the study site to the estuary mouth which facilitates flushing of the estuarine water with water from the open coast. During the ebb tide estuarine water and suspended sediment will be exported from the study area and replaced during the flooding tide with water from the open coast which will have lower levels of suspended sediment. This reduced suspended sediment load during the flood means there is less available sediment available to deposit on the intertidal flat during high water slack. The efficiency of this suspended sediment dispersion will reduce with distance from the mouth and with increased sediment load into the estuary relative to the mixing efficiency of estuarine and ocean water and the dispersion of fine sediment outside of the estuarine mouth. In the Waingaro arm, erosion has previously been attributed to exposure to the prevailing wind direction which allows generation of short period wind waves and suspension of fine sediment which is then dispersed out of the study area by tidal processes (Hunt et al., 2015; Hunt et al., 2016, Hunt et al. 2017). As for the Firth of Thames the reason for the initiation of erosion in the Waingaro arm is unknown. Possible reasons could include a reduction in sediment supply relative to wave forcing or a change in the wave climate. A further possibility is that the erosion is part of a cyclical feedback between intertidal height and hydrodynamics whereby intertidal levels accrete to a level where orbital velocities from waves can begin to erode the intertidal. There is not enough evidence to confirm either of these hypothesises and will be the subject of ongoing investigations and further monitoring.

4.2 Effectiveness of methodology for measuring sedimentation.

4.2.1 Plate subsidence

Out of the 50 plates buried and deployed over a decade, only one has shown clear evidence of tilting and this tilting has likely occurred due to erosion and uncovering of the plate by waves. There is no strong evidence to suggest plates are sinking and overall the methodology presents a robust measurement that can record estimates of intertidal SAR over a longer time scale when short term variability is smoothed out.

Comparison of SAR recorded over the plates with SAR derived from cores in Whaingaroa (Raglan) Harbour suggests that the average SAR over a decadal scale is being recorded accurately and consequently there is no evidence of significant subsidence of the plates. Overall it is considered that there is not enough evidence to identify subsidence of the sediment plate through the mudflat in the Firth of Thames or Whaingaroa (Raglan) Harbour and the plates should be considered as largely stable.

Measuring against a buried plate is preferential to measurements relative to a marker that extends above the intertidal surface such as a peg or rod, as a buried plate avoids scour (Woods and Kennedy, 2011). The use of buried plates is only suitable within a net-depositional environment, if the bed erodes and the plate becomes exposed, measurements can no longer be taken and scour can occur around the plate causing the level of the plate to change. The majority of the plates that were uncovered and inspected as part of this research were level with the exception of Plate 3 at Gun Club. Plate 3 at Gun Club became exposed in 2008 and 2009 and although the plate subsequently re-buried the uncovering is thought to have caused the plate to tilt. Checking the plate condition and tilt after 15 years indicates that if the plates remain covered they are unlikely to undergo differential settlement and therefore are reliable for measuring long-term SAR. Plates 1, 2 and 3 at both Miranda and Gun Club are buried under only a thin layer of sediment and there is a risk that they could become uncovered in the future. It is recommended that if plates become uncovered they should be reburied at a deeper depth and this reburial marked clearly on the monitoring records. If the plate continues to become exposed and monitoring resources are limited then the site should be abandoned and the plates relocated to a depositional environment.

4.2.2 Plate material

All sites used the same concrete plates and an inspection of a subset of these plates indicates that there has been no degradation. Based on this assessment it is considered that the plate material is suitable and should be used for further sedimentation monitoring.

4.2.3 Measurement technique

The current sampling methodology uses 10 replicate measurements across each plate. The use of replicates is important for three reasons: Firstly, a comparison of replicates during sampling has helped identify and repeat erroneous measurements e.g., due to shell material, specifically if one needle is substantially higher than the others it indicates that it has not reached the plate surface and can be repeated. Secondly, a high number of replicates reduces the influence of any individual measure, and dampens some of the natural variation attributable to bed forms (e.g. ripples) or biogenic influences. This smoothing benefits the data when assessing changes over time in mean sediment depth. Thirdly, continued high intra-plate variability between replicates may help identify an uneven plate and therefore provide an additional function of quality control.

Determining the optimum number of replicates is complicated and likely variable across sites as it will depend on the variability in bed height over a given plate. The main consideration should be to use a consistent number of replicates (10) and to stratify these across the plate surface.

4.2.4 Temporal scale of measurements

The optimum frequency of measurements depends on the study purpose and the characteristics of the study site. For example, high frequency monitoring can identify short-term depositional and erosional events, whereas less frequent but long-term monitoring will identify long-term trends. An example of the distinction was shown from intertidal flat elevation measurements taken every month over a 15 month period at 122 locations in the Pauatahanui Inlet, Porirua Harbour (Pickrill, 1979). Monthly bed level changes ranged between 47 and -28 mm but generally measured less than +/- 10 mm, with 55.5% of monthly changes being less than +/- 2 mm and less than 6% of measurements exceeded +/- 15 mm. Depositional events were as frequent as erosional events. Annual SAR ranging between 47 and – 64 mm/yr and a net average deposition of 2.9 mm/yr across all measurement locations was calculated.

4.2.4.1 Measuring event scale trends

Intra-annual variability is reflected in the data from the Firth of Thames and Whaingaroa (Raglan) Harbour which shows variability between individual measurements with repeated episodic events of accretion and erosion around, and often in exceedance of, the long-term trend. Comparison of the monthly data collected in the first 6 years (2003 – 2009) of the Firth of Thames monitoring is summarised in Figure 19. The analysis of bed changes between months shows that the range of variability is large and can be greater than the overall trend of accretion or erosion. For example, episodic depositional events as large as ~ 12 cm were recorded at Kuranui Bay and ~ 5 cm at the other sites (Figure 19). Erosional events appear to be slightly larger than accretional events. The most common bed level changes, with occurrences greater than 5 %, amount to less than approximately +/- 10 mm (Figure 19).

Sedimentation events recorded using high frequency automated continuous measurements in the Westerschelde Estuary in the SW Netherlands showed that measurable changes in bed level occur between tidal cycles and storm events (Hu et al., 2015). Changes in bed level amounting to ~50 mm were measured between tidal cycles and changes of up to ~ 100 mm were measured following a storm at an estuarine site exposed to small waves with a significant wave height of between 0.1 and 0.6 m (Hu et al., 2015). At a sheltered site with significant wave heights of < 0.1 m the changes were less and amounted to no more than 25 mm between tidal cycles (Hu et al., 2015). The fine temporal scale of bed level changes means that in general daily measurements (i.e. tidal-cycle scale) would be required to fully characterise episodic sedimentation events.

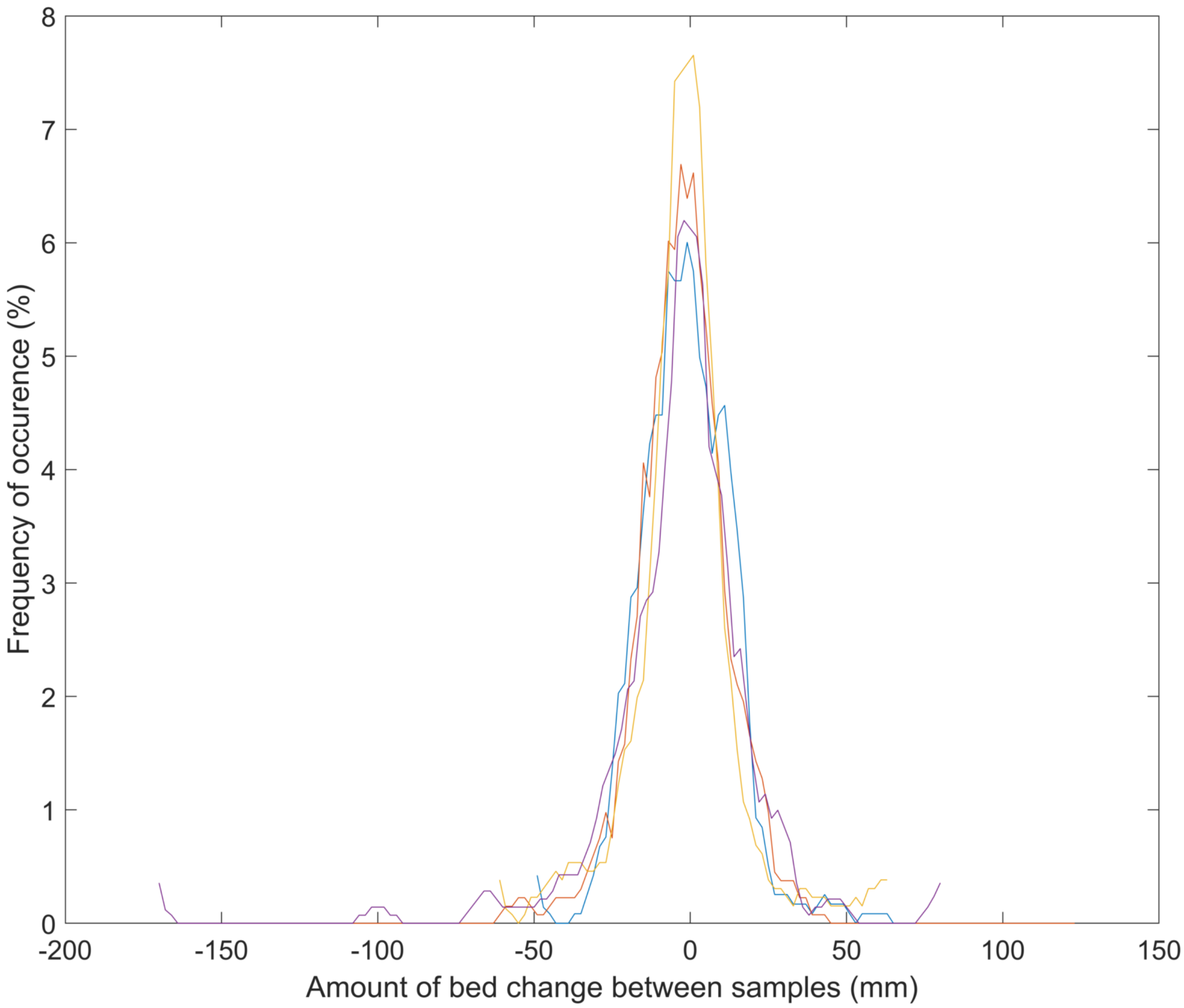

Figure 19: Frequency of occurrence of bed level change between monthly samples expressed as a percentage occurrence for Kaiaua (blue line), Miranda (red line), Gun Club (yellow line) and Kuranui Bay (purple line).

The bed change data has been binned at a 2 mm intervals and the curve has been smoothed using a 5 point running average before being converted to a percentage of the total amount of monthly samples.

4.2.4.2 Measuring long-term trends

The sedimentation data collected in Whaingaroa (Raglan) Harbour and the Firth of Thames have been collected with varying frequencies, ranging from monthly to annual. To demonstrate the effect of reducing the sampling frequency and monitoring over different timescales, the SAR has been calculated using both the full record and a reduced record where only measures from October of each year have been used, using data collected over 2 years, 5 years, 10 years and over the entire record. Linear trends were then applied to each sampling regime for each plate and the calculated SAR compared using regression analysis (Figures 20 and 21) and expressed as the coefficient of determination (R^2) (Figure 22). It is important to note that the length of the entire record varies between different datasets and therefore the SAR calculated from the entire record is not directly comparable between each site but has been included for completeness (Figure 20d and 21d).

The results show that although there were small differences between the two sampling regimes, there was no systematic advantage to using a higher frequency of sampling for estimating annual average SAR providing that the monitoring data was collected for at least 10 years (Figures 20c, 21c and 22). There were smaller differences between sedimentation calculated using the full and reduced frequency records for Whaingaroa (Raglan) Harbour compared to the Firth of Thames. This smaller difference is likely due to the more infrequent level of sampling over the full record at Whaingaroa (Raglan) Harbour and therefore less difference compared to the reduced frequency record. The main differences between the two sampling frequencies in the Firth of Thames occurred at sites that are eroding, with a small apparent increase in scatter (Figure 20). The difference at the erosional sites is not systematic but could relate to the stochastic nature of erosion over the intertidal. Erosion here is thought to occur due to waves and therefore is dependent on the occurrence of wave events. If the generation of these waves is essentially random and unevenly spaced throughout the record then the erosion would occur during a single event which might easily be missed by the resampling. In contrast deposition due to tides would be more repeatable and gradual and therefore better represented in both the original and resampled record. The comparison demonstrates that if a monitoring programme is being undertaken to track long-term annual SAR then annual measurements are likely to be sufficient providing that the monitoring points are taken at regular intervals (to avoid confounding seasonality) and over at least a decadal timescale to provide reliable estimates of sedimentation and trends.

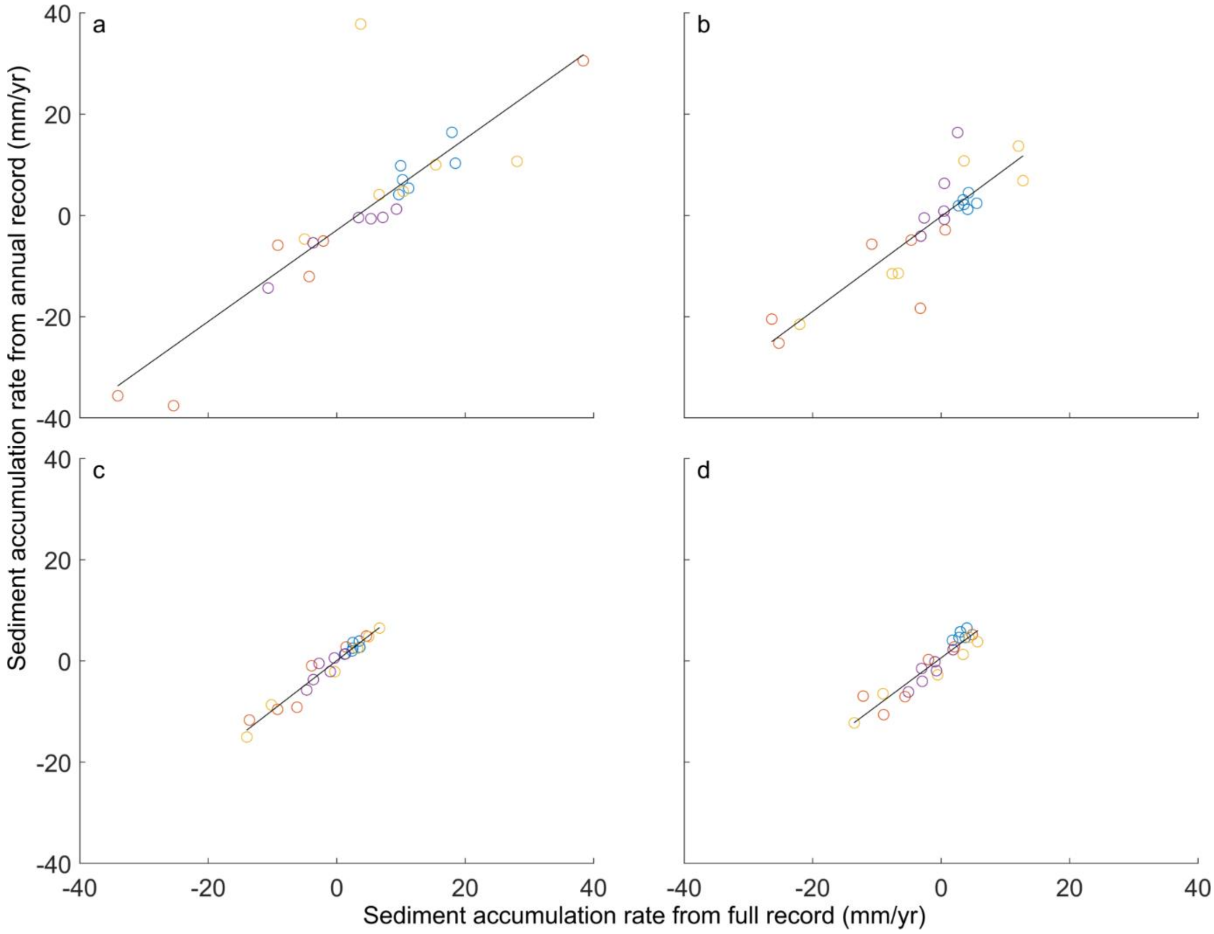

Figure 20: SAR determined from analysis of the full record and a sub-sampled annual record for the Firth of Thames.

Kaiaua = dark blue, Miranda = red, Gun Club = orange and Kuranui Bay = purple. The linear regression is shown by the solid black line (r^2 = 0.88) and the 1:1 fit is shown by the black dotted line for comparison. The SAR have been calculated and compared for data recorded over 2 years (a), 5 years (b), 10 years (c) and the entire record (d).

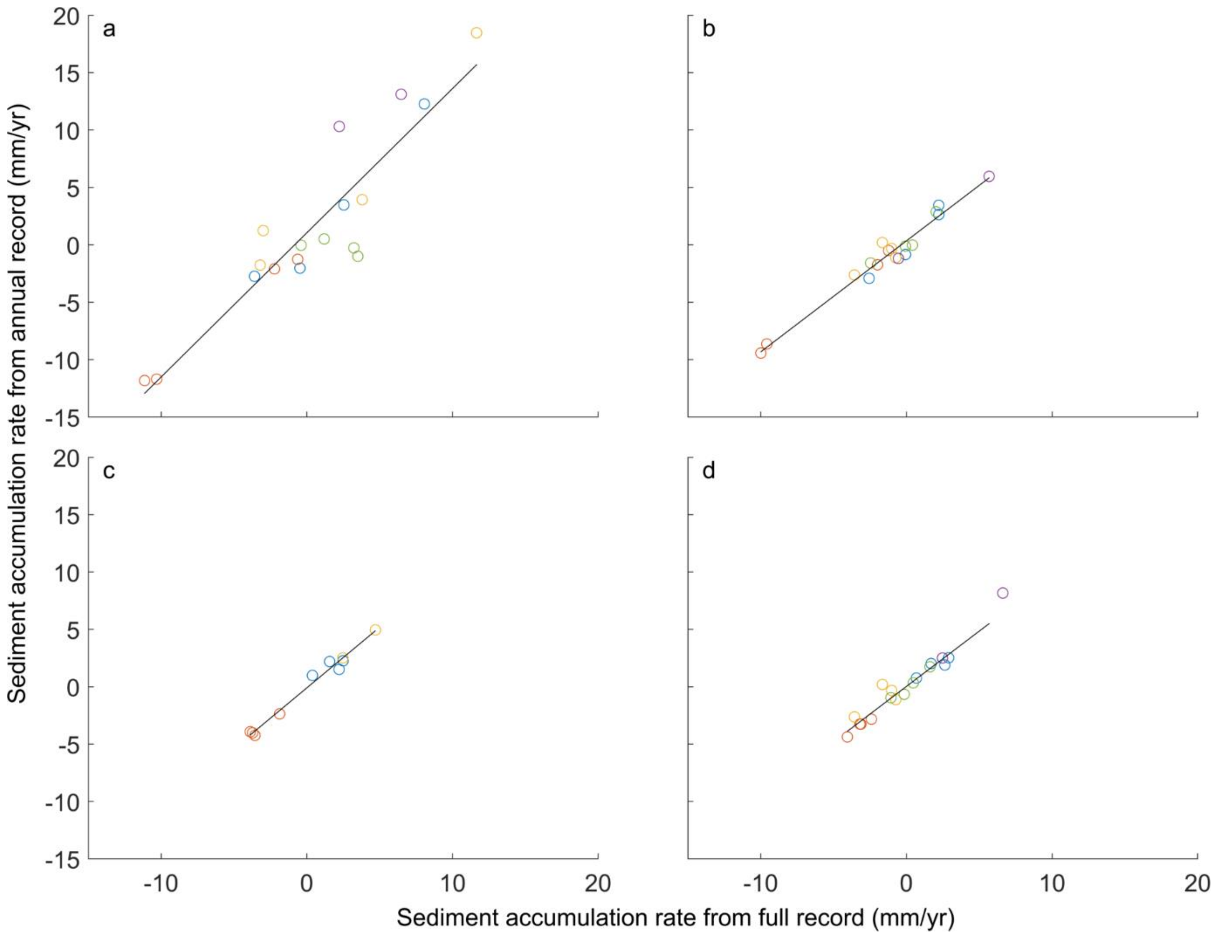

Figure 21. SAR determined from analysis of the full record and a sub-sampled annual record for Whaingaroa (Raglan) Harbour.

Haroto Bay = dark blue, Whatitirinui Island = red, Te Puna Point = orange, Okete Bay = purple, Ponganui Creek = green. The linear regression is shown by the solid black line (r^2 = 0.95) and the 1:1 fit is shown by the black dotted line for comparison. The SAR have been calculated and compared for data recorded over 2 years (a), 5 years (b), 10 years (c) and the entire record (d).

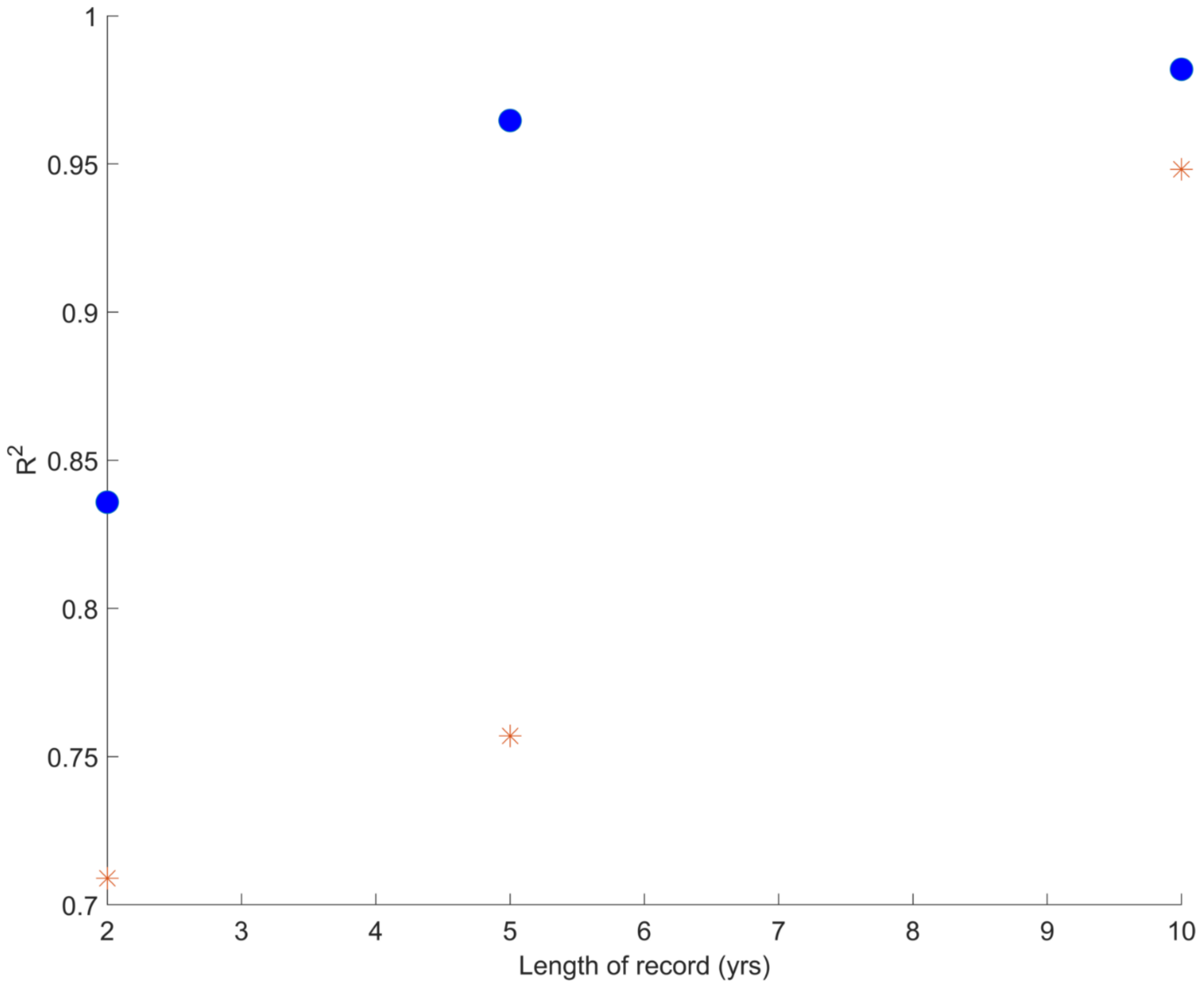

Figure 22. Summary of values of R2 from data comparison in Figures 20 and 21.
The blue circles show data from the Whaingaroa (Raglan) Harbour sediment plates and the red stars show data from the Firth of Thames plates.

4.2.5 Spatial configuration and coverage

The SAR show a marked spatial distribution not only within sub-sections of an estuary but also within a single monitoring site. This spatial distribution illustrates that plates need to be widely distributed in terms of a range of morphological and hydrodynamic environments, and water depths to characterise SAR within an estuary. Without a variety of sampling locations, the distinction between each part of the estuary is lost and demonstrates the importance of selecting an adequate number of sedimentation sites to measure this variability and not reducing sedimentation estimates throughout an estuary down to a single metric. Comparison of SAR calculated from all plate measurements within a site compared to SAR at individual plate locations within the same site (Tables 1 and 2) indicates that data should also not be averaged over multiple plates within a single site unless these plates are in close proximity and exhibit similar morphological, depth and sedimentation characteristics. It is also 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 SAR 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 SAR have been included, these sites will reduce and 'dilute' the magnitude of the overall SAR, 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.

It is likely that, although the sedimentation monitoring identified spatial variability, it would not have captured the full variability as the measurements are limited to a small number of discrete sampling locations. This important limitation of the analysis means that the optimum spatial distribution is not known for the estuaries sampled. Although there will always be variability and nuances outside of what can be feasibly measured, we have demonstrated that well positioned plates within Whaingaroa (Raglan) Harbour and the Firth of Thames, provide insight into the sediment dynamics and behaviours across different sections of these systems. The appropriate spatial distribution of monitoring plates will also likely vary in between estuaries depending on their characteristics and spatial heterogeneity.

SAR vary with water depth and this variability is due to a combination of dissipation and attenuation of orbital velocities from waves and variations in tidal currents at different stages of the tide. This depth variability indicates that a transect of plates arranged across a variety of depths is the optimum configuration (generally perpendicular to the subtidal channel). SAR along transects are easier to compare with transects at other sites if they occupy similar water depths or at least have some overlap in terms of water depths such as the southern Firth of Thames plates (Miranda and Gun club). Comparison between the southern Firth of Thames transects and those at Kuranui Bay and Kaiaua has been hindered by the differing intertidal elevations and water depths.

Monthly sedimentation measurements at 122 locations in the Pauatahanui Inlet, Porirua Harbour showed a large spatial distribution in sedimentation with the most stable areas at the head of the inlet in the sheltered parts of the estuary (Pickrill, 1979). The only way to capture the full variability will be through the use of remote techniques such as LiDAR which cover a wider area. The compromise in using a remote technique is that the accuracy is generally less, for example high resolution LiDAR in

New Zealand has an expected accuracy of +/- 7.5 cm. Photogrammetry data collection through Unmanned Aerial Vehicles (UAV) can achieve a higher accuracy with researchers reporting 1.5 – 2.5 cm accuracy when measuring intertidal levels in an estuary (Jaud et al., 2016) but trials over Raglan Beach by the University of Auckland and WRC indicate that flight times required to cover larger estuaries such as those in the Waikato are considerable when using a quadcopter. Therefore the use of LiDAR from a fixed wing aircraft might be more practical although further trials are being undertaken by WRC using a Real Time Kinematic (RTK) enabled fixed wing UAV. Although remote sensed data is typically not accurate enough to characterise SAR relative to the 2 mm/yr required, a survey of the estuary every 10 years would help to identify bulk movements of sediment around the harbour even if only in a relative sense. These bulk movements are useful for two reasons. Firstly, the measurements allow identification of any part of an estuary that might be particularly susceptible to sedimentation and this knowledge could help direct catchment management and restoration efforts. Secondly, these measurements would identify if the plates have a good spatial distribution and could indicate if the plates are recording sedimentation in areas of high or low SAR in the context of the whole estuary. If necessary the plates could be reviewed every 10 years and the positions revised.

A final important consideration is the location of any sediment plates relative to any features of interest such as benthic monitoring areas. The large spatial variability in SAR across some estuaries means that the plates would have to be located in close proximity. At the Gun Club and Miranda sites the SAR vary along each transect, yet the benthic monitoring site in the centre of these transects may mean the ecological samples are collect from sites experiencing lower rates of change (Table 1) relative to higher up and lower down the shore where sedimentation is actually measured. This indicates a possible disconnect between ecological and biophysical measures recorded within the REMP programme.

Overall, the spatial variabilities identified within this study indicate that there are two types of spatial configuration which are dependent on the purposes of the monitoring. If the purpose of monitoring sedimentation is providing environmental information for a macrobenthic core (e.g. REMP) then the plates should be situated immediately adjacent to the coring site as wider spatial variability in SAR outside of the immediate monitoring area is of no interest. If the purpose of the monitoring is characterising sedimentation across a system (e.g. Sea Change monitoring) then a transect approach should be used but the transects need to be at equivalent depths at each site and need to extend further landward and seaward than those in the Firth of Thames. To allow normalisation of depths between different transects plates should extend from mean high water to mean low water at each site. This configuration will ensure overlap in depth ranges between different parts of estuaries and between different estuaries. In enclosed funnel shaped (e.g. Tairua and Wharekawa) and dendritic estuaries (e.g. Whangapoua and Raglan) the transects should extend either side of the subtidal channel to form a continuum across the entire estuary. For embayed estuaries (e.g. Coromandel Harbour) there is not a defined subtidal channel so all the transects will be generally parallel across the intertidal flat. Intertidal flat elevations from LiDAR or photogrammetry, water levels from tide data and aerial photos will all assist in positioning the transects in appropriate and equivalent positions.

5 Conclusions and recommendations.

The technique of measuring intertidal SAR using buried plates is a simple, repeatable, effective and affordable technique. Under ideal conditions, the plate methodology should be capable of recording SAR with a sufficient accuracy and precision to identify sedimentation of consequence to benthos (2 mm/yr above background) but there are some limitations to this technique:

1. Temporal scales:
   Sedimentation operates over a range of complex temporal scales with short-term changes between each sample larger than the net long-term average rate.

2. Spatial distribution:
   The variability in sedimentation between the plates suggests that single plate measurements are unlikely to provide representative measures of estuary wide SAR.

3. Operational issues
   In areas of continued erosion the plates can become uncovered and scour can cause those plates to tilt. Poor choice of plate locations has led to infrequent sampling due to restrictions around access, weather and tides.

The specific design of a sedimentation monitoring programme will vary according to purpose but some general recommendations to manage these limitations can be made based on this review.

5.1 Plate setup.

Plates should be buried to a depth of ~30 cm and levelled with a spirit level. The location of the plate should be marked with pegs and recorded by GPS. The pegs should be situated ~ 2.5 m away from the centre of the plate to avoid scour and debris (e.g. seaweed) that can catch on the pegs and influence sedimentation processes over the plate.

If the plate becomes uncovered it should be re-buried and levelled. If the plate continues to become uncovered then consideration should be given to selecting a new monitoring site. The plate should not be left to cover with sediment as scour during the period of exposure will likely cause the plate to tilt.

5.2 Plate positioning

Plates should be well distributed around an estuary and take into account the likely hydrodynamic environment and ease of access. Easy access will ensure an easily repeatable and achievable survey and should preferably avoid the need for a boat. Access requirements, tidal and weather restrictions have led to the WRC sedimentation measurements being temporally variable and this variability has affected the quality of the data.

If the purpose of the survey is to record SAR associated with benthic health (such as REMP) then the plate should be positioned as close to the benthic monitoring area as possible to record similar sedimentation conditions to those experienced at the monitoring site. If the monitoring is being used to assess wider trends of sedimentation (such as Sea Change) then the plates should be orientated along a series of transects evenly distributed throughout the estuary orientated between and extending from mean high water to mean low water. This orientation and coverage allows the variability in sedimentation with changing water depths to be characterised and provides a more thorough record of sedimentation trends.

For either type of survey, it is recommended that remote sensing such as LiDAR is flown every 10 years. Remote surveys are not accurate enough to record SAR with an accuracy of 2 mm/yr but they are able to identify bulk patterns of sedimentation. These bulk patterns allow the sedimentation trends at the plates to be put in context of the wider trends of sediment accumulation elsewhere in the estuary. These periodic remote sensed surveys might identify preferable places to position plates and allow optimisation of the spatial configuration.

5.3 Temporal frequency of measurements

Sedimentation events of consequence (i.e. > 2 mm/yr) can feasibly occur over a single storm event so tracking sedimentation at the event-scale using the plate methodology is prohibitively time consuming. To measure net annual sedimentation a regularly spaced annual measurement is sufficient providing the monitoring is undertaken for at least 10 years.

5.4 Measurement method

Replicate measurements above the plate provide a quality check during collection of the data and prevent false sediment depths being measured due to shell material preventing the needle from reaching the true surface of the plate. The replicates also allow an average depth to be recorded by smoothing out variability caused by bedforms or bioturbation. The use of replicates is considered preferential to the artificial smoothing of the seabed during the measurements as this modifies the seabed over the plate and obscures the natural sedimentation processes.

High variability between replicates is also diagnostic of a tilting plate. If plates are thought to have become tilted they can be uncovered, levelled and reburied. In the data reviewed here the plates only appeared to tilt if they had been uncovered by erosion and subject to scour.

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Appendix A. Heights of plates from LiDAR and tide gauge data

Although the level of the REMP site has not been surveyed relative to a known datum it is possible to measure an approximate level using WRC LiDAR data at the Thames (Table A1) and Raglan sites (Table A2). The WRC LiDAR data in the Firth of Thames was flown in 2007 and 2008 and is measured relative to Tararu 1952 vertical datum (TVD-52). The WRC LiDAR data in Raglan was flown between 2010 and 2011 and is measured relative to Moturiki Vertical Datum 1953 (MVD-53). Using information from an analysis of WRC tide gauges (NIWA, 2015) the Firth of Thames elevations were converted from TVD-52 to contemporary sea levels at the WRC Tararu tide gauge (See Figure 1 for location of tide gauge) and the Raglan elevations were converted from MVD-53 to contemporary mean sea level at the WRC Kawhia gauge.

The Firth of Thames elevations relative to TVD-52 were converted to Moturiki Vertical Datum 1953 (MVD-53), MVD-53 is below TVD-52 and therefore 0.1184 m was added to the LiDAR data to convert between the two datums. Secondly the elevations relative to MVD-53 were converted to modern mean sea level measured at the Tararu tide gauge. Modern mean sea level is higher than MVD-53 and therefore 0.18 m was subtracted from MVD-53 to convert the elevations to mean sea level. Finally, the water level has been related to actual water depth over each plate during minimum high water (MinHW), Mean High Water Springs that are exceeded 10% of the time (MHWS-10), Mean High Water Springs that are exceeded 6% of the time (MHWS-6), Mean High Water Perigean Springs (MHWPS) and Maximum High Water (MaxHW) using measured data at the WRC Tararu tide gauge (NIWA, 2015).

The Raglan elevations were already known relative to MVD-53, as modern mean sea level is higher than MVD-53 0.13 m was subtracted from MVD-53 to convert the elevations to mean sea level. The water level has also been related to actual water depth over each plate during minimum high water (MinHW), Mean High Water Springs that are exceeded 10% of the time (MHWS-10), Mean High Water Springs that are exceeded 6% of the time (MHWS-6), Mean High Water Perigean Springs (MHWPS) and Maximum High Water (MaxHW) using measured data at the WRC Kawhia tide gauge (NIWA, 2015).

Table A 1: Depths of intertidal at each plate location in the Firth of Thames.

From GPS					From GIS		Water depth calculations						
Site	Plate	Easting NZTM	Northing NZTM		Elevation from LiDAR (m)		Converted to MVD	To Mean Sea Level at local tide gauge	Water depth at Minimum HW (m)	Water depth at MHWS-10 (m)	Water depth at MHWS-6 (m)	Water depth at MHWPS (m)	Water depth at Max HW (m)
Gun Club	1	1825415	5884415		0.257		0.375	0.185	0.548	1.424	1.489	1.516	1.734
Gun Club	2	1825378	5884411		0.143		0.261	0.071	0.662	1.538	1.603	1.630	1.848
Gun Club	3	1825343	5884408		0.093		0.212	0.022	0.711	1.587	1.652	1.679	1.897
Gun Club	4	1825263	5884397		-0.164		-0.045	-0.235	0.968	1.844	1.909	1.936	2.154
Gun Club	5	1825227	5884391		-0.184		-0.066	-0.256	0.989	1.865	1.930	1.957	2.175
Gun Club	6	1825200	5884388		-0.199		-0.081	-0.271	1.004	1.880	1.945	1.972	2.190
Kaiaua	1	1804261	5889164										
Kaiaua	2	1804296	5889176										
Kaiaua	3	1804362	5889195										
Kaiaua	4	1804447	5889222										
Kaiaua	5	1804483	5889232										
Kaiaua	6	1804515	5889241										
Kuranui Bay	1	1824411	5889009		-0.379		-0.260	-0.450	1.183	2.059	2.124	2.151	2.369
Kuranui Bay	2	1824382	5888989		-0.545		-0.427	-0.617	1.350	2.226	2.291	2.318	2.536
Kuranui Bay	3	1824355	5888971		-0.657		-0.538	-0.728	1.461	2.337	2.402	2.429	2.647
Kuranui Bay	4	1824283	5888923		-0.924		-0.806	-0.996	1.729	2.605	2.670	2.697	2.915
Kuranui Bay	5	1824248	5888899										
Kuranui Bay	6	1824219	5888881										
Miranda	1	1806611	5882495		0.249		0.368	0.178	0.555	1.431	1.496	1.523	1.741
Miranda	2	1806659	5882512		0.098		0.216	0.026	0.707	1.583	1.648	1.675	1.893
Miranda	3	1806713	5882528		0.023		0.142	-0.048	0.781	1.657	1.722	1.749	1.967
Miranda	4	1806799	5882552		-0.162		-0.044	-0.234	0.967	1.843	1.908	1.935	2.153
Miranda	5	1806848	5882563		-0.208		-0.090	-0.280	1.013	1.889	1.954	1.981	2.199
Miranda	6	1806891	5882577		-0.256		-0.137	-0.327	1.060	1.936	2.001	2.028	2.246

Table A 2: Table A2. Depths of intertidal at each plate location in Raglan (Whaingaroa) Harbour.

From GPS					From GIS		Water depth calculations						
Site	Plate	Easting NZTM	Northing NZTM		Elevation from LiDAR (m)		Converted to MVD	To Mean Sea Level at local tide gauge	Water depth at Minimum HW (m)	Water depth at MHWS-10 (m)	Water depth at MHWS-6 (m)	Water depth at MHWPS (m)	Water depth at Max HW (m)
Haroto Bay	A	1771202	5816125		0.210		0.210	0.080	0.484	1.528	1.604	1.637	1.859
Haroto Bay	B	1771200	5816122		0.260		0.260	0.130	0.434	1.478	1.554	1.587	1.809
Haroto Bay	C	1771281	5815920		0.380		0.380	0.250	0.314	1.358	1.434	1.467	1.689
Haroto Bay	D	1771285	5815919		0.420		0.420	0.290	0.274	1.318	1.394	1.427	1.649
Okete Bay	A	1768825	5815591		-1.100		-1.100	-1.230	1.794	2.838	2.914	2.947	3.169
Okete Bay	B	1768828	5815593		-1.200		-1.200	-1.330	1.894	2.938	3.014	3.047	3.269
Te Puna Point	A	1768568	5817178		-0.400		-0.400	-0.530	1.094	2.138	2.214	2.247	2.469
Te Puna Point	B	1768568	5817175		-0.440		-0.440	-0.570	1.134	2.178	2.254	2.287	2.509
Te Puna Point	C	1768688	5817027		0.440		0.440	0.310	0.254	1.298	1.374	1.407	1.629
Te Puna Point	D	1768687	5817024		0.490		0.490	0.360	0.204	1.248	1.324	1.357	1.579
Whatitirinui Island	A	1769062	5818565		-0.510		-0.510	-0.640	1.204	2.248	2.324	2.357	2.579
Whatitirinui Island	B	1769063	5818570		-0.530		-0.530	-0.660	1.224	2.268	2.344	2.377	2.599
Whatitirinui Island	C	1769000	5818691		-0.300		-0.300	-0.430	0.994	2.038	2.114	2.147	2.369
Whatitirinui Island	D	1768996	5818691		-0.350		-0.350	-0.480	1.044	2.088	2.164	2.197	2.419
Ponganui Creek	A	1765083	5816341		-0.700		-0.700	-0.830	1.394	2.438	2.514	2.547	2.769
Ponganui Creek	B	1765085	5816344		-0.710		-0.710	-0.840	1.404	2.448	2.524	2.557	2.779
Ponganui Creek	C	1765024	5816454		-0.010		-0.010	-0.140	0.704	1.748	1.824	1.857	2.079
Ponganui Creek	D	1765025	5816456		0.020		0.020	-0.110	0.674	1.718	1.794	1.827	2.049

Appendix B. Wave model

Using the representative wind speeds, fetch lengths and depths the significant wave height (H_s) and wave period (T) can be estimated using equations in CERC (1984). These wave statistics can then be used to calculate wave orbital velocity at the bed (U_w) and bed shear stress due to waves (τ_w) based on equations in Soulsby (1997).

τ_w is highly sensitive to the chosen friction factor (f_w), here the friction factor has been calculated using the procedure outlined by Soulsby (1997) that incorporates a roughness length (z_o) which depends on the bed sediment and morphology. The sediment variation throughout the plate locations is not known but sediment samples have been taken annually by WRC within the benthic monitoring area at each REMP site and the grain sizes are analysed using a Malvern Multisizer. These sediment samples are known to be unsuitable for tracking environmental change (Hunt and Jones, 2018) but they are considered suitable for characterising sedimentary conditions for numerical modelling. The sediment grain size results between 2008 and 2016 have been summarised for the Firth of Thames (Table A1) and show mixed sediments containing varying proportions of sand and mud. The z_0 can be estimated from grain size using equation (1):

$$z_o = d_{50}/12 \tag{1}$$

Where d_{50} is the median sediment grain size, z_0 has been calculated using equation (1) and the average d_{50} for all samples collected at each site (Table A1) and shows that z_0 varies between 0.01 and 0.029 mm at the Firth of Thames sites. Recommended representative values of z_o for a mixed sediment bed based on actual measurements over natural sea beds are presented in Soulsby (1997). The representative values are useful as they take into account interactions between the mixed sediments that are not represented by the above equation. When the sediment samples are described according to the Folk Scale (Tables A1) the predominant sediment type in the Firth of Thames is muddy sand (mS) which is most similar to either the silt/ sand or mud / sand bed type which are represented by z_o = 0.05 mm and z_o = 0.7 mm, respectively (Soulsby, 1997). Based on the calculations and the representative values an intermediate value of 0.2 mm has been chosen for the Firth of Thames.

To assess the magnitude of τ_w required to mobilise seabed material a representative value of critical bed shear stress (τ_{crit}) is calculated for the seabed material type. In general, when $\tau_w > \tau_{crit}$ the seabed is mobile and sediment deposition cannot occur. Calculating τ_{crit} for a mixed sediment bed is problematic due to the interactions between the sediment types which can increase values of τ_{crit} far above the typical values for the individual grains (Whitehouse et al., 2000). Here, the sediment data in Table A1 has been used with the methods outlined in Whitehouse et al. (2000) to estimate τ_{crit} for the bed types at each REMP site. In the Firth of Thames values of τ_{crit} range between 0.6 and 0.8 N m^2 and a representative value of 0.7 N m^2 has been adopted.

Table A 3: Sediment analysis at each benthic monitoring area in the Firth of Thames

Sediment description	Statistic	Gun Club	Miranda	Kuranui Bay
Mud	Minimum (%)	3	1	4
	Maximum (%)	38	40	63
	Median (%)	11	12	18
	Mean (%)	13	14	22
Very fine sand	Minimum (%)	1	26	4
	Maximum (%)	12	62	19
	Median (%)	4	49	11
	Mean (%)	5	48	11
Fine sand	Minimum (%)	7	22	18
	Maximum (%)	26	56	49
	Median (%)	15	33	41
	Mean (%)	16	36	39
Medium sand	Minimum (%)	21	0	11
	Maximum (%)	50	19	41
	Median (%)	36	1	27
	Mean (%)	37	3	27
Coarse sand	Minimum (%)	10	0	0
	Maximum (%)	38	0	3
	Median (%)	27	0	1
	Mean (%)	26	0	1
Gravel	Minimum (%)	0	0	0
	Maximum (%)	10	0	0
	Median (%)	3	0	0
	Mean (%)	4	0	0
Mud	Mean (%)	13	14	22
Sand	Mean (%)	83	86	78
Gravel	Mean (%)	4	0	0
Sediment type (Folk scale)		mS	mS	mS
mean d_{50} (µm)		351	117	172
τ_{crit}		0.80	0.60	0.80
z_0 (mm) from samples		0.029	0.01	0.014
Number of sediment samples		70	101	100

Table A 4: Mean values of z0 for different sea bed types (Soulsby, 1997)

Bottom type	Z0 (mm)
Mud	0.2
Mud / sand	0.7
Silt / sand	0.05
Sand (unrippled)	0.4
Sand (rippled)	6
Sand / shell	0.3
Sand / gravel	0.3
Mud / sand / gravel	0.3
Gravel	3