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Sediment accumulation rates in Whāingaroa (Raglan) Harbour and the Firth of Thames, 2002/2003 to 2021

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Abstract

Sediment accumulation rates (SAR) have been monitored by WRC at sites across Whāingaroa (Raglan) Harbour and the Firth of Thames using sediment plates since 2002/2003. Sediment depths have been periodically measured over each plate and the changes in sediment depth have been analysed to calculate SAR. Sedimentation (accretion) is occurring at 7 sites within Whāingaroa Harbour and at 11 sites within the Firth of Thames.

In Whāingaroa Harbour, SAR at 2 plates, both of which are at the same monitoring site, exceeded the ANZECC guideline value of 2.2 mm/y estimated for the Waikato region. In the Firth of Thames, SAR at 7 plates across 2 of the 4 monitoring sites exceeded the same ANZECC guideline value. There are also sites displaying ongoing trends of erosion in both Whāingaroa Harbour and the Firth of Thames. The reason for this erosion is not clear but it may be due to reworking of relict sediment deposited following initial catchment clearance. This reworked sediment could be deposited elsewhere in the estuaries or exported out of the estuary to the wider Coastal Marine Area. For example, a known area of rapid sediment deposition is the southern Firth of Thames mangrove forest.

Low SARs are not necessarily an indicator of good estuarine health without consideration of the wider environmental context. It is necessary to consider other environmental pressures in the historical context of each estuary to provide a more comprehensive description of the health of an estuary. Despite the evidence of low SAR at some locations as presented in this report, there is evidence that sites in the Waikato region are exhibiting a decline in estuarine health.

1 Introduction

Sediment levels in Whāingaroa (Raglan) Harbour and the Firth of Thames have been recorded since either 2002 or 2003 as part of the Regional Estuary Monitoring Programme (REMP). Sediment accumulation rates (SAR) were previously calculated using the pre-2015 component of this sediment-level data (Hunt, 2019a). Since analysis of these data, further data has been collected. Quality control of sediment-level time series data has determined that on occasion records were attributed to the wrong plate; these problems have now been rectified. This report presents an updated calculation of SAR using the full quality-controlled sediment-level dataset up to November 2021.

Sediment levels are also recorded in Tairua, Coromandel Harbour, Wharekawa and Whangapoua since 2019, but not included here due to the shorter duration of these records.

The following terminology is used in this report:

- **Sediment level** is the depth of sediment relative to a buried sediment plate.
- **Sediment Accumulation Rate (SAR)** is a change in the sediment level over time. Positive SAR is accumulation or deposition, negative SAR is erosion.
- **Seabed elevation** is the height of the seabed relative to a known datum, usually measured by GPS.
- **Water depth** is the height of the water column relative to the seabed or a known datum. When measured relative to an intertidal flat, water depth at high **seabed elevation** is less than water depth at low **seabed elevation** at the same time of the tide.

2 Method

2.1 Sediment accumulation rates

The methodology for measuring sediment levels is unchanged from that previously described (Hunt, 2019a). In summary, the sediment level is measured relative to a series of buried plates. Simultaneous replicate measurements distributed over the surface of each plate are taken; the number of replicates has varied over time but is now standardised at ten.

There are five sediment-level monitoring sites in Whāingaroa (Raglan) Harbour (Figure 1). All sites except for Okete Bay have four plates situated in two clusters of two; A and B form the first cluster; C and D form the second cluster. At Okete Bay there is a single cluster comprising plates A and B. Measurements were not taken at Te Puna Point between 2009 and 2016 and at Ponganui Creek between 2011 and 2016.

In the Firth of Thames (Figure 2) there are four monitoring sites and each of these sites has six plates arranged in a cross-shore (i.e. deep to shallow water depths) transect. The plates extend a total of ~100 m seaward and ~100 m landward of a benthic monitoring plot with a ~50 m gap between each plate.

Sediment accumulation rate is calculated from the change in sediment level over time at each plate (positive change equals accumulation). To calculate SAR at each site over the entire monitoring period, replicates were averaged for each plate and for each sampling occasion, and a linear trend fitted to the averaged sediment-level data. The average rate of sediment accumulation was calculated in mm/day from the slope of the linear trend line and then converted to mm/y. The 95% confidence interval for the SAR has been calculated for the linear trend at each plate.

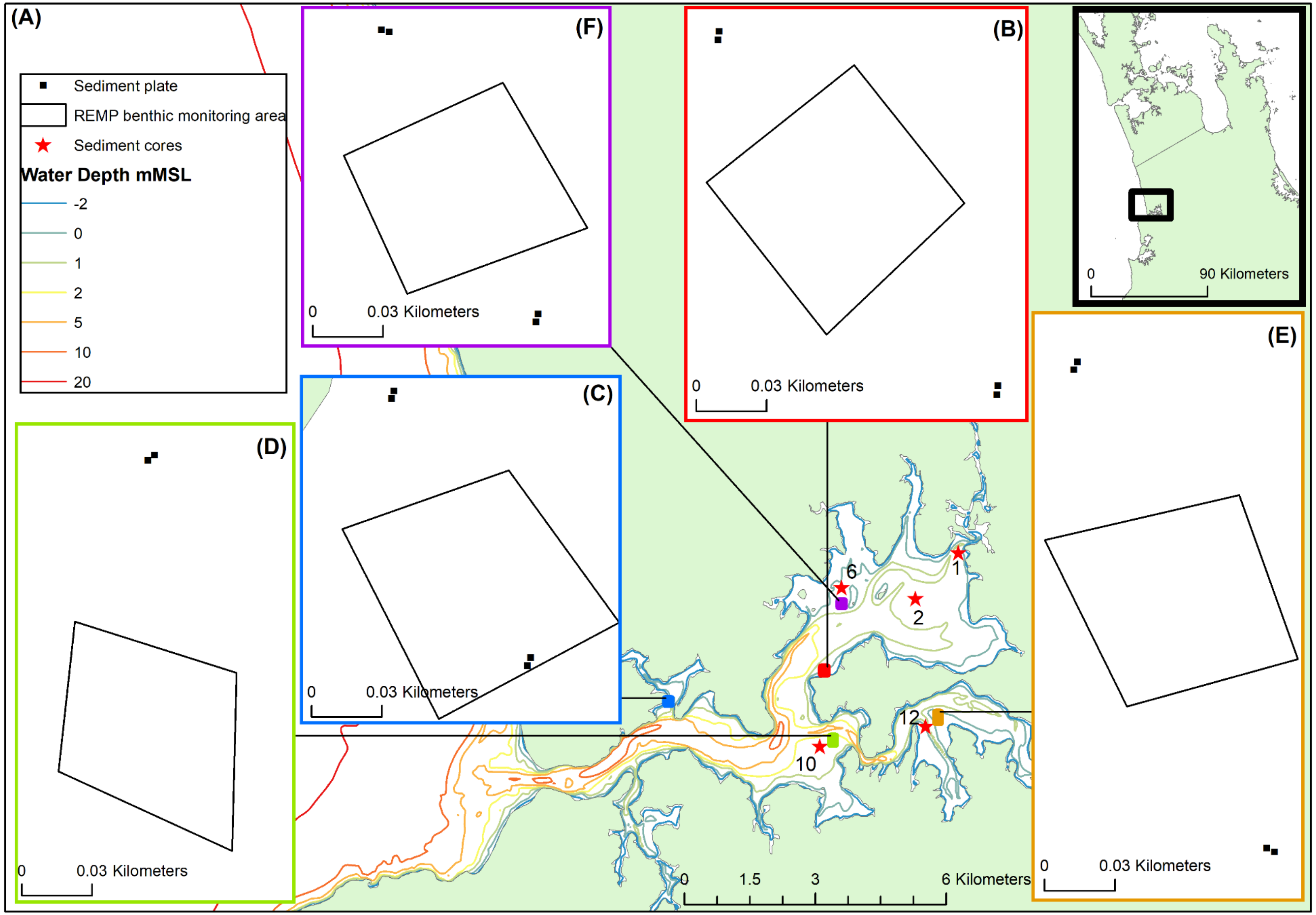

Figure 1. Whāingaroa (Raglan) Harbour location map showing WRC sediment plate locations, WRC REMP benthic monitoring areas and sediment cores collected by NIWA on behalf of WRC to measure rates of historic SAR (Swales et al., 2005) (A). Map insets show Te Puna Point (B) Ponganui Creek (C), Okete Bay (D), Haroto Bay (E) and Whatitirinui Island (F). Note that Okete Bay only has two sedimentation plates, all other sites have four plates. Depth contours are from regional bathymetry compiled Gardiner and Jones (2020).

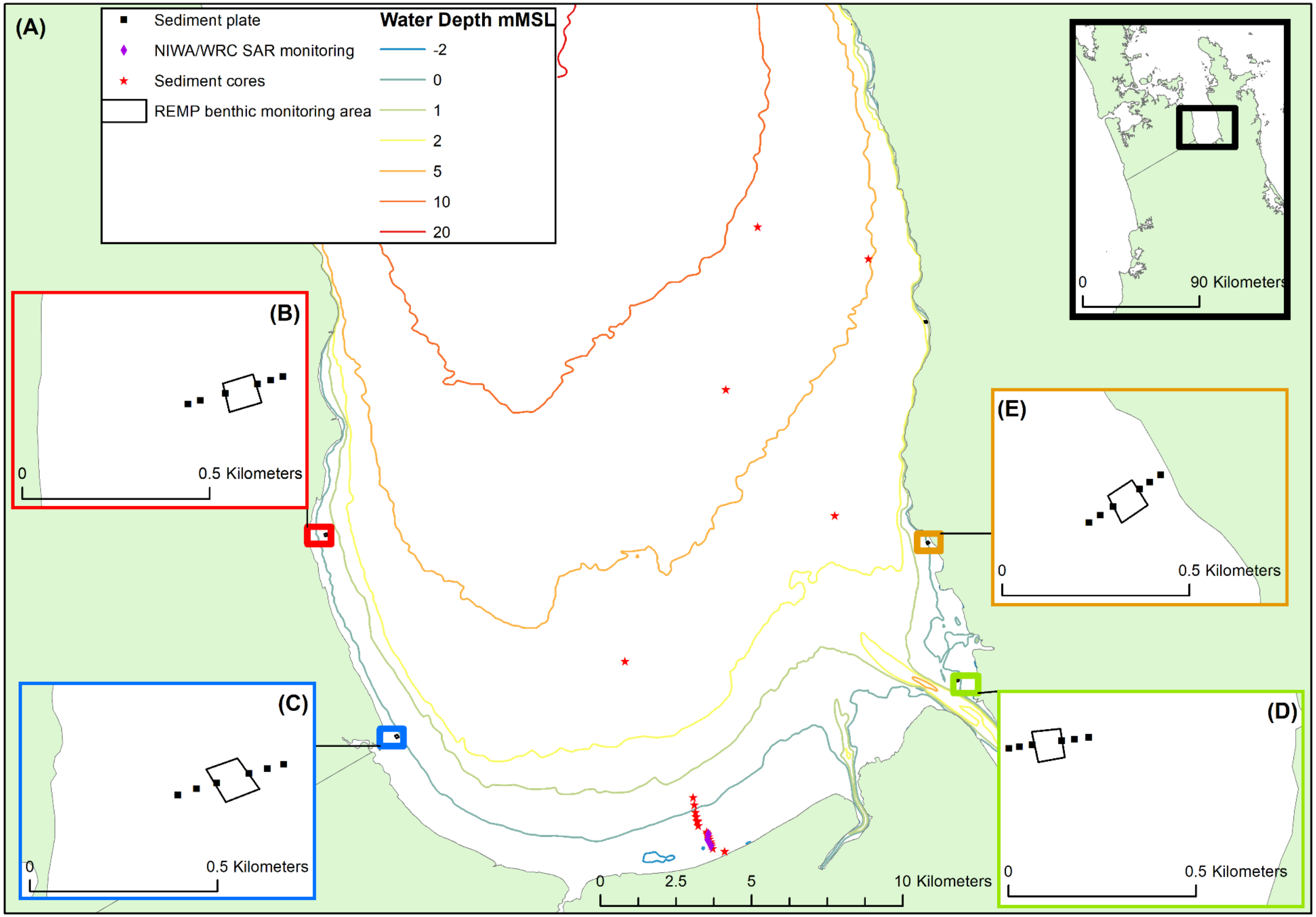

Figure 2. Firth of Thames location map showing WRC sediment plate locations, WRC REMP benthic monitoring areas, NIWA / WRC SAR monitoring locations (Swales and Lovelock, 2020) and locations of sediment cores collected to measure historic rates of SAR (Hume and Dahm, 1992; Swales et al., 2007; Zeldis et al., 2015) and / or sediment source tracking (Swales et al., 2016a) (A). Map insets show Kaiaua (B), Miranda (C), Gun Club (D) and Kuranui Bay (E). Depth contours are from regional bathymetry compiled Gardiner and Jones (2020).

2.2 Plate integrity check

A subset of plates was uncovered in Whāingaroa (Raglan) Harbour in 2017 and the Firth of Thames in 2018 to check the physical integrity of the plates and to ensure that they had remained level since installation. The results of the plate check are reported in Hunt (2019a). In this report, the sediment levels measured prior to the plate being uncovered are compared to subsequent measurements to assess if the process of uncovering the plate had affected the monitored sediment levels.

2.3 GPS measurements of seabed elevation

Seabed elevations (usually expressed relative to mean sea level) at the Whāingaroa and Firth of Thames monitoring sites have previously been obtained from LiDAR, but these measurements did not cover the two seaward plates at Kuranui Bay (Firth of Thames) or any of the plates at Kaiaua (also Firth of Thames) (Hunt, 2019a).

Seabed elevations at all Whāingaroa and Firth of Thames monitoring sites were measured on the 31st August and 1st September 2019 using Real Time Kinematic GPS (Sandwell and Bryan, 2020). The 2019 GPS seabed elevations are more accurate and more recent than the previous LiDAR seabed elevations.

3 Results

3.1 Whāingaroa (Raglan) Harbour

The SAR (Table 1) estimated from the trend line fitted to the sediment level data (Figures 3 – 7) indicates that with the exception of Haroto Bay, the best estimate of SAR at all sites was less than the ANZECC guideline value (Townsend and Lohrer, 2015) of 2.2 mm/y estimated for the Waikato region (Hunt, 2019b). The 95% confidence intervals show that there is variability around the average linear SAR (Table 1 and Figure 8) although this confidence interval does not change the overall assessment of the SAR at each plate relative to the ANZECC guideline value. The widest confidence interval is at Okete Bay due to a period of significant historical sediment accumulation followed by erosion (Figure 6). Field notes indicate that the sediment accumulation between 2012 and 2017 was due to the temporary formation of a mussel bed and consequently continued monitoring is required here to further understand the SAR.

Comparison of SAR with seabed elevation showed no clear relationship (Figure 8).

As part of the plate integrity check, (Hunt, 2019a) half the plates at each site were uncovered on the dates shown by the vertical dashed line in Figures 3 – 7. There was no evidence to suggest that uncovering the plates impacted the subsequent recorded sediment levels.

Table 1. Summary of SAR (mm/yr) estimated from the trend line fitted to the sediment-level data for the entire record to November 2021

Site	Plate	SAR	Lower 95% confidence interval	Upper 95% confidence interval
Haroto Bay	A	0.43	-0.12	0.98
	B	-0.03	-0.63	0.56
	C	3.03	2.36	3.70
	D	2.98	2.41	3.56

Whatitirinui Island	A	-1.42	-1.95	-0.89
	B	-1.56	-2.06	-1.07
	C	-1.66	-2.31	-1.01
	D	-1.53	-1.93	-1.14
Te Puna Point	A	-1.58	-2.15	-1.02
	B	-1.75	-2.41	-1.09
	C	-0.34	-0.87	0.19
	D	-1.58	-1.97	-1.18
Okete Bay	A	-0.25	-1.13	0.64
	B	-0.23	-1.36	0.91
Ponganui Creek	A	0.24	-0.21	0.70
	B	0.29	-0.15	0.74
	C	0.17	-0.25	0.59
	D	0.27	-0.19	0.74

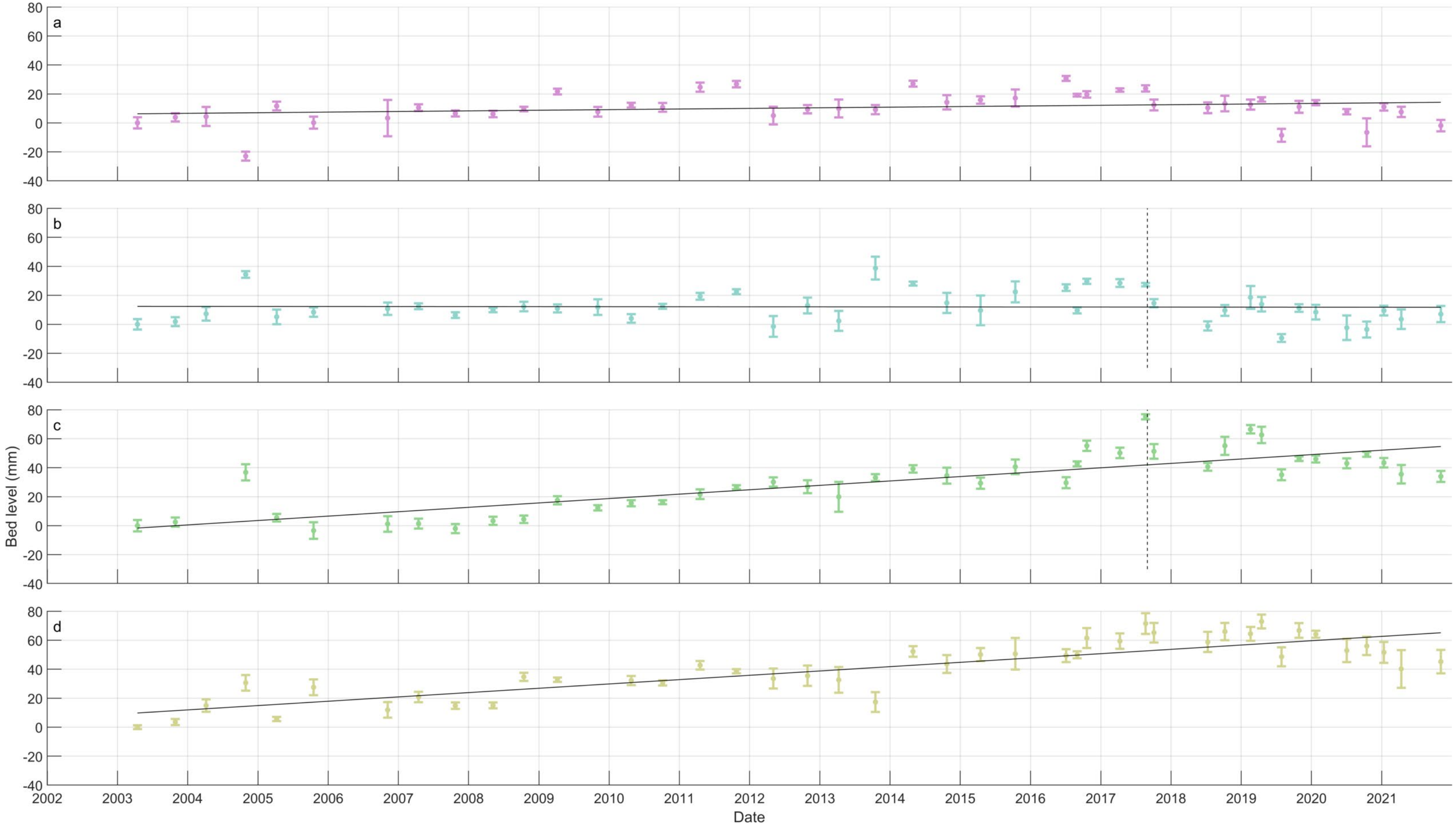

Figure 3. Sediment levels (relative to sediment plate) at Haroto Bay. Averages for the replicate measurements at Plate A (a), Plate B (b), Plate C (c) and Plate D (d) are shown, and error bars show the standard deviation around the average. The thin black lines (a, b, c, d and e) show the linear trend on which SAR (Table 1) is based for each plate. Plates C and D are landward, plates A and B are seaward of the benthic monitoring site. The dashed vertical line shows the date on which plates B and C were uncovered for inspection; the plotted sediment level was recorded prior to the plate being uncovered.

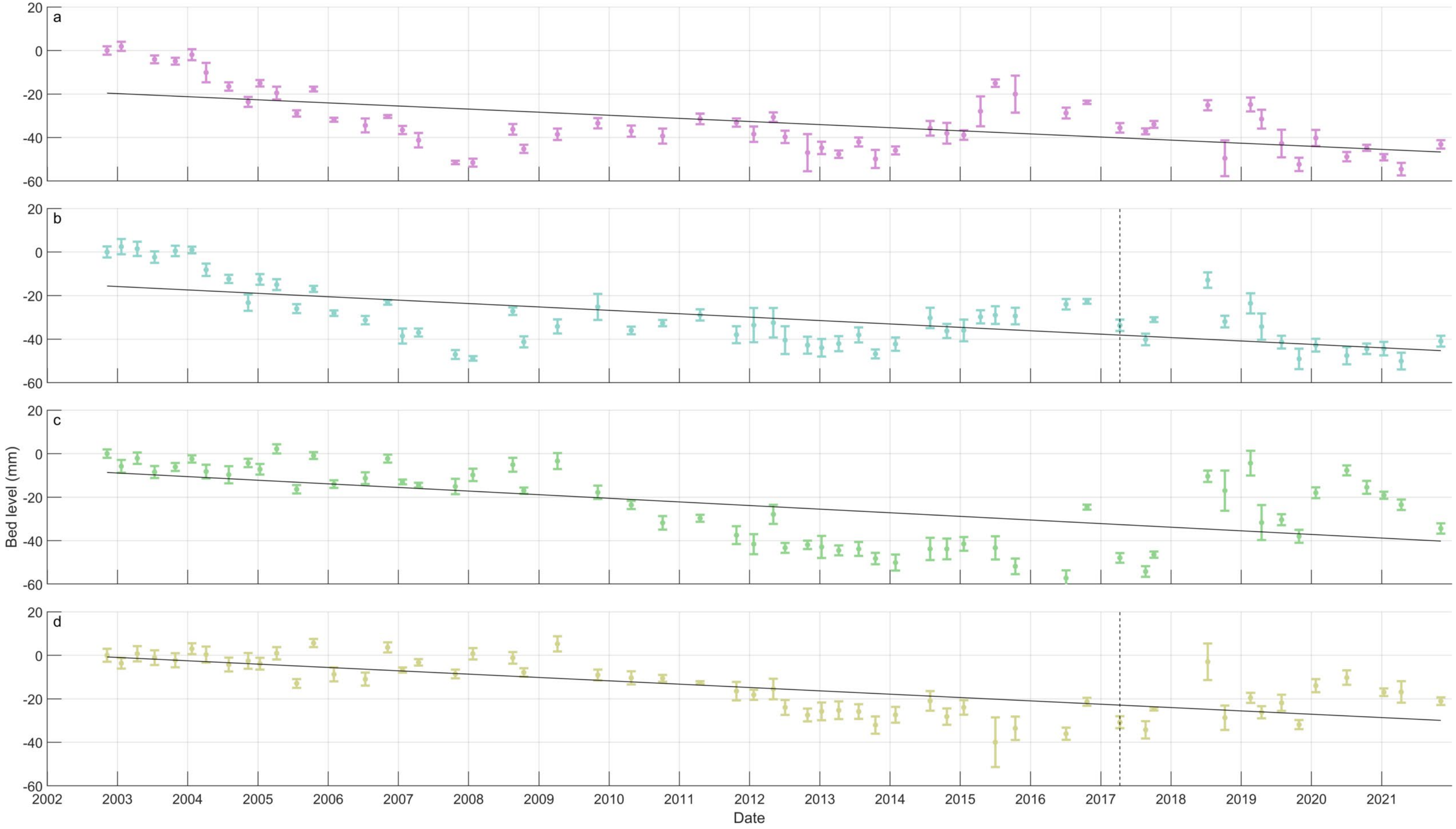

Figure 4. Sediment levels (relative to sediment plate) at Whatitirinui Island. Averages for the replicate measurements at Plate A (a), Plate B (b), Plate C (c) and Plate D (d) are shown, and error bars show the standard deviation around the average. The thin black lines (a, b, c, d and e) show the linear trend on which SAR (Table 1) is based for each plate. Plates C and D are landward, plates A and B are seaward of the benthic monitoring site. The dashed vertical line shows the date on which plates B and D were uncovered for inspection; the plotted sediment level was recorded prior to the plate being uncovered.

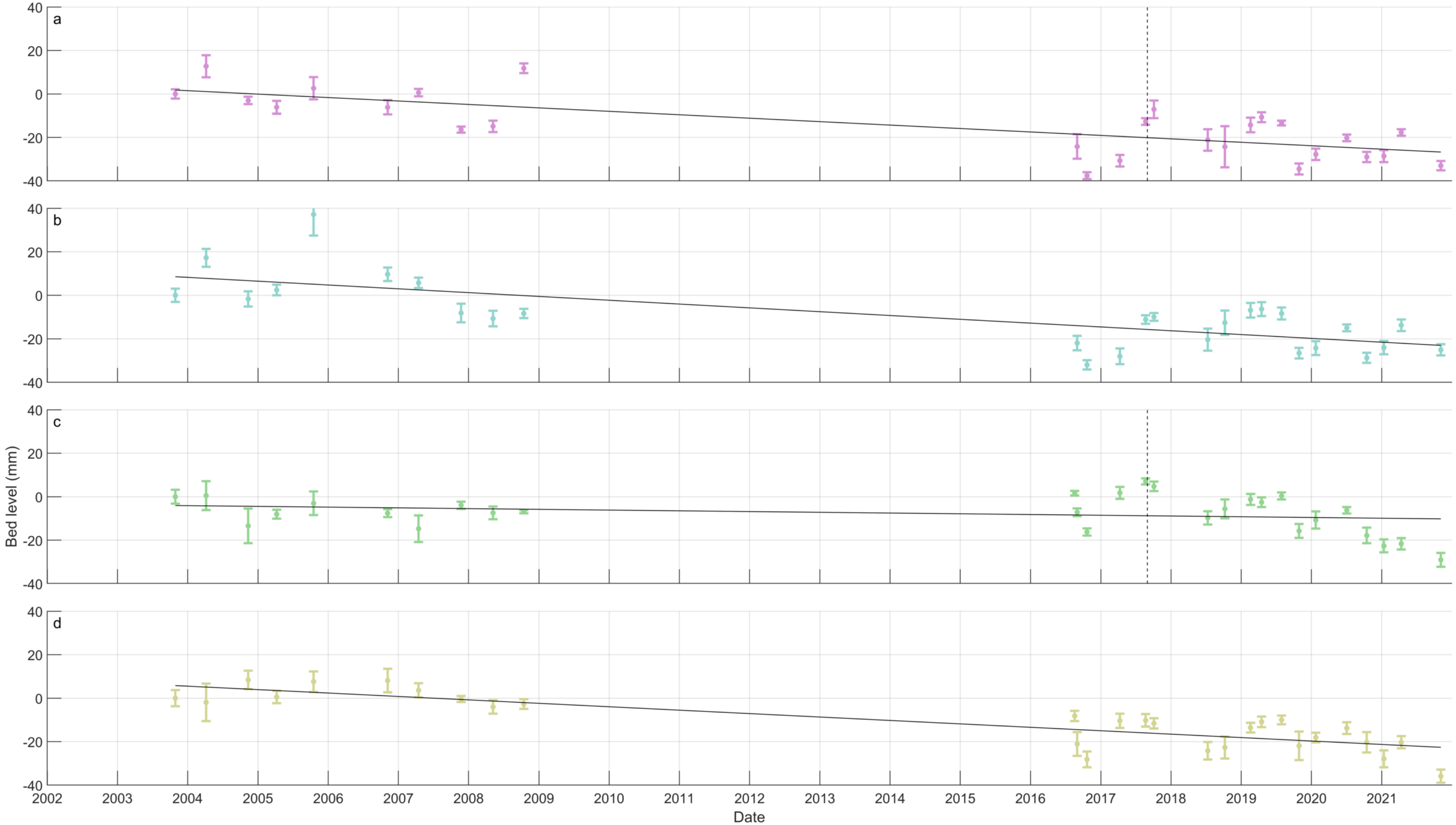

Figure 5. Sediment levels (relative to sediment plate) at Te Puna Point. Averages for the replicate measurements at Plate A (a), Plate B (b), Plate C (c) and Plate Dare shown, and error bars show the standard deviation around the average. The thin black lines (a, b, c, d and e) show the linear trend on which SAR (Table 1) is based for each plate. Plates C and D are landward, plates A and B are seaward of the benthic monitoring site. The dashed vertical line shows the date on which plates A and C were uncovered for inspection; the plotted sediment level was recorded prior to the plate being uncovered.

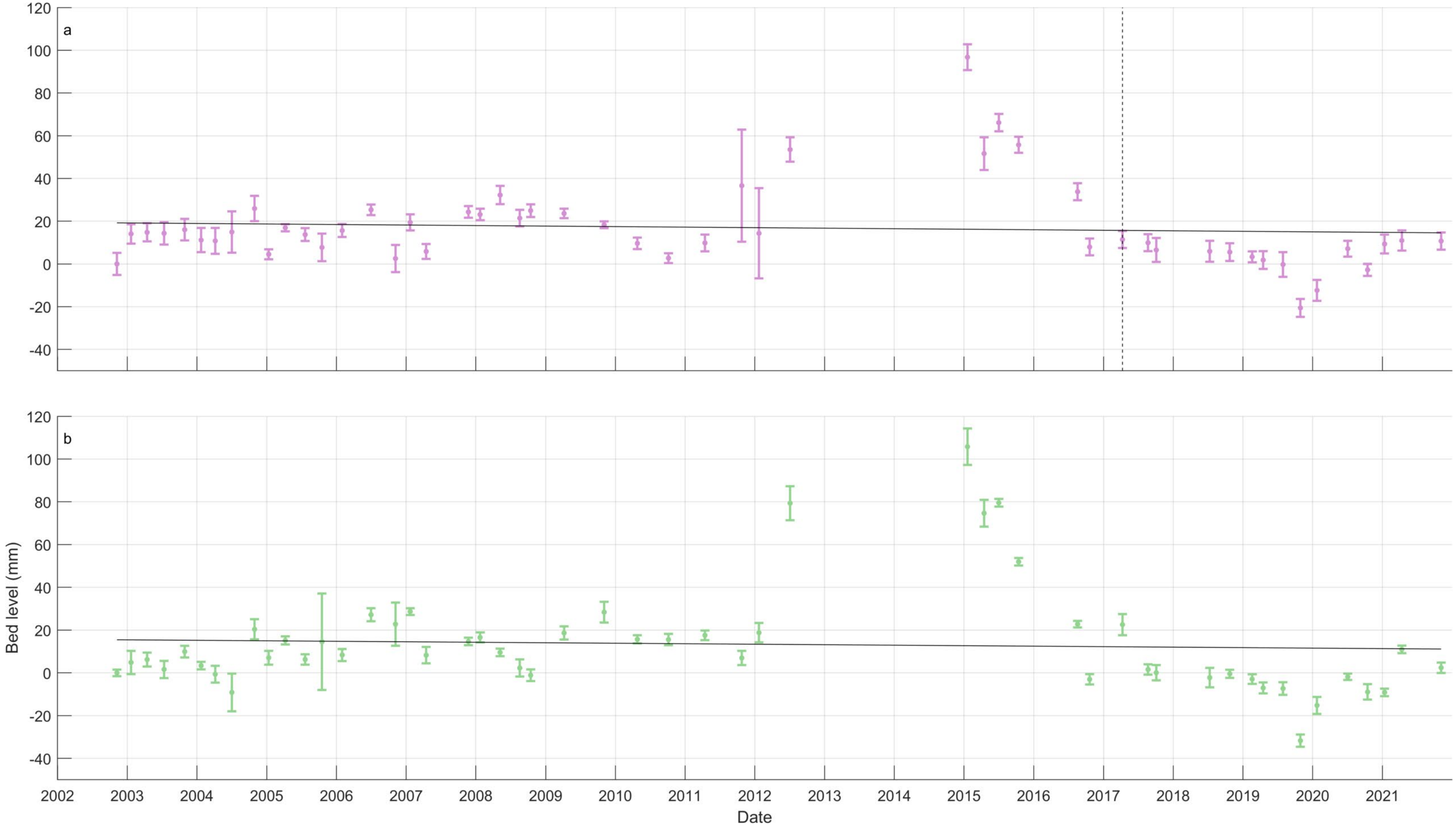

Figure 6. Sediment levels (relative to sediment plate) at Okete Bay. Averages for the replicate measurements at Plate A (a), and Plate B (b) are shown, and error the standard deviation around the average. The thin black lines (a, b and c) show the linear trend on which SAR (Table 1) is based for each plate. Plates A and B are seaward of the benthic monitoring site. The dashed vertical line shows the date on which plate A was uncovered for inspection; the plotted sediment level was recorded prior to the plate being uncovered.

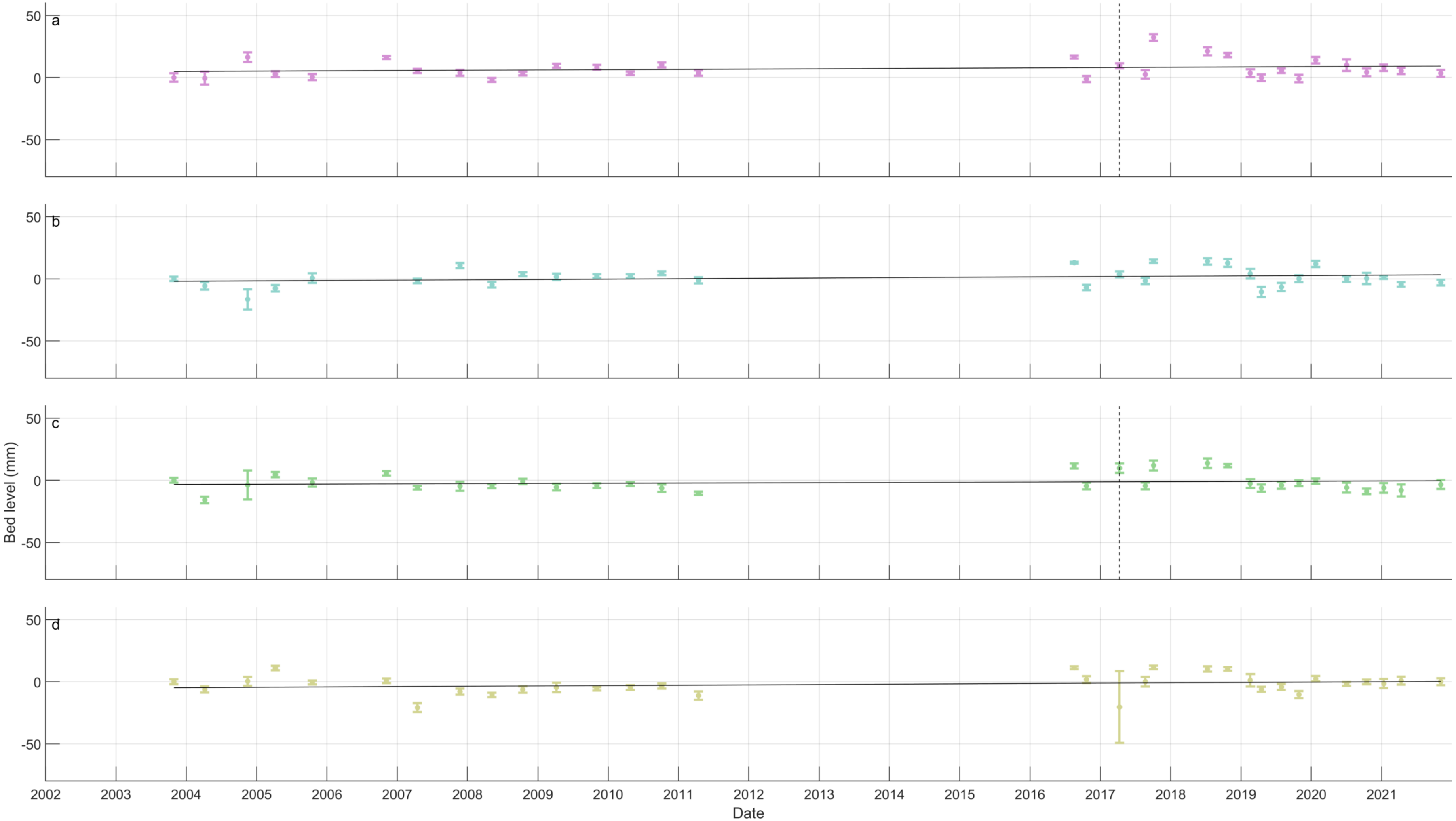

Figure 7. Sediment levels (relative to sediment plate) at Ponganui Creek. Averages for the replicate measurements at Plate A (a), Plate B (b), Plate C (c) and Plate n, and error bars show the standard deviation around the average. The thin black lines (a, b, c, d and e) show the linear trend on which SAR (Table 1) is based for each plate. Plates C and D are landward, plates A and B are seaward of the benthic monitoring site. The dashed vertical line shows the date on which plates A and C were uncovered for inspection; the plotted sediment level was recorded prior to the plate being uncovered.

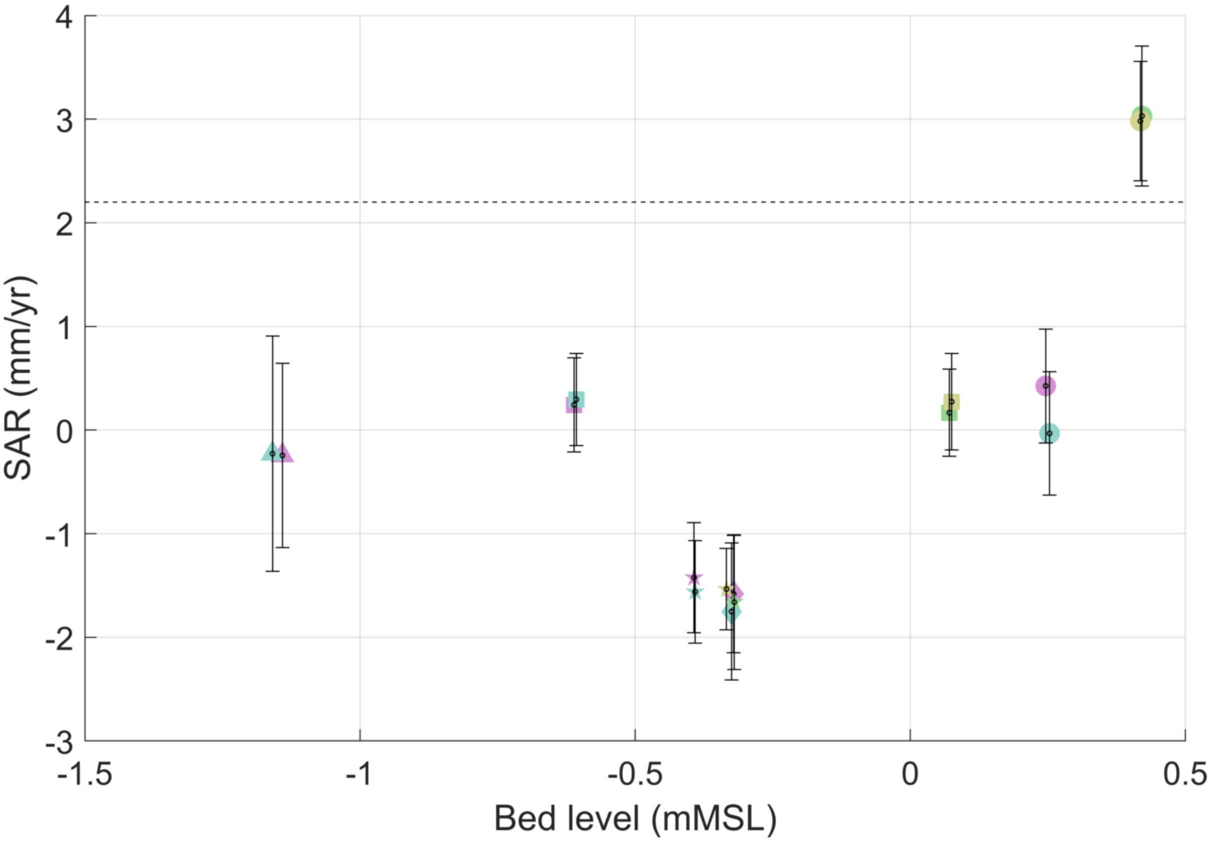

Figure 8. Comparison of SAR with elevation of monitoring site (Sandwell and Bryan, 2020). Data from the Haroto Bay (circles), Okete Bay (triangles), Te Puna Point (diamonds), Whatitirinui Island (stars) and Ponganui Creek (squares) monitoring sites. The colour of each symbol denotes the plate number: Plate A (pink symbol), Plate B (blue symbol), Plate C (green symbol) and Plate D (yellow symbol). Error bars show the 95% confidence interval. The dashed black line shows the ANZECC guideline value of 2.2 mm/y estimated for the Waikato region.

3.2 Firth of Thames

Throughout the Firth of Thames the magnitude of SAR (Table 2) as estimated from the trend line fitted to the sediment level data (Figures 9 – 12) was highly variable. Along the western side of the Firth at Kaiaua and Miranda SAR exceeded the ANZECC guideline value (Townsend and Lohrer, 2015) of 2.2 mm/y estimated for the Waikato region (Hunt, 2019b). Also, there are distinct differences in SAR with differences in seabed elevation (Figure 13), with plates at Kaiaua, Gun Club and Miranda generally showing a pattern of erosion at higher seabed elevations (shallower water) and deposition at lower seabed elevations (deeper water). The 95% confidence interval shows that there is variability around the SAR calculated from the average linear trend (Table 2 and Figure 13). The SAR from the upper confidence interval puts Plate 1 at Kaiaua and Plate 6 at Gun Club above the ANZECC guideline value. The widest confidence interval is for the shallow eroding plates at Gun Club and Miranda (Figure 13).

As part of the plate integrity check (Hunt, 2019a), two plates at the Gun Club and Miranda site were uncovered on the dates shown by the vertical dashed line in Figures 10 and 11. There was no evidence to suggest that uncovering plates significantly impacted the subsequent recorded sediment levels.

Table 2. Summary of SAR (mm/yr) estimated from the trend line fitted to the sediment-level data for the entire record to November 2021

Site	Plate	SAR	Lower 95% confidence interval	Upper 95% confidence interval
Kaiaua	1	1.79	1.00	2.57
	2	2.46	1.75	3.17
	3	4.02	3.23	4.81
	4	3.83	3.04	4.63
	5	4.01	3.31	4.71
	6	4.33	3.68	4.97
Gun Club	1	-0.54	-1.61	0.53
	2	-4.87	-6.42	-3.33
	3	-1.30	-3.00	0.41
	4	-1.16	-2.82	0.49
	5	0.30	-0.99	1.58
	6	0.85	-0.85	2.55
Miranda	1	-10.27	-11.45	-9.10
	2	-7.92	-9.07	-6.77
	3	-4.13	-5.25	-3.01
	4	0.99	-0.08	2.06
	5	2.35	1.75	2.95
	6	4.49	3.96	5.02
Kuranui Bay	1	-0.60	-2.19	0.98
	2	-4.56	-5.56	-3.56
	3	-5.86	-6.57	-5.14
	4	-4.34	-4.84	-3.83
	5	-2.92	-3.59	-2.24
	6	-1.43	-2.34	-0.53

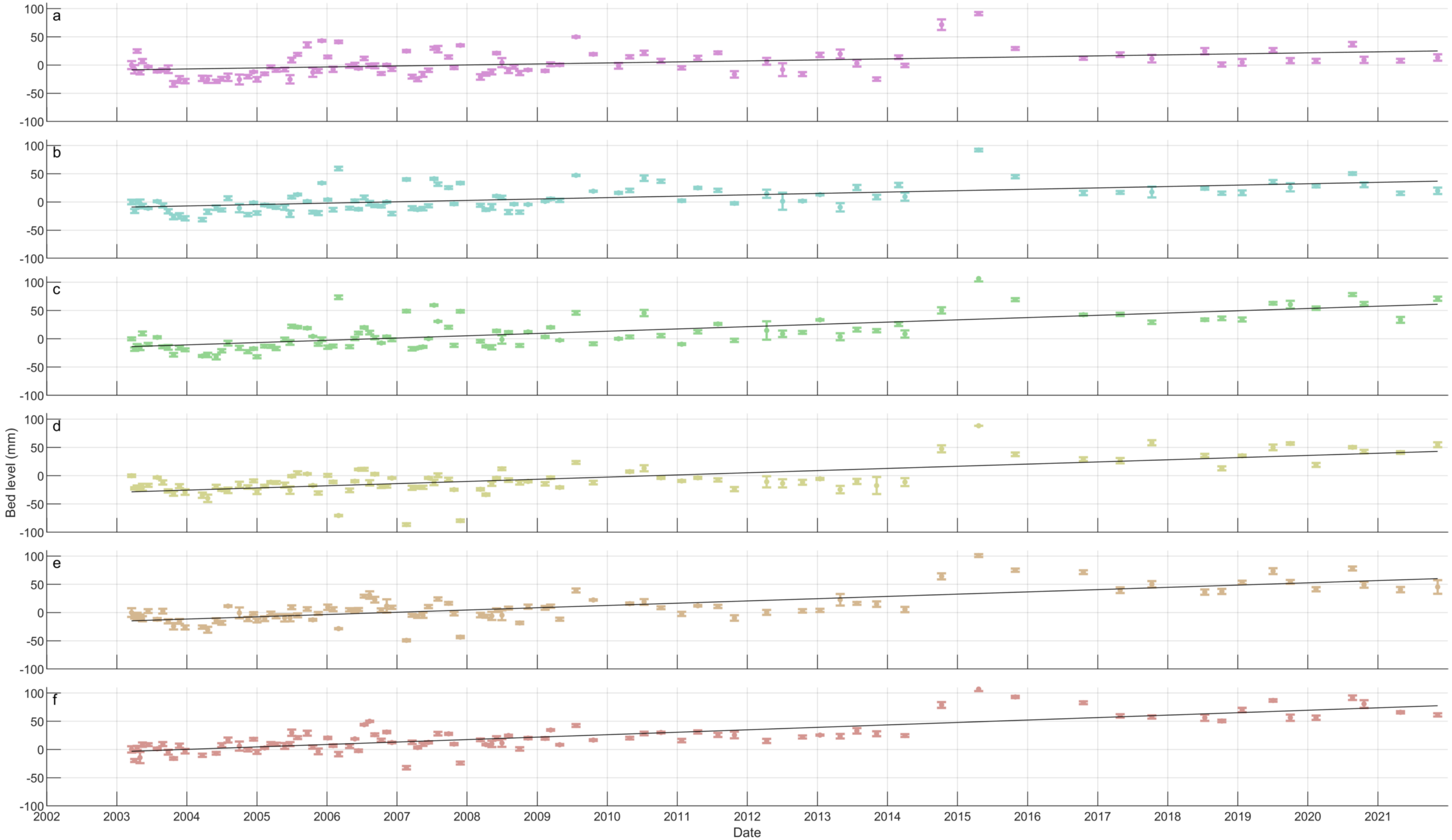

Figure 9. Sediment levels (relative to sediment plate) at Kaiaua. Averages for the replicate measurements at Plate 1 (a), Plate 2 (b), Plate 3 (c), Plate 4 (d), Plate 5 (e) and Plate 6 (f) are shown, and error bars show the standard deviation around the average. The thin black lines (a, b, c, d, e, f and g) show the linear trend on which SAR (Table 3) is based for each plate. Plates 1, 2 and 3 are landward, plates 4, 5 and 6 are seaward of the benthic monitoring site.

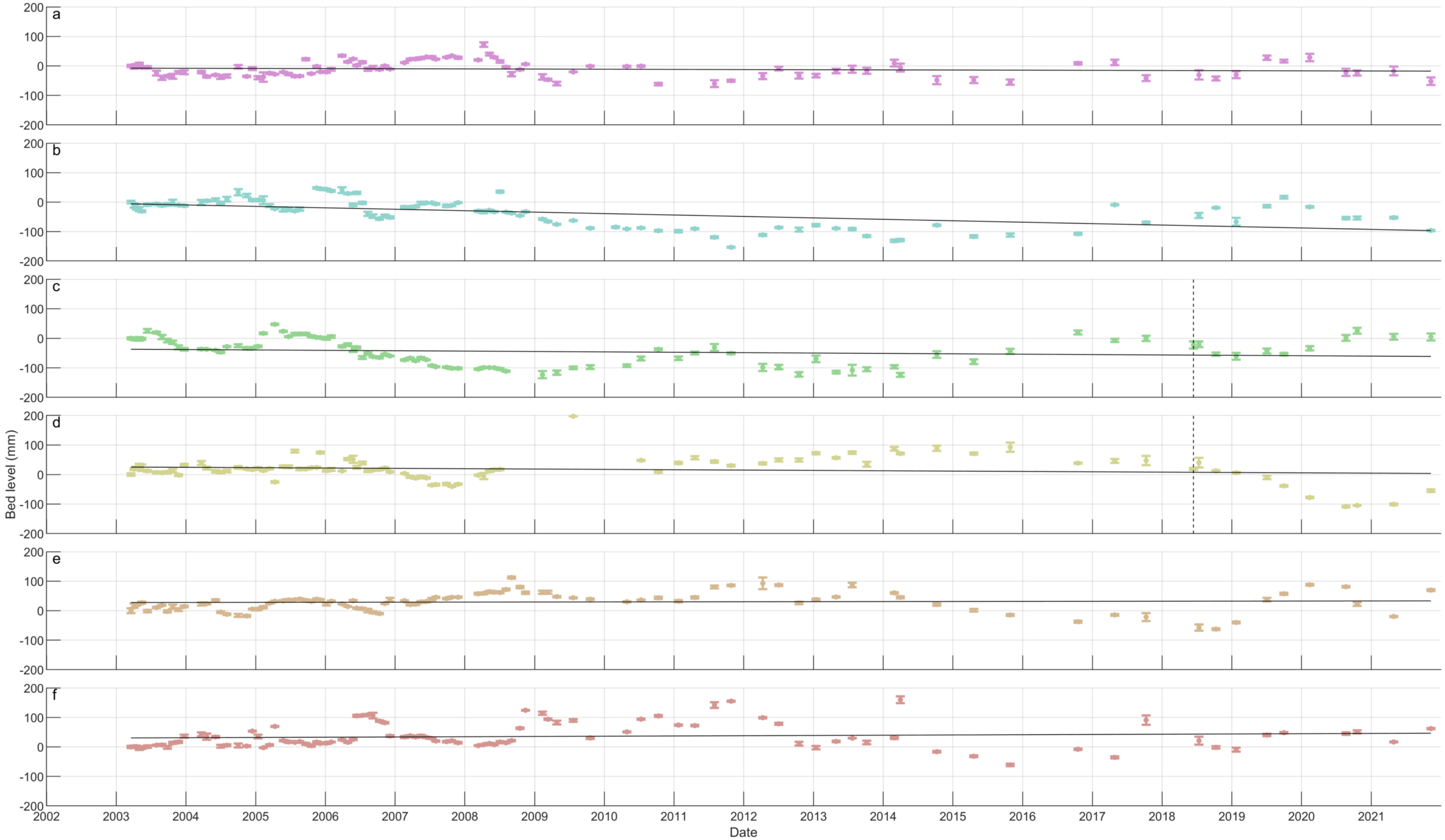

Figure 10. Sediment levels (relative to sediment plate) at Gun Club. Averages for the replicate measurements at Plate 1 (a), Plate 2 (b), Plate 3 (c), Plate 4 (d), Plate 5 (e) and Plate 6 (f) are shown, and error bars show the standard deviation around the average. The thin black lines (a, b, c, d, e, f and g) show the linear trend on which SAR (Table 3) is based for each plate. Plates 1, 2 and 3 are landward, plates 4, 5 and 6 are seaward of the benthic monitoring site. The dashed vertical line shows the date on which plates 3 and 4 were uncovered for inspection; the plotted sediment level was recorded prior to the plate being uncovered.

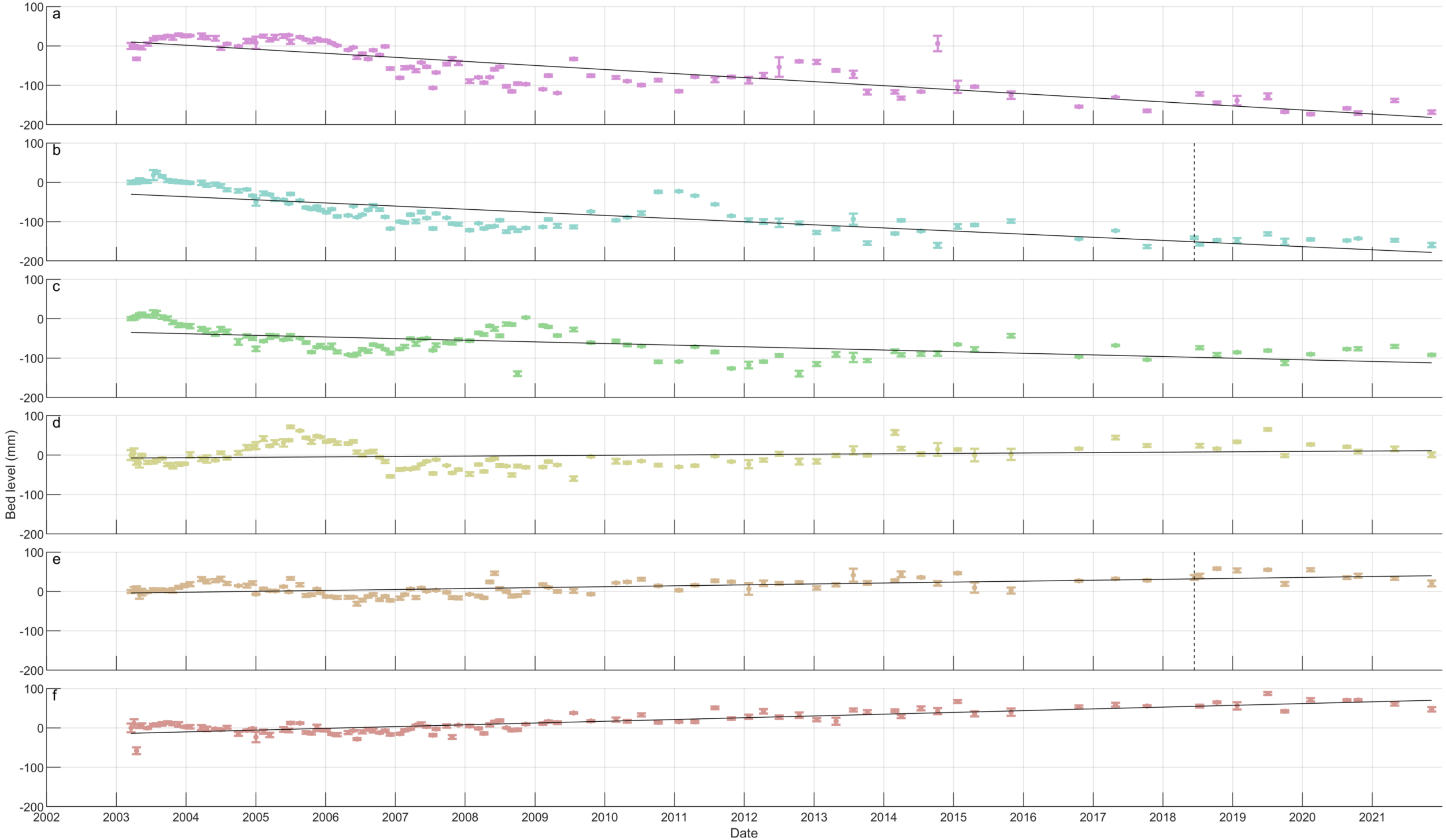

Figure 11. Sediment levels (relative to sediment plate) at Miranda. Averages for the replicate measurements at Plate 1 (a), Plate 2 (b), Plate 3 (c), Plate 4 (d), Plate 5 (e) and Plate 6 (f) are shown, and error bars show the standard deviation around the average. The thin black lines (a, b, c, d, e, f and g) show the linear trend on which SAR (Table 3) is based for each plate. Plates 1, 2 and 3 are landward, plates 4, 5 and 6 are seaward of the benthic monitoring site. The dashed vertical line shows the date on which plates 2 and 5 were uncovered for inspection; the plotted sediment level was recorded prior to the plate being uncovered.

Figure 12. Sediment levels (relative to sediment plate) at Kuranui Bay. Averages for the replicate measurements at Plate 1 (a), Plate 2 (b), Plate 3 (c), Plate 4 (d), Plate 5 (e) and Plate 6 (f) are shown, and error bars show the standard deviation around the average. The thin black lines (a, b, c, d, e, f and g) show the linear trend on which SAR (Table 3) is based for each plate. Plates 1, 2 and 3 are landward, plates 4, 5 and 6 are seaward of the benthic monitoring site.

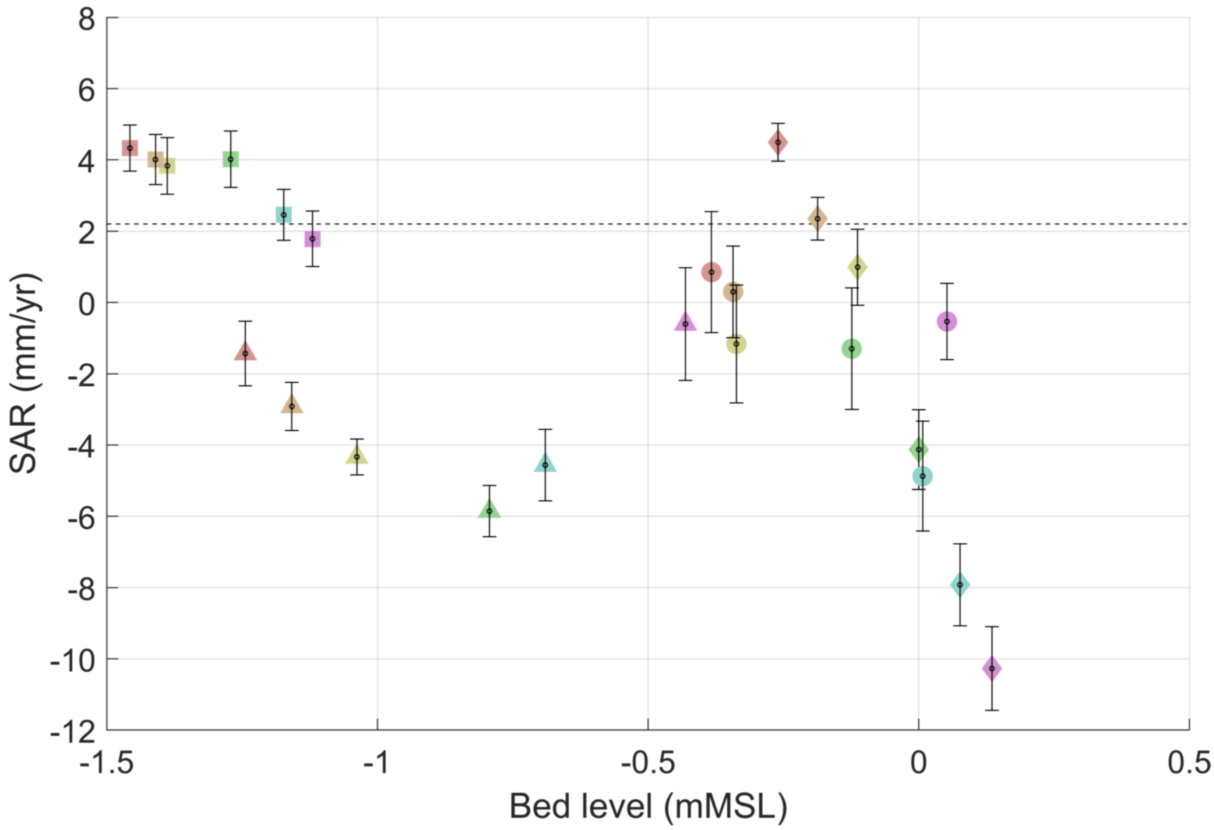

Figure 13. Comparison of SAR with elevation of monitoring site (Sandwell and Bryan, 2020). Data from the Gun Club (circles), Kuranui Bay (triangles), Miranda (diamonds) and Kaiaua (squares) monitoring sites. The colour of each symbol denotes the plate number, Plate 1 (pink symbol), Plate 2 (blue symbol), Plate 3 (green symbol), Plate 4 (yellow symbol), Plate 5 (orange symbol) and Plate 6 (red symbol). Error bars show the 95% confidence interval. The dashed black line shows the ANZECC guideline value of 2.2 mm/y estimated for the Waikato region.

4 Discussion

Rates of sediment accumulation typically vary with elevation of the seabed across an intertidal flat. Intertidal monitoring sites will only be submerged during certain stages of the tide, and variations in tidal-current velocities (speed and direction) during the tidal cycle mean that different sites at different elevations will be exposed to different tidal processes. Wave-orbital velocities mobilise sediments and are attenuated by water depth (height of the water column relative to the seabed) meaning that sedimentation rates are influenced through a combination of wave height, inundation time and water depth.

4.1 Whāingaroa (Raglan) Harbour

In Whāingaroa (Raglan) Harbour there is no clear consistent relationship between seabed elevation (or water depth) and SAR (Figure 8). This may be due to the dendritic form of the estuary and the limited spatial extent of the monitoring whereby each site is recording SAR in an environment with specific elevation, hydrodynamic regime and sediment supply.

Where sediment is accumulating, that accumulation is characteristically small in Whāingaroa (Raglan) Harbour with only 2 out of 18 monitoring sites recording accumulation above the ANZECC guideline value of 2.2 mm/y estimated for the Waikato region. Of note is the ongoing trend of erosion at Te Puna Point and Whatitirinui Island, which could suggest loss of previously deposited sediment and therefore adjustment from a previous morphological state at these locations.

The catchment of Whāingaroa (Raglan) Harbour has been considerably modified by humans and substantial quantities of sediment have been historically delivered in freshwater runoff to the estuary. Between 1890 and the mid-1920s much of the catchment was deforested and converted to pasture (Swales et al., 2005); this catchment clearance would have contributed a large amount of sediment to the estuary. During the 1980s and 1990s some of the catchment was converted to plantation forestry with the planting of pines; this land conversion and any subsequent harvesting of the timber would also contribute sediment to the estuary (Swales et al., 2005).

Historical and contemporary loads of sediment into Whāingaroa (Raglan) Harbour are not known but modelled estimates of annual suspended-sediment yield indicate that 60,424 t/yr is currently supplied from catchment sources. Of this annual load, the majority is from the Waitetuna (24,421 t/yr) and the Waingaro (20,982 t/yr) sub-catchments (Hicks et al., 2019). Catchment models indicate that prior to human settlement, the sediment load was 30% lower at 42,539 t/yr (Hicks et al., 2019). Evidence of the impacts of catchment modification is shown by sedimentation recorded in cores (Swales et al., 2005). In Whāingaroa (Raglan) Harbour, sediment cores have been collected at similar locations as the present-day monitoring sites at Okete Bay, Whatitirinui Island and Haroto Bay (Swales et al., 2005) and it is therefore possible to compare contemporary SAR with historic SAR and hence infer how SAR has changed over recent history.

At Okete Bay the sediment plate data indicates that the seabed is approximately stable with erosion occurring only at a very small rate ranging between -0.23 and -0.25 mm/yr. A large amount of accretion between 2012 and 2015 was caused by the temporary formation of a mussel bed, but now the mussel bed no longer exists. Sediment bed levels in Figure 6 indicates that SAR before the formation of the mussel bed was approximately the same as SAR after the mussel bed, with both being approximately zero. The sediment core collected at this site (core 10, Figure 1 and Table 3) indicates that SAR was positive (accumulation) historically with a pre-human rate of 0.5 mm/yr and a rate of 8 mm/yr between 1990 and 2002 (Swales et al., 2005). The change to approximate stability at this site post–2002 may be due to either a reduction in sediment supply compared to the historic sediment supply or a lack of accommodation space for further deposition of sediment. Lack of accommodation space arises from the seabed infilling to a level at which no more sediment can accumulate either due to frequent resuspension by waves and/or strong tidal currents, or through a shorter inundation time such that there is insufficient time for significant quantities of sediment to fall out of suspension. As the seabed elevation at this site is low (Figure 8), it seems likely that wave-orbital velocities are an important process, but strong tidal currents from the Narrows (the constricted mouth of the Waitetuna Arm to the east of the monitoring site) may also help to remove sediments and transport them elsewhere. Regardless of the physical processes controlling the sediment dynamics, the seabed appears to be in a state of dynamic equilibrium in which it neither infills nor erodes consistently over time, notwithstanding any temporary disturbances such as establishment of a mussel bed. Continued monitoring at this site will confirm if the bed level remains stable and provide further information on the sediment dynamics leading to this apparent stability.

Table 3. Summary of historic SAR at each core with date range and method (Swales et al., 2005). The descriptive epochs are based on the classification used by Hunt (2019b). The location of each core Is shown in Figure 1. Note that no dateable material was identified in core 6. Blank cells in the table indicate that SAR could not be measured.

	Core ID	1	2	10	12
SAR (mm/yr)	Early estuarine formation				
	Pre-human		0.34 (post 6300 yr BP from C^{14})	0.5 (post 7900 yr BP from C^{14})	0.35 (post 7900 yr BP from C^{14})
	Polynesian				
	Early European				1.1 (post 1890 from pollen). 5.0 (post 1890 from lead-210, less reliable than pollen in this case)
	Late European				
	Contemporary	4 (post 1990 from pollen)		8 (post 1990 from pollen)	2.5 (post 1990 from pollen)

At Haroto Bay, SAR is positive (accumulation) and large at two of the sites (between 2.98 and 3.03 mm/yr) and close to zero or negligible (between -0.03 and 0.43 mm/yr) at the other two sites. Nearby sediment core data (core 12 in Figure 1 and Table 3) indicate that SAR was historically lower than it is today, with pre-human SAR of around 0.35 mm/yr, 1.1 mm/yr following European arrival and rising again to 2.5 mm/yr between 1990 and 2002 (Swales et al., 2005). Continued accumulation at this site suggests that sediment input into the Waitetuna arm is still high. Haroto Bay appears to be susceptible to sediment accumulation, in that it is in a sheltered part of the Waitetuna arm and therefore experiences only infrequent wave energy that would otherwise erode the intertidal flats (Hunt et al., 2015; 2016). The Haroto Bay site is also the muddiest of all the sites, with a mud content (particle size < 63 µm) of c.46% (Jones, 2021).

In the Waingaro Arm of the estuary at Te Puna Point and Whatitirinui Island there is a trend of erosion, with SAR ranging between -0.34 and -1.75 mm/yr. There is no modern deposited material preserved in cores 2 and 6 (Figure 1 and Table 3), indicating no deposition for the past 150 years, however core 2 does indicate that pre-human sediment accumulation rates were around 0.34 mm/yr (Swales et al., 2005). Small amounts of pine pollen in the upper part of sediment core 1 at the mouth of the Waingaro River (Figure 1 and Table 3) indicate a deposition rate of around 4 mm/yr between 1990 and 2002. Therefore, SAR could be higher at the mouth of the Waingaro River compared to at the WRC sediment-plate sites and at core sites 2 and 6, but the evidence for long-term sediment accumulation at core 1 is similarly limited (Swales et al., 2005).

Absence of sediment accumulation in the Waingaro Arm of the estuary has been attributed to the erosive action of waves (Swales et al., 2005, Hunt et al., 2015; 2016; 2017), which are readily generated here due to the orientation of the arm relative to the prevailing southwesterly winds. Importantly, the ongoing trend of erosion at the WRC sediment-plate sites indicates that waves might not only be preventing contemporary deposition, as indicated by the absence of modern sediments in the cores, but could also be removing historically deposited material, suggesting that there has either been a significant reduction in sediment supply or a change in hydrodynamics. One possibility is that a large amount of sediment was introduced into the Waingaro Arm of the estuary, perhaps during initial deforestation and land clearance, and now that sediment is being steadily removed and re-worked by waves. Ongoing removal of historically introduced sediment would also explain the absence of recently deposited sediments in cores 2 and 6 (Figure 1 and Table 3). Sediment eroded by waves would be transported by tidal currents and wind-driven circulation and deposited elsewhere in the estuary and offshore. Erosion would be expected to continue until an equilibrium is reached between sediment supply and erosion by waves.

It is important to note that although the plates at Whatitirinui Island show a trend of erosion, there is considerable variability around this trend with periods of erosion punctuated by periods of stability and some accretion (Figure 4). It is possible that the long-term trend is for a dynamic equilibrium in which the bed infills until it reaches a level at which wave-orbital velocities are capable of continuously removing any sediment that deposits at the site. At dynamic equilibrium, the bed is eroded until wave-orbital velocities are attenuated by the water depth and are no longer able to erode the sediment. The bed level will vary due to minor fluctuations in wave climate and sediment input, with erosion occurring during episodes of low sediment input and / or particularly energetic waves, and deposition occurring during years with larger sediment inputs and / or less energetic waves. Hence, the bed level will vary slightly in response to climatic factors but will be maintained at a similar level over time. The distinction between a seabed at dynamic equilibrium as opposed to a seabed undergoing erosion is crucial as the former does not necessarily indicate a reduction in sediment supply, but the latter could indicate that the sediment supply has been reduced and the morphology is adjusting through the erosion of legacy sediments. The ongoing erosion recorded here over 20 years indicates that erosion is ongoing but continued monitoring will show if the trend for erosion continues or if there are cycles of periods of erosion and accretion.

The sedimentation plates at Ponganui Creek show a slow accumulation of sediment at a rate between 0.17 and 0.29 mm/yr. The site is low on the intertidal flat, which suggests that there is capacity for sediment accumulation at this location; however, being near the mouth of Ponganui Creek, the site is probably exposed to strong tidal currents and waves generated in the main arm of the estuary, which would tend to erode and prevent the deposition of sediment. Furthermore, the site is close to the estuary mouth and the water flooding the site during the incoming tide would be mostly from outside the estuary and therefore have relatively low suspended-sediment concentrations. Catchment models indicate that Ponganui Creek has a relatively small (compared to other parts of the harbour) sediment input of 1461.2 t/yr (Hicks et al., 2019), which could be another contributing factor to the small SAR. Despite the small SAR, Ponaganui Creek is the only site in Raglan where sediment samples show a statistically significant increase in mud content, although mud content (particle size < 63 µm) is low at c.14% (Jones, 2021).

4.2 Firth of Thames

Where sediment is accumulating in the Firth of Thames, that accumulation is characteristically small, with only 7 out of 24 monitoring sites recording accumulation above the ANZECC guideline value of 2.2 mm/y estimated for the Waikato region. Of note is the number of monitoring sites exhibiting trends of long-term erosion, which indicates loss of previously deposited sediment and therefore a morphological adjustment from a previous state. Low rates of accumulation (where accumulation exists) and erosional trends are unexpected, as monitoring elsewhere in the Firth indicates considerably rapid and widespread accumulation of sediment. For example, sediment level measurements over buried sediment plates made by NIWA and WRC in the southern Firth of Thames mangrove forest between 2012 and 2019 show that SAR ranged between 17 - 41 mm/yr (Swales and Lovelock, 2020). Similarly, cores collected in the intertidal region adjacent to the mangrove forests indicated SAR ranging between 26 and 43 mm/yr between 1996 and 2006 (Zeldis et al., 2015).

It is known that the Firth of Thames catchment has been considerably modified by humans and consequently substantial quantities of sediment have been historically delivered to the estuary. Activities that are thought to have contributed to catchment erosion include deforestation, initially by Māori and then further permanent large scale-deforestation following European settlement (Phillips, 2000). There was also mining between the late 1800s and 1950s, both in the wider catchments (Philips, 2000; Hume and Dahm, 1992) and immediately adjacent to the Firth of Thames shoreline (Figure 14) (Nolan, 1977). Construction of stopbanks to convert wetland to pasture and prevent flooding, along with other engineering works, channelised the estuary and likely prevented deposition of sediment over the floodplain, thereby also increasing the delivery of sediment from the Waihou and the Piako rivers to the Firth of Thames. Stopbanks were built along both sides of the Waihou River, the lower Ohinemuri River and along the Firth of Thames coast between 1913 and 1919 (Phillips, 2000). By the 1930s, various sections of the Waihou River had been re-channelled and straightened (Phillips, 2000). Further work, including raising and realignment of the stopbanks and straightening of streams, was undertaken following the flooding in 1977 (Philips, 2000). Work on the Piako River and some of its tributaries commenced in 1908, including stop-bank construction, drainage and reclamation of the floodplain, dredging, canalisation, and also straightening and rerouting of some rivers. The majority of the work was completed by 1939, although periodic large-scale works continued until the 1970s (Jones and Dickie, 1990). The stopbanks on both the Waihou and Piako rivers continue to be periodically raised to ensure they continue to effectively prevent flooding.

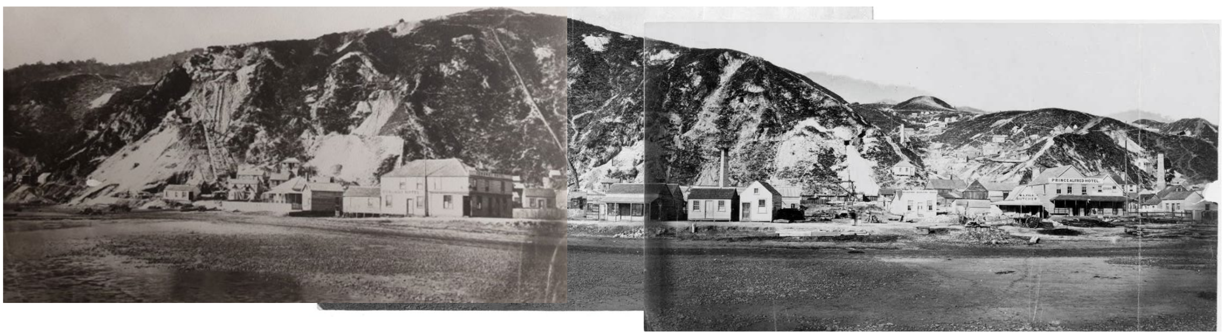

Figure 14. Example of catchment modification through deforestation and mining activities. This picture was taken in c1868 at the Kuranui Bay foreshore, approximately 1 km south of the Kuranui Bay monitoring site (Images ½-065407-F, ½-065408-F, and ½-065409-F from Alexander Turnbull Library). The hills in this picture are now covered in regenerating native bush and the foreshore is now reclaimed land (Nolan, 1977).

Modelled estimates of annual suspended-sediment load indicate that around 152,517.4 t/yr is currently supplied to the Firth of Thames from catchment sources. The majority of the annual load is from the Waihou (115,112 t/yr) and the Piako (22,111 t/yr) (Hicks et al., 2019) catchments. Catchment models also indicate that, prior to catchment modifications, sediment load was 40% lower at around 90,931 t/yr (Hicks et al., 2019). Evidence of the impacts of catchment modification is shown by sedimentation recorded in cores and the rapid expansion of the mangrove forest in the southern Firth of Thames (Naish, 1990, Hume and Dahm, 1992; Swales et al., 2007; Zeldis et al., 2015; Swales et al. 2016a; Hunt et al, 2019b). Although the contemporary catchment sediment load entering the Firth of Thames is far higher than that prior to human settlement, it is likely that the sediment load was even higher during the peak of the historic catchment modification. Sediment budgets (Zeldis et al., 2015) and analysis of the source of deposited sediments in sediment cores (Swales et al., 2016a) indicate that legacy sediments that were supplied to the Firth during the peak of this historic activity are still a significant contributor to sedimentation as they are resuspended, reworked and subsequently re-deposited elsewhere in the Firth of Thames.

When the estimates of SAR from the Miranda, Gun Club and Kaiaua sites are viewed in aggregation, there appears to be a non-linear relationship between seabed elevation / water depth and SAR. To show this relationship, Figure 15 shows the same information as Figure 13, but SAR is plotted against water depth at high water during an average spring tide. Specifically:

- There is **erosion** (negative SAR) at the shoreward plates situated in higher bed levels / shallower water levels (< ~ 1.7 m MSL) situated at the Gub Club and Miranda sites. These plates also exhibit the widest confidence intervals, indicating variability in recorded bed levels around the mean, linear trend.
- The amount of erosion decreases with reduced bed level / increased water depth, with **accretion** (positive SAR) recorded at some of the seaward Gun Club and Miranda plates and at all the Kaiaua plates. These plates also exhibit the narrowest confidence intervals, indicating less variability in recorded bed levels around the mean, linear trend.

Waves mobilise sediment through orbital velocities and these orbital velocities become less effective at eroding sediment in deeper water. Therefore, this varying pattern of increased SAR with lower seabed levels / deeper water depths is expected for a wave influenced estuarine environment (Fagherazzi et al., 2006, 2007; Mariotti and Fagherazzi, 2013a, 2013b; Hunt et al., 2015, 2016, 2017).

Specifically, in shallower water (< ~1.9 m at MHWS) there is a rapid attenuation of orbital velocities from waves with increasing water depths (Figure 15). This attenuation means that the SAR switches from erosional in the shallower water, where sediment is eroded by waves, to depositional in the deeper water where waves have less influence. Wave erosion will occur when wind speed and direction are able to generate sufficient wave energy to mobilise sediments and therefore erosion is likely to be episodic and interspersed by sedimentation during periods of low wave energy. The variability in recorded sediment bed levels around the average linear trend as shown by the relatively wide confidence intervals could be indicative of episodic wave erosion at these plates (Figure 15).

In deeper water at Kaiaua there is evidence of a further increase in SAR with increasing water depth, but the relationship is not as pronounced as in the shallower monitoring sites and the rates of SAR recorded at Kaiaua are of a similar magnitude to those recorded at Miranda in shallower water. Overall, it seems that there is a rapid gradient in orbital velocity attenuation and reduced SAR between 1.4 and 1.9 m, beyond this depth the orbital velocities are fully attenuated at high water meaning that increases in water depth only result in negligible increases in SAR. The narrower confidence interval in SAR at these deeper, accreting sites (Figure 15) indicates that measured bed levels are less variable around the average linear trend and therefore episodic wave erosion is a less important control on bed levels when compared to the shallower sites.

The sediment erosion over the upper intertidal areas may also be indicative of the intertidal flat tending towards a semi-stable 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).

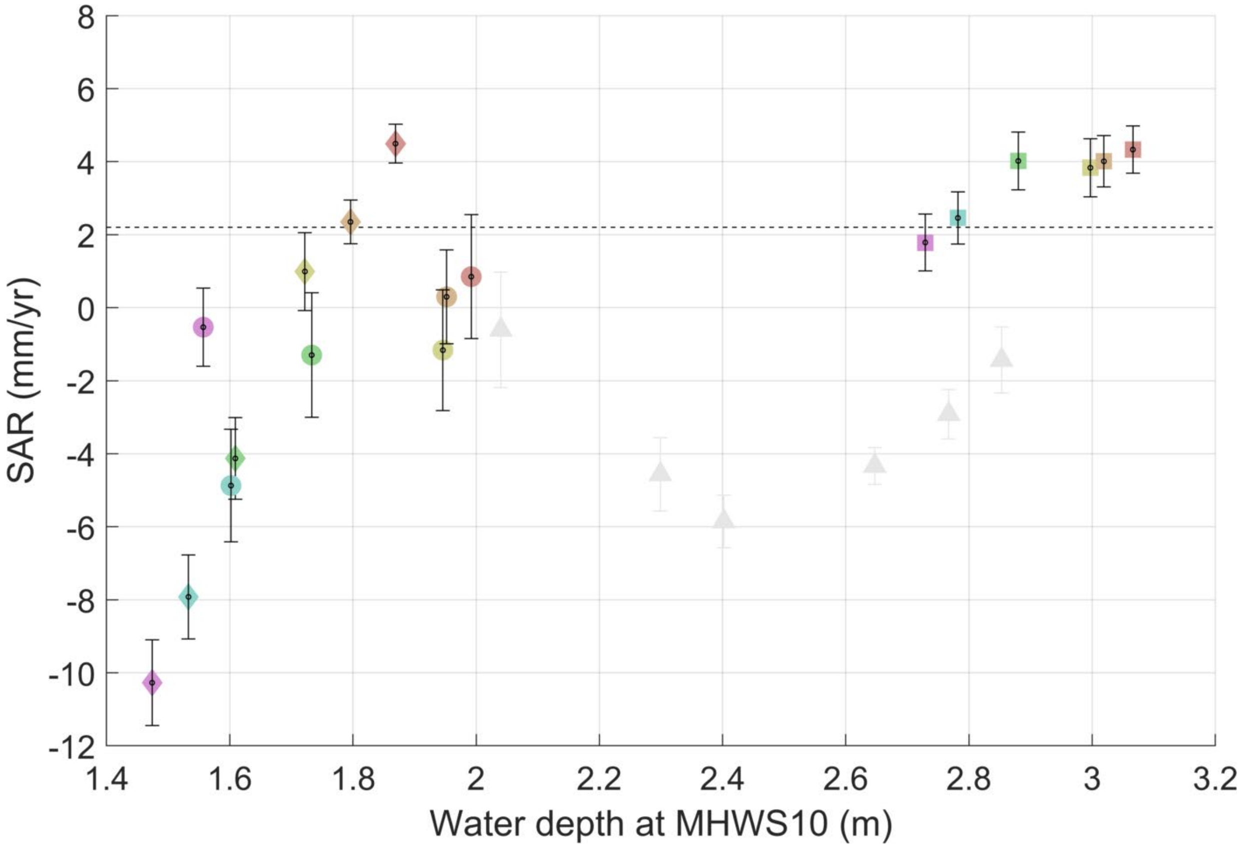

Figure 15. Comparison of SAR with water depth at Mean High Water Springs. Data from the Gun Club (circles), Miranda (diamonds) and Kaiaua (squares) monitoring sites is coloured according to plate number: Plate 1 (pink symbol), Plate 2 (blue symbol), Plate 3 (green symbol), Plate 4 (yellow symbol), Plate 5 (orange symbol) and Plate 6 (red symbol). Data from Kuranui Bay (triangles) are coloured grey. Error bars show the 95% confidence interval. The dashed black line shows the ANZECC guideline value of 2.2 mm/y estimated for the Waikato region. The water depths at Mean High Water Springs are exceeded only 10 % of the time (MHWS10). The water depths are based on seabed elevation measured using RTK (Sandwell and Bryan, 2020) and water levels are from an analysis of the Thames Tararu tide gauge record (Stephens et al., 2015).

Although wave processes appear to provide a coherent explanation for the spatial distribution of SAR across the intertidal flats observed in the Firth of Thames, the aggregated data set should be interpreted with caution as there are subtle differences in sediment supply, sediment type and hydrodynamics from site to site. An obvious example of this is the monitoring site at Kuranui Bay (Figure 15, grey triangles) where all plates exhibit erosion despite the water being relatively deep. The plates at Kuranui Bay are situated close (plate 1 ~ 33 m and plate 6 ~ 260 m) to a vertical rock wall that supports State Highway 25. It is possible that this wall causes wave reflection and scour at this site. Furthermore, the site is situated adjacent to the stream delta at the mouth of the Tararu River, which may modify the hydrodynamics and sediment transport patterns in its vicinity. Kuranui Bay could also be exposed to strong and asymmetric tidal currents, alongshore wave-driven transport and/or wind-driven estuarine circulation, all of which could prevent sediment accumulation. The relatively narrow confidence intervals at Kuranui Bay indicates that the recorded bed levels are less variable around the mean linear trend when compared to the shallow eroding sites at Miranda and Gun Club and could indicate that erosion at Kuranui Bay is not due to episodic waves.

Sediment samples taken at the benthic monitoring sites situated between plates 3 and 4 (see Figure 2 for locations) indicate that the WRC sediment-plate sites are predominantly sandy, which contrasts with the muddy sediment encountered in the depositional Firth of Thames mangroves, the depositional subtidal and intertidal cores (Hume and Dahm, 1992; Zeldis et al., 2015; Swales et al, 2016a) and the wider sediment mapping of the Firth (Carter and Eade, 1980). When considering mud content (<63 µm) at the WRC sediment-plate sites, the deepest depositional site at Kaiuau is the muddiest (c.19%) compared to the eroding site at Kurunui Bay (c.9%) and the partly eroding sites at Gun Club (c.5%) and Miranda (c.8%), which are predominantly sandy (Jones, 2021). The sediment samples also indicate that there has been a statistically significant, albeit slight, increase in muddiness at Miranda (Jones, 2021) which could reflect the relatively higher rates of deposition at the plates seaward of the benthic monitoring site (Figure 15). The relative lack of fine sediment at the eroding sites indicates that it is predominantly the finer fractions of sediment that are being eroded by waves.

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 using high precision GPS have shown evidence of deep subsidence within the Firth of Thames basin (Swales et al., 2016b). Within the mangrove forest, subsidence ranges between 7.7 ± 0.5 to 9.4 ± 0.5 mm/yr and at the Tararu tide gauge a subsidence rate of 3.6 ± 0.7 mm/yr was measured. Subsidence is attributed mainly to sediment compaction, with a smaller contribution from vertical land movement (Swales et al., 2016b). Based on measured subsidence, the Firth could have potentially sunk by between 65 and 170 mm between 2003 and 2021. A drop in bed height would increase water depths which in turn would attenuate orbital velocities and increase sediment accommodation space. In general, subsidence of the basin and associated increases in water depth should increase SAR, but the effects are likely to be complex and should become more apparent with further monitoring.

Based on the available data, the similar patterns of erosion in shallower water depths and accretion over deeper water depths at Gun Club and Miranda are likely controlled by the strength of orbital velocities from locally generated short period waves relative to sediment supply. Similarly, the trend of deposition at the deeper Kaiaua site is likely due to attenuation of orbital velocities in deep water. The reason for the ongoing trend of erosion over the deeper (relative to Miranda and Gun Club) Kuranui Bay sites is not known but may be wave driven. It is hypothesised here that the historically large amount of sediment supplied to the Firth of Thames was able to overcome the ability of waves to remove the sediment resulting in a large amount of deposition over the entire estuary. Now that the sediment supply to the Firth has reduced slightly, these considerable volumes of legacy sediments are being eroded in some areas, mainly by wave processes and the erosion of finer sediments. This ongoing trend of erosion will likely continue until a stable bed level is reached at equilibrium with contemporary sediment supply. The eroded legacy sediments are being transported by tidal currents and wind-driven circulation and deposited on the adjacent lower intertidal (such as at the WRC monitoring site at Kaiaua and the seaward / deeper Miranda and Gun club WRC monitoring sites) or within the extensive mangrove forests (Swales et al., 2015; Swales et al., 2019) and fringing mudflats in the southern Firth of Thames (Zeldis et al., 2015; Swales et al., 2016a) or possibly the deeper subtidal regions of the estuary (Hume and Dahm, 1992; Swales et al., 2016a) (see Figure 2 for locations of sediment cores and contemporary NIWA/ WRC monitoring sites).

Although some of the plates at Gun Club, Miranda and Kuranui Bay show a marked trend of erosion there is variability around this trend with periods of erosion punctuated by periods of stability and some accretion. Therefore, there is still uncertainty as to whether the trend of erosion is an ongoing removal of legacy sediments or part of a longer-term trend of dynamic equilibrium whereby the bed varies through cycles of erosion and accretion due to small changes in the wave climate or sediment supply and the feedback between bed levels and wave energy.

Erosion by waves is initiated when the elevation of an intertidal flat reaches the level through sedimentation at which orbital velocities from waves can mobilise sediments at a greater rate than deposition. The bed is then eroded until orbital velocities can no longer mobilise sediments and accretion of sediments resumes. This feedback between elevation and orbital velocities would likely result in either a slowing of erosion rates or a dynamic equilibrium and a quasi-stability arising from alternating period of accretion and erosion. The long-term trend of erosion observed here seems unlikely to fit this model and suggests instead an ongoing erosion and re-working of historically deposited material. Ongoing monitoring will confirm if the erosional trend continues or if it is part of a long-term cycle of alternating periods of erosion and accretion.

4.3 Sedimentation and estuarine health

Although sedimentation is a natural process, elevated SAR can adversely impact estuarine health through the smothering of benthic estuarine habitats (Townsend and Lohrer, 2015). To avoid adverse impacts from sedimentation, SAR should be less than 2 mm/yr above natural, pre-human SAR (Townsend and Lohrer, 2015). In the Waikato region an appropriate SAR threshold is 2.2 mm/yr (Hunt, 2019b) and in this report the measured SAR have been compared against this threshold to assess the risk of adverse impacts on estuarine health from sedimentation.

SAR is a useful metric, but estimating estuarine health using a single, indirect metric is problematic as other pressures such as water quality, turbidity, sediment quality and sediment composition (e.g., proportions of gravel/sand/mud fractions) can also all adversely affect estuarine health. Oceanographic processes are also critical as they control circulation, estuarine flushing, the residence time of water and any associated contaminants within the estuary and the export of water to the open coast and the wider CMA. Measurement and interpretation of long-term SAR as presented here, can also fail to record, or characterise sedimentation from severe but temporary depositional events that could conceivably cause significant harm to estuarine health. The spatial limitations of this monitoring also mean that severe sedimentation could be occurring elsewhere in the estuaries.

Therefore, low SAR is not necessarily an indicator of good estuarine health without consideration of the wider environmental context. Instead, it is necessary to attempt to integrate and consider all the various pressures and put them in the historical context of each estuary to provide a more comprehensive description of the health of an estuary. Despite the evidence of low SAR at some locations as presented in this report, there is compelling evidence that many estuarine sites in the Waikato region are exhibiting a decline in estuarine health (Jones, 2021; Jones et al., 2022).

5 Conclusions

The WRC sedimentation monitoring dataset is now well established with a > 20-year record of sediment levels at 18 sediment-plate monitoring sites within Whāingaroa (Raglan) Harbour and at 24 sediment-plate monitoring sites within the Firth of Thames.

5.1 Observations

Analysis of the sediment-level dataset indicates that sedimentation (accretion) is occurring at 7 sediment-plate monitoring sites within Whāingaroa (Raglan) Harbour (Figure 16) and at 11 sediment-plate monitoring sites within the Firth of Thames (Figure 17).

In Whāingaroa (Raglan) Harbour (Figure 16), SAR at 2 plates, both of which are at the same monitoring site, exceeded the ANZECC guideline value (Townsend and Lohrer, 2015) of 2.2

mm/y estimated for the Waikato region (Hunt, 2019b). In the Firth of Thames (Figure 17), SAR at 7 plates across 2 of the monitoring sites exceeded the same ANZECC guideline value. Of note are the sites where there is an ongoing trend of erosion in both Whāingaroa (Raglan) Harbour and the Firth of Thames.

5.2 Processes

Notwithstanding the lack of supporting hydrodynamic data and typically complex interactions between sediment supply, hydrodynamics and estuarine morphology, the following conclusions can be made:

1. Persistent erosion (negative SAR) (where observed) is likely due to a reduction in catchment sediment supply in a historical context. Large amounts of sediment were supplied to both the Firth of Thames and Whāingaroa (Raglan) Harbour during the peak of historical catchment disturbance, but the sediment supply is now likely reduced, and the legacy sediments are being reworked and deposited elsewhere in the estuary or offshore. This is not necessarily a positive indicator of environmental change, but rather a small reduction of a significantly large historical sediment input and a subsequent redistribution of the considerable amount of sediment already deposited in the respective estuaries. Further monitoring will help determine if these erosional trends constitute ongoing removal of legacy sediments or arise from alternating cycles of erosion and accretion in dynamic equilibrium over the longer term.
2. Stable bed level (zero or very small SAR) (where observed) may be due to either:
    a. Reduced sediment supply resulting in limited or no sediment deposition.
    b. Steady sediment supply but waves and/or tidal currents preventing deposition. Sediment prevented from depositing is likely to deposit elsewhere in the estuary or be flushed offshore.
3. Persistent sediment accumulation (positive SAR) (where observed) is due to an ample supply of sediment and hydrodynamics and morphology that favour deposition. The accumulating sediment could be a combination of contemporary and legacy sediments.
4. It is known that sediment can accumulate rapidly outside of the WRC SOE monitoring sites, notably in the southern Firth of Thames mangroves.

5.3 Recommendations

Further targeted hydrodynamic data collection and numerical modelling will help understand basic patterns of circulation and wave distribution in both Whāingaroa (Raglan) Harbour and the Firth of Thames. The following is reccomended:

- Measurements of tides, waves and suspended-sediment concentrations and calibrated / validated hydrodynamic models, which would be relatively easy to initiate using data already held by WRC.
- An understanding of contemporary sediment inputs into the Firth of Thames and Raglan Harbour.

Finally, a comparison of estuary-wide remote-sensed elevations will help determine if the measurements of SAR at the WRC monitoring sites are representative of each estuary.

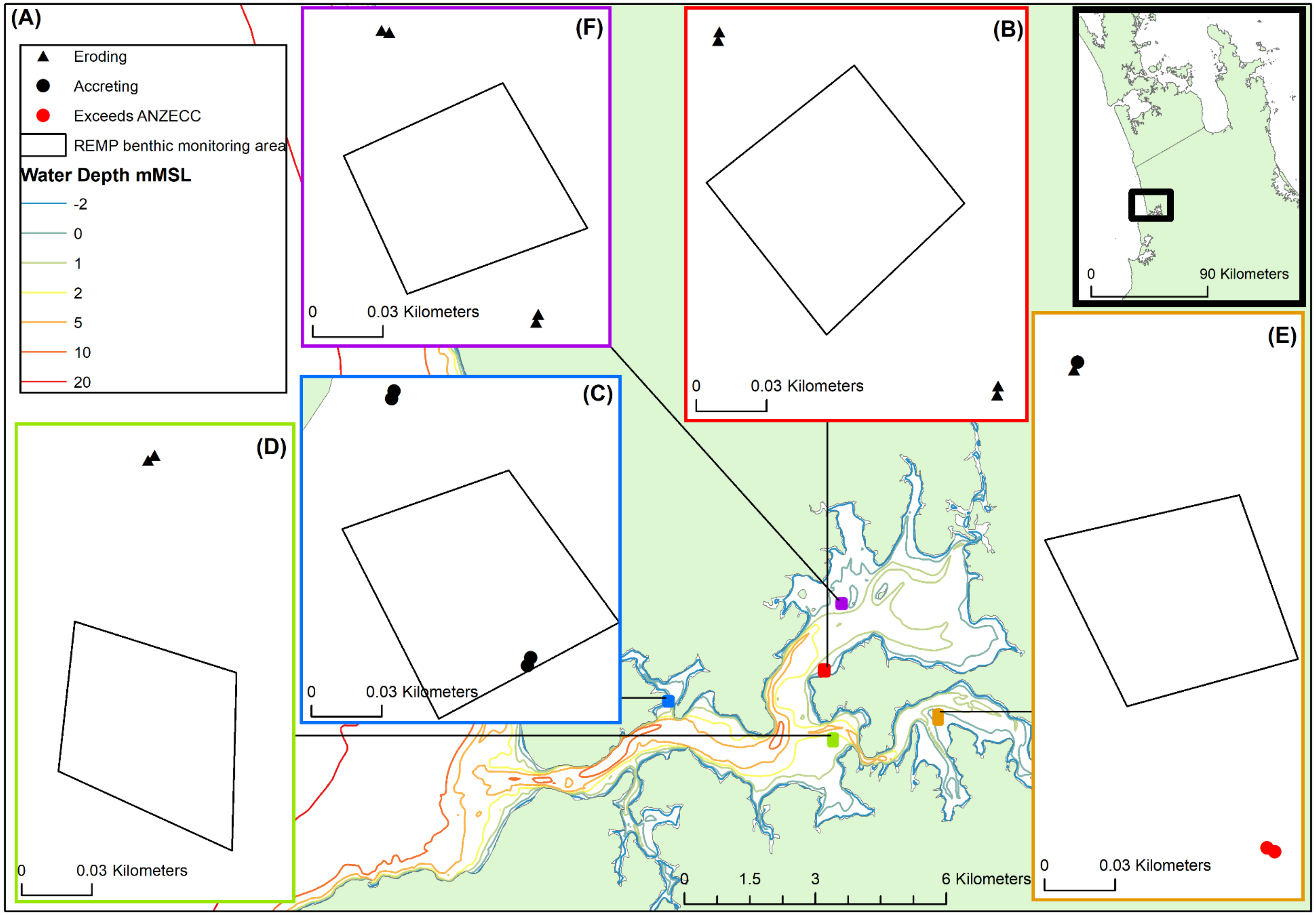

Figure 16. Whāingaroa (Raglan) Harbour location map showing WRC sediment plate locations and WRC REMP benthic monitoring areas (A). Map insets show Te Puna Point (B), Ponganui Creek (C), Okete Bay (D), Haroto Bay (E) and Whatitirinui Island (F). Note that Okete Bay only has two sedimentation plates, all other sites have four plates. The sedimentation trends estimated from the trend line fitted to the sediment level data are shown for each plate, accretion indicates that sediment deposition and therefore sedimentation is occurring over the plate, it is also shown where the SAR exceeds ANZECC guidelines. Depth contours are from Waikato regional bathymetry compiled by Gardiner and Jones (2020).

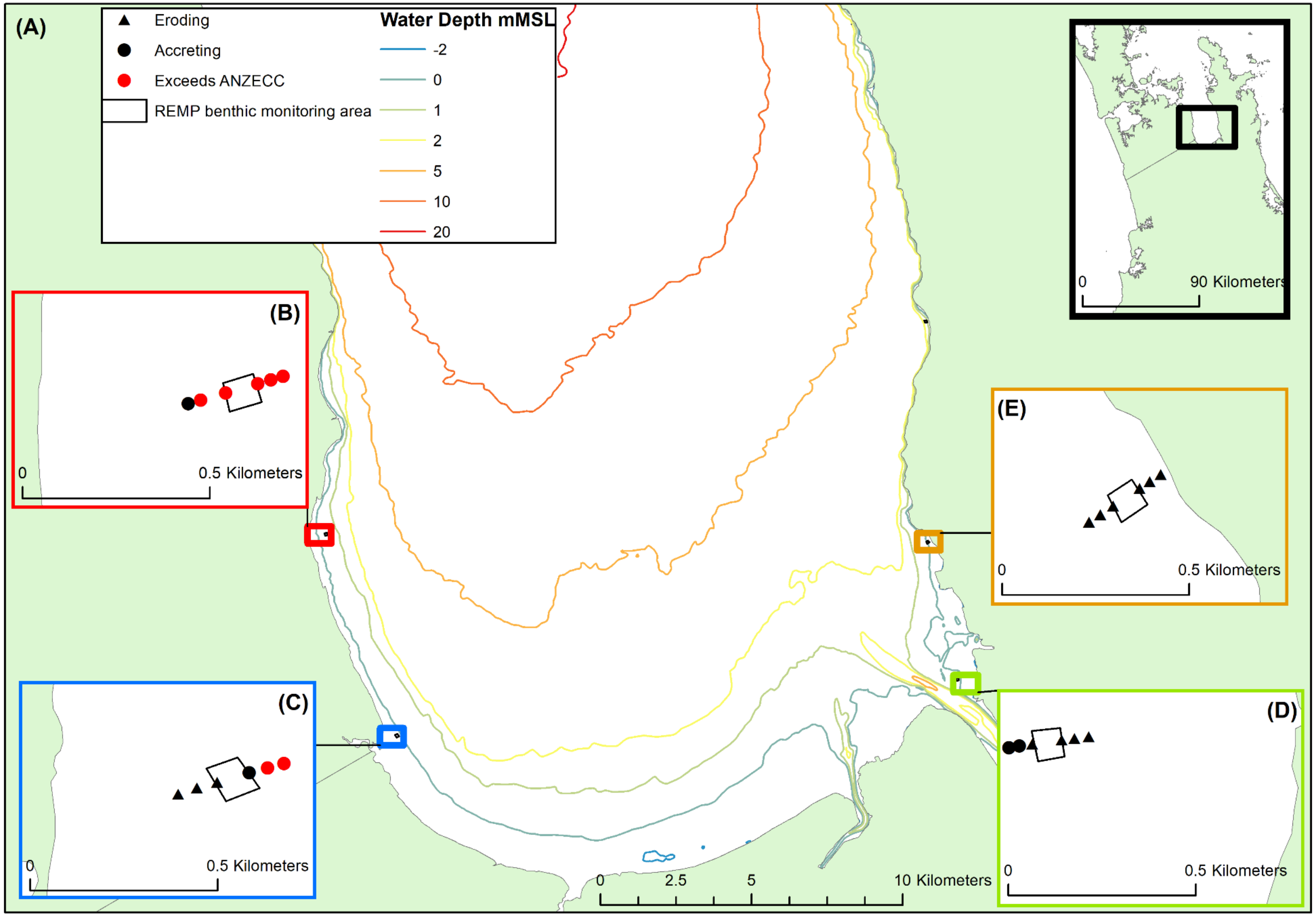

Figure 17. Firth of Thames location map (A) showing WRC sediment plate locations and WRC REMP benthic monitoring areas (A). Map insets show Kaiaua (B), Miranda (C), Gun Club (D) and Kuranui Bay (E). The sedimentation trends estimated from the trend line fitted to the sediment level data are shown for each plate, accretion indicates that sediment deposition and therefore sedimentation is occurring over the plate, it is also shown where the SAR exceeds ANZECC guidelines. Depth contours are from Waikato regional bathymetry compiled by Gardiner and Jones (2020).

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