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Summary of historic estuarine sedimentation measurements in the Waikato region and formulation of a historic baseline sedimentation rate

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Abstract

Sedimentation within estuaries is a natural process but excessive sedimentation can lead to poor ecological health. Current guidance suggests that sediment accumulation rates (SAR) should not exceed 2 mm/yr above pre-catchment disturbance SAR. Thus, in order to put contemporary measurements of estuarine sedimentation in context, the background rate of sedimentation prior to catchment modification is required. Historic sedimentation data has been collected using cores throughout various estuaries in the Waikato Region and this report uses the historic SAR to formulate (i) an understanding of changes in SAR through time and (ii) establish an appropriate pre-catchment disturbance SAR. This research indicates that estuarine SAR pre-catchment disturbance was low in magnitude and varied little between locations both between estuaries and within the same estuary. The reason for this low variability and magnitude of SAR was the small input of sediment into estuaries in the Waikato Region. With little sediment availability, sedimentation rates appeared to have been low regardless of the estuarine morphology or hydrodynamic environment. Following human settlement, both the magnitude and variability of sedimentation increased and available evidence indicates that this increase is primarily due to catchment disturbance and the associated increase in sediment supply to the estuaries. Using this historic sedimentation data, a pre-catchment disturbance SAR of 0.2 mm/yr has been determined for estuaries within the Waikato Region. Based on the historical SAR and current sedimentation guidance, contemporary SAR should therefore not exceed 2.2 mm/yr in estuaries within the Waikato Region.

1 Introduction

Although sedimentation is a natural process, sedimentation rates in estuaries have accelerated in response to a range of anthropogenic impacts and contemporary sedimentation rates are higher than rates prior to human settlement. Lower sedimentation rates prior to European and Polynesian settlement reflect a time when New Zealand's catchments were intact and dominated by native forests. Current guidelines on sedimentation seek to use both contemporary and historic sedimentation rates to determine allowable limits for an estuary, or part of an estuary.

Guidance documents (Townsend and Lohrer, 2015; Sea Change, 2017) recommend an acceptable contemporary sediment accumulation rate (SAR) relative to a historic baseline, with the historic baseline being the SAR that occurred when the catchment was undisturbed pre-human settlement. The current acceptable contemporary Sediment Accumulation Rate (SAR) is thought to be no more than 2 mm/yr above the historic baseline. In this context, the term "acceptable contemporary SAR" is defined as a SAR where it is anticipated that damage to the community of macrobenthic organisms is avoided.

To obtain historic SAR for the Waikato Region, sediment cores have been previously collected from estuaries and subjected to different dating methods by various researchers. The purpose of this report is to collate and summarise this sediment accumulation data and assess the spatial and temporal coverage throughout the estuaries of the Waikato Region. This will determine the viability for establishing a historical baseline against which WRC contemporary sedimentation measurements can be assessed.

Specifically, this report will address the following:

1. Identify all data describing historic SARs in the Waikato Region and their period of coverage.
2. Assess the reliability of the historic SARs.
3. Assess the temporal and spatial coverage of historic SAR and the ability to adequately characterise a pre-catchment modification SAR against which a contemporary monitoring network can be established.
4. Derive an appropriate SAR for use as a historic baseline in the Waikato Region.
5. Identify any data gaps and therefore priority areas in which coring effort should be directed in the future.

2 Methods for calculating SAR

Sediment cores have been collected in estuaries around the Waikato Region since the late 1970s and different dating methodologies have been employed depending on cost, study aims and available technology. This section briefly reviews the various methods.

2.1 Pollen

The type of pollen present in a core can reflect the vegetation cover within the estuary catchment such as the presence of native forest, pasture or plantations such as pine. If the vegetation type has changed in the catchment and the dates of change known, then the presence or absence of pollen in specific sediment layers can be used to calculate SAR between different periods of history. Although the analysis of pollen assemblages in sediment cores is a simple and effective way of measuring historical sedimentation there are a number of crucial limitations that can impact on the final calculations of SAR. Firstly, there is sometimes a delay between the planting of a vegetation type within the catchment and the production of pollen by the plant (Swales *et al*., 2005a). Secondly, different pollen types are transported, deposited, reworked and degraded in different ways by different physical processes such as wind, freshwater flow and tides thus influencing the final assemblage observed in the sediment core (Hume and Dahm, 1992). Bioturbation by benthic organisms can also result in vertical mixing of the pollen through the seabed surface sediments and therefore modify the pollen record (Hume and Dahm, 1992). Furthermore, incomplete or inaccurate historical records of land use change can also hinder the accurate dating of pollen in sediment. Because of these potential inaccuracies it is preferential to support pollen analysis with an independent absolute dating method.

2.2 Caesium-137

Caesium-137 (^{137}Cs) is a radioactive isotope that was first introduced in New Zealand due to atmospheric nuclear tests in the Pacific in 1953 and subsequently in 1955-1956 and 1963-1964. ^{137}Cs will be deposited both directly into the estuary and also on the catchment soils which are then subsequently eroded and washed into the estuary. Due to the combination of direct (into the estuary) and indirect (from eroding catchment soils) delivery of ^{137}Cs, a peak concentration is difficult to detect in New Zealand estuaries and precludes dating of sediment layers. However the absolute depth of ^{137}Cs can be used to determine the depth of the initial ^{137}Cs release and therefore the depth of the sediments deposited in 1953 (Swales *et al*., 2005a).

2.3 Lead 210

Lead-210 (^{210}Pb) is a naturally occurring radioactive isotope with a half-life of 22.3 years and can be used for measuring sedimentation that has occurred over the last c. 120 years (Chagué-Goff *et al*., 2000). As Radon gas in the atmosphere decays, it creates ^{210}Pb which accumulates in estuarine sediments (Swarzenski, 2015). ^{210}PB decays with age as it is buried through sedimentation so that ^{210}Pb concentration decreases with depth below the seabed and with the age of the sediment. Therefore the date of sediment deposition can be determined based on the concentration profile of ^{210}Pb through a sediment core (Swarzenski, 2015). Bioturbation by benthic organisms and physical processes such as waves and tides can mix seabed surface sediments, modify the resultant vertical distribution of Lead 210 and therefore influence the calculated rate of SAR (Bentley et al., 2014).

2.4 Radiocarbon dating (Carbon-14)

Following the death of an organism Carbon-14 (^{14}C) decays at a known rate, enabling the date of death to be determined. ^{14}C dating can be used on plant and animal remains older than 500 years up to a limit of 50,000 years Before Present (BP) with present defined as 1950 (Jull and Burr, 2015). In estuarine sediments, shell is typically used for ^{14}C dating (e.g. Hume and Dahm, 1992). Inaccuracies in dating can result from shell being transported and redeposited from elsewhere in the estuary, this can be avoided by selecting intact shells that have not been abraded (Hume and Dahm, 1992). Error can also be introduced by sampling from the shell of organisms that have burrowed through the sediment prior to death resulting in an underestimation of the sediment age at the same depth as the shell (Swales *et al*., 2005a).

3 Sedimentation from cores

A literature review of all known peer reviewed journals, student theses, WRC (and the predecessors to the WRC) technical reports and commercial research identified a range of coring studies across estuaries in the Waikato Region (Figure 3.1, Table 3.1). These studies were collected and analysed by different researchers and for different purposes, and as such the dating terminology is inconsistent. To make the SAR data comparable an attempt has been made to standardise the data in terms of epochs as follows:

Early estuarine formation
This period refers to SAR during the period of marine transgression (rapid sea level rise) and subsequent elevated sea levels following the last glaciation between 14,000 and 10,000 yrs BP (Stevens, 1985).

Pre-human
This refers to SAR following the period of marine transgression and elevated sea levels when sea levels and shelf sea oceanographic conditions were similar to those encountered today.

Polynesian
This is the period following settlement by Maori c. 1300 AD.

Early European
This is the period following initial settlement by Europeans and generally represents a period of large scale deforestation, mining and catchment clearance for settlement and farming. This epoch generally represents the period c. 1890 – 1945 AD.

Late European
This period can be difficult to separate from the early European epoch but typically represents a period of pine plantation post 1945 AD.

Contemporary
This is also difficult to separate from the other European epochs but represents the most recent information from the cores if available. This epoch is SAR post c. 1980.

SAR presented in the source material do not fall cleanly into these epochs as many of the cores do not identify all of these epochs and/or some of these epochs were not represented within a given catchment. Therefore a degree of judgment has been used when assigning the SAR to a given epoch and the actual dates obtained from the core sediments have been included in brackets to show the date range over which the SAR was based (Table 3.1). SAR have also been summarised as a series of time series plots, classified according to contemporary estuarine environment (Figure 3.2) and estuary name (Figure 3.3). The date format used in the source material varied and was standardised to an arbitrary date format of “years before 2018” to make the SAR comparable between the different studies. If dates in the source material were expressed as years before present (conventionally defined as 1950 AD), a quoted date of 20 yrs BP is converted to 88 yrs before 2018. If dates in the source material were expressed as a calendar year, a quoted date of 1930 is also converted to 88 yrs before 2018. To plot a representative data point, the SAR was plotted against average year before 2018 within the date range that the SAR represented. For example if the SAR represented sediment deposited between 1000 and 1500 years before 2018, the SAR data were plotted with the x-axis point located at 1250 years before present with error bars extending between 1000 and 1500 years to show the actual date range.

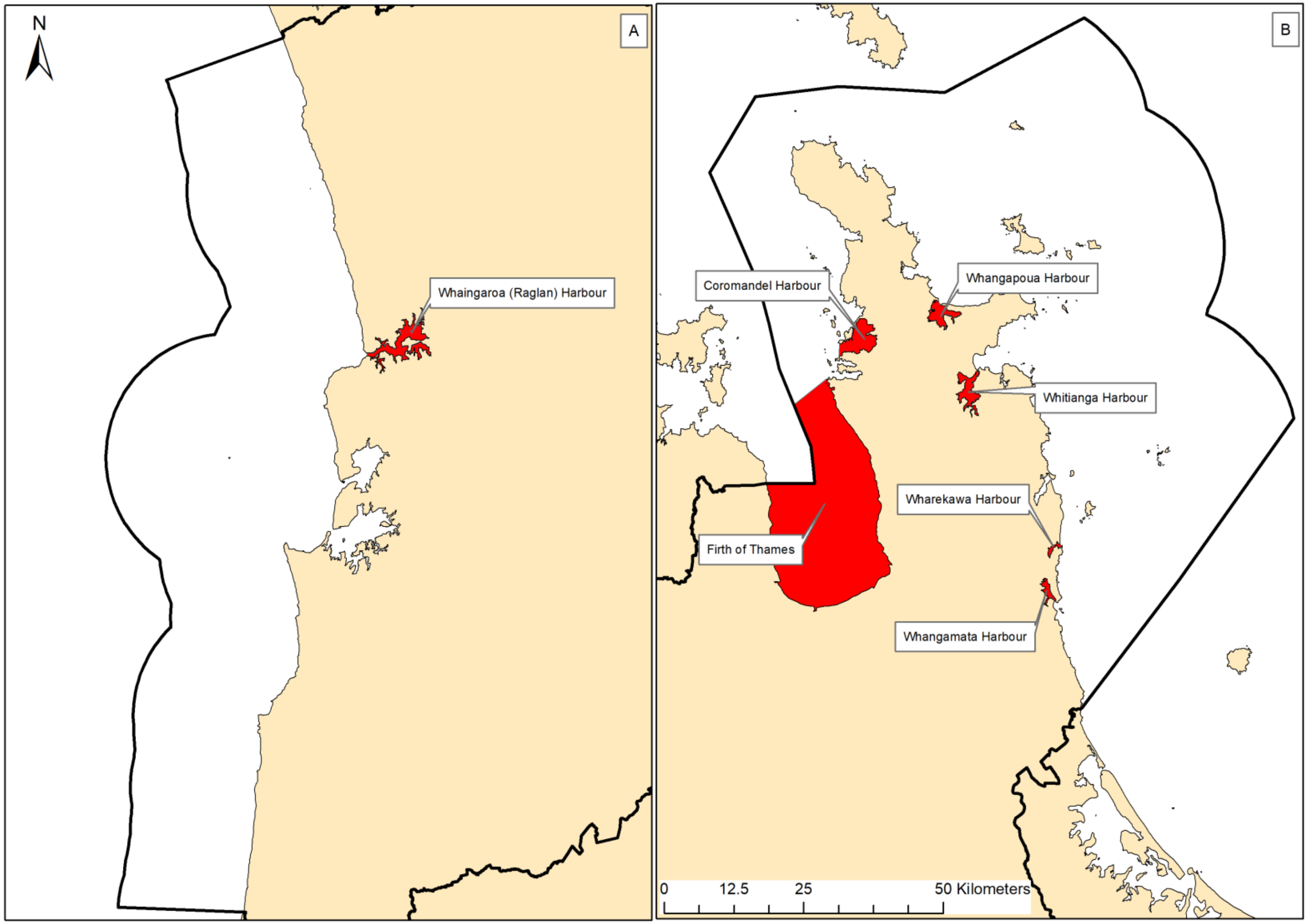

Figure 3.1 Estuaries where cores have been collected for measuring historic SAR on the west (A) and Coromandel coasts (B).

Table 3.1 Summary of estuaries and available sedimentation records in the Waikato region.

Estuary	Classification (Hume *et al.*, 2016)		Summary of sedimentation measurement methodology	Contemporary Environment	Core ID from report	Sedimentation rates (mm/yr)						References
	Geomorphic class	Geomorphic subclass				Early estuarine formation	Pre-human	Polynesian	Early European	Late European	Contemporary	
Whaingaroa (Raglan) Harbour	Shallow drowned valley	N/A	Radioisotopes (caesium-137 and lead-210), Pollen and Radiocarbon (C^{14}) dating.	Intertidal	Core 12B		0.35 (post 7900 yr BP from C^{14})		1.1 (post 1890 from pollen) 5.0 (post 1890 from lead-210, less reliable than pollen in this case)		2.5 (post 1990 from pollen)	Swales et al. (2005a).
				Intertidal	Core 1A						4 (post 1990 from pollen)	
				Intertidal	Cores 2B and 6A		0.34 (post 6300 yr BP from C^{14}, 1 core only)					
				Intertidal	Cores 10B		0.5 (post 7900 yr BP from C^{14})				8 (post 1990 from pollen)	
			Radioisotopes (caesium-137, lead-210 and beryllium-7). Introduced tracer (Magnetite sand layer).	Intertidal	Cores 1, 2 and 3						2.5 (year range not known, not included on Figures)	Bentley et al. (2014).
Coromandel Harbour	Shallow drowned valley	N/A	Pollen and Radiocarbon (C^{14}) analysis from sediment cores.	Intertidal	Core C1	0.52 (6500-6420 yr BP) 0.09 (6420-5010 yr BP)	0.02 (5010-700 yr BP)	0.07 (700 yr BP– 1830 AD)	0.82 (1830-1988 AD)			Hume and Dahm (1992) (incorporates and supersedes analysis of same cores by McGlone (1989a))
				Subtidal	Core C2		0.07 (3510-700 yr BP)	0.05 (700 yr BP-1830 AD)	0.31 (1830-1988 AD) N/A			
				Intertidal	Core C4		0.94 (1120 - 6/800 yr BP) 0.49 (2540-1790 yr BP) 0.49 (1790-1120 yr BP)	0.39-0.57 (6/800 – 160 yr BP)	1.01 (160 yr BP - ~1970 AD)		~11.7 (1970 – 1988 AD)	

			Pollen, pyritic layer dating (ASL) and Radiocarbon (C^{14}) analysis from sediment cores.	Intertidal	005		0.47 ± 0.03 (from C^{14}, pre 700 yr BP) 0.25 ± 0.02 (from C^{14} and pollen, pre 700 yr BP)	0.13 ± 0.04 (pollen, 700 yr BP – 1820 AD)	0.52 ± 0.25 (from pollen, 1820 – 2015 AD)			Harpur (2016).
				Subtidal	CH1		0.25 ± 0.01 (from ASL and pollen, pre 700 yr BP) 0.22 ± 0.04 (from ASL and C^{14}, pre 700 yr BP)	0.05 ± 0.05 (from pollen, 700 yr BP – 1820 AD)			10.37 ± 1.8 (~1975-2015 inferred from sediment thickness)	
				Subtidal	CH2						3.52 ± 0.62 (~1975-2015 inferred from sediment thickness)	
				Subtidal	CH3	0.45 ± 0.08 (7500 – 7130 yr BP)	0.23 ± 0.03 (from C^{14} and ASL, 7130 – 700 yr BP)				4.98 ± 0.88 (~1975-2015 inferred from sediment thickness)	
				Subtidal	CH5		0.22 ± 0.01 (from C^{14}, pre 700 yr BP)				2.2 ± 0.66 (~1975-2015 inferred from sediment thickness)	
				Subtidal	CH7	0.31 ± 0.01 (7500 – 5000 yr BP)	0.1 ± 0.02 (from C^{14} and pollen, 5000 – 700 yr BP)	0.07 ± 0.07 (from pollen, 700 yr BP – 1820 AD)	0.77 ± 0.26 (from pollen, 1820 - 2015)			
				Subtidal	CH9						3.94 ± 0.7 (~1975-2015 inferred from sediment thickness)	
				Subtidal	CH10		1.8 ± 0.21 (from C^{14}, pre 700 yr BP) 0.22 ± 0.09 (from C^{14}, pre 700 yr BP).					

Firth of Thames	Deep drowned valley	N/A	Pollen and radiocarbon analysis from sediment cores.	Subtidal	T1A		0.09 (3170-700 yr BP)	0.13 (700 yr BP– 1850 AD)	0.50 (1850-1950 AD)	0.53 (1950 – 1988 AD)		Hume and Dahm (1992) (incorporates and supersedes analysis of same cores by McGlone (1989a)).
				Subtidal	T2A		0.18 (1380-700 yr BP)	0.07 (700 yr BP – 1988 AD)				
				Subtidal	T4	1.30 (3130 – 2720 yr BP) 1.46 (2720 – 2440 yr BP)	0.10 (2440 – 700 yr BP)	0.38 (730 yr BP – 1850 AD)	1.50 (1850-1950 AD)	1.3 (1950 – 1988 AD)		
				Mangrove	LC3				21 (1923 – 1953 AD)	57 (1953 – 1969 AD)	8 (1969 – 2005 AD)	Swales et al. (2007a).
				Mangrove	LC4				22 (1938 – 1964 AD)	100 (1964 – 1972 AD)	12 (1972 – 2005 AD)	
				Mangrove	LC5				10 (1926 – 1960 AD)	46 (1960 – 1984 AD)	7 (1984 – 2005 AD)	
				Mangrove	LC6				12 (1946 – 1963 AD)	108 (1963 – 1969 AD)	4 (1969 – 1994 AD) 71 (1994 – 2005 AD)	
				Mangrove	LC7				8 (1939 – 1964 AD)	33 (1964 – 1992 AD)	56 (1992 – 2005 AD)	
				Mangrove	LC8					25 (1954 – 1983 AD)	53 (1983 – 2005 AD)	
				Mangrove	LC9				20 (1948 – 1977 AD)	49 (1977- 1993 AD)	211 (1993 – 1995 AD) 19 (1995 - 2005 AD)	
				Intertidal	LC10				8 (1879 – 1967 AD)	87 (1967 – 1973 AD) 9 (1973 – 1991 AD)	90 (1991 – 1993 AD) 13 (1993 – 2005 AD)	
				Intertidal	LC11				11 (1919 – 1983 AD)		31 (1983 – 2005 AD)	
				Intertidal	LC12						25 (1977 – 2005 AD)	
				Subtidal	21	0.4 (3580 – 1170 yr BP)	1.8 (1170 – 750 yr BP)	0.3 (750 – yr BP – 1987 AD)				Naish (1990)
				Subtidal	31	1.9 (2370 yr BP – 1987AD)						
				Subtidal	40	2.0 (4260 – 2590 yr BP)	0.66 (2590 yr BP – 1987 AD)					
				Subtidal	37	1.0 (4960 – 2740 yr BP) 0.75 (2740 – 1750 yr BP)	0.14 (1750 yr BP – 1987 AD)					
				Intertidal	T200						43 (1996 – 2006 AD)	Zeldis et al. (2015), also reported by Swales et al., (2007b) but without detailed description of SAR.
				Intertidal	T400						36 (1994 – 2006 AD)	
				Intertidal	T600						26 (1990 – 2006 AD)	

				Intertidal	T800						27 (1990 – 2006 AD)	
				Intertidal	T1000						26 (1990 – 2006 AD)	
			Radioisotopes (caesium-137, lead-210 and beryllium-7) and Radiocarbon (C^{14}) dating.	Intertidal	FT-1			0.69 (1313/28 – 1870 AD)	2.9 (1870 – 1963 AD)	18.5 (1963 – 1974 AD)	10.1 (1974 – 2015)	Swales et al., 2016.
				Intertidal	FT-2			0.43 (1134/36 – 1906 AD)	5.6 (1906 – 2015 AD)			
				Subtidal	FT-3				3.4 (1924 – 2015 AD)			
				Subtidal	FT-4		0.9 (80/290 – 1037/42 AD)	0.2 (1037/42 – 1924 AD)	6.7 (1924 – 2015 AD)			
Whangapoua Harbour	Tidal lagoon	Permanently open	Pollen and radiocarbon (C^{14}) dating.	Intertidal	W1A	0.50 (6500 – 5890 yr BP)	0.03 (5890 – 4000 yr BP)	0.13 (700 yr BP – 1850 AD)	1.3 (1850 – 1960 AD)	0.89 (1960 – 1988 AD)		Hume and Dahm (1992) (incorporates and supersedes analysis of same cores by McGlone (1988)).
				Intertidal	W2B	0.13 (4000 – 1060 yr BP)	0.08 (1060 – 700 yr BP)	0.12 (700 yr BP – 1850 AD)	1.5 (1850 – 1950 AD)	1.33 (1950 – 1988 AD)		
Whitianga Harbour	Tidal lagoon	Permanently open	Pollen	Intertidal	1A			0.89 (600 yr BP – 1850 AD)	1 (1850 – 1970 AD)		9.11 (1970 – 1988 AD)	McGlone (1988).
				Intertidal	2A			0.43 (600 yr BP – 1850 AD)	1.1(1850 – 1950 AD)	12 (1950 – 1970 AD)	4.4 (1970 – 1988 AD)	
			Radioisotope (lead-210) dating.	Intertidal	A					31 (Pre 1950 AD)	4.9 (1950 – 2007)	Reeve (2008)
				Intertidal	C						4.9 (1950 – 2007)	
				Intertidal	D					21.6 (Pre 1950 AD)	8.2 (1950 – 2007)	
				Intertidal	E					30.3 (Pre 1950 AD)	9.6 (1950 – 2007)	
Wharekawa Harbour	Tidal lagoon	Permanently open	Pollen and radiocarbon (C^{14}) dating.	Intertidal	WH1			0.6 (385 yr BP – 1945 AD)	5.8 (1880 – 1945 AD)	28.5 (1945 – 1975 AD)	8 (1975 – 1995 AD)	Swales and Hume (1995)
										20.3 (1945 – 1995 AD)		
				Intertidal	WH2			0.80 (354 yr BP – 1880 AD)	7.2 (1880 – 1945 AD)	3.5 (1945 – 1995 AD)		
				Intertidal	WH3	0.11 (7525 yr BP – 1880 AD)			3.6 (1880 – 1945 AD)	8.2 (1945 – 1995 AD)		
				Intertidal	WH4						8 (1975 – 1995 AD)	
				Intertidal	WH5		0.10 (4137 yr BP – 1880 AD)		4.9 (1880 – 1945 AD)	5.3 (1945 – 1995 AD)		

Whangamata Harbour	Tidal lagoon	Permanently open	Radioisotope (^{210}Pb), Pollen and radiocarbon analysis from sediment cores.	Intertidal	Causeway	0.06 (6710 – 1140 yr BP)		0.28 (1140 yr BP – 1940 AD)		11 (1940 – 1990 AD)	Sheffield (et al., 1995).
				Intertidal	Boat ramp	ND	ND	ND	18 (1920 – 1940 AD)	19.8 (1940 – 1990 AD)	
				Intertidal	Sandflats		0.35 (3000 – 1300 yr BP)	0.31(1300 yr BP – 1940 AD)		6.6 (1940 – 1990 AD)	
			Pollen and radiocarbon (C^{14}) dating.	Intertidal	W1	0.14 (6590 yr BP – 1940 AD)				5 (1940 – 1994 AD)	Swales and Hume (1994)
					W2	0.18 (6990 yr BP – 1940)				5 (1940 – 1994 AD)	
					W3	0.17 (7240 yr BP – 1940)				5 (1940 – 1994 AD)	
					W4	0.10 (5360 yr BP – 1940)				5 (1940 – 1994 AD)	

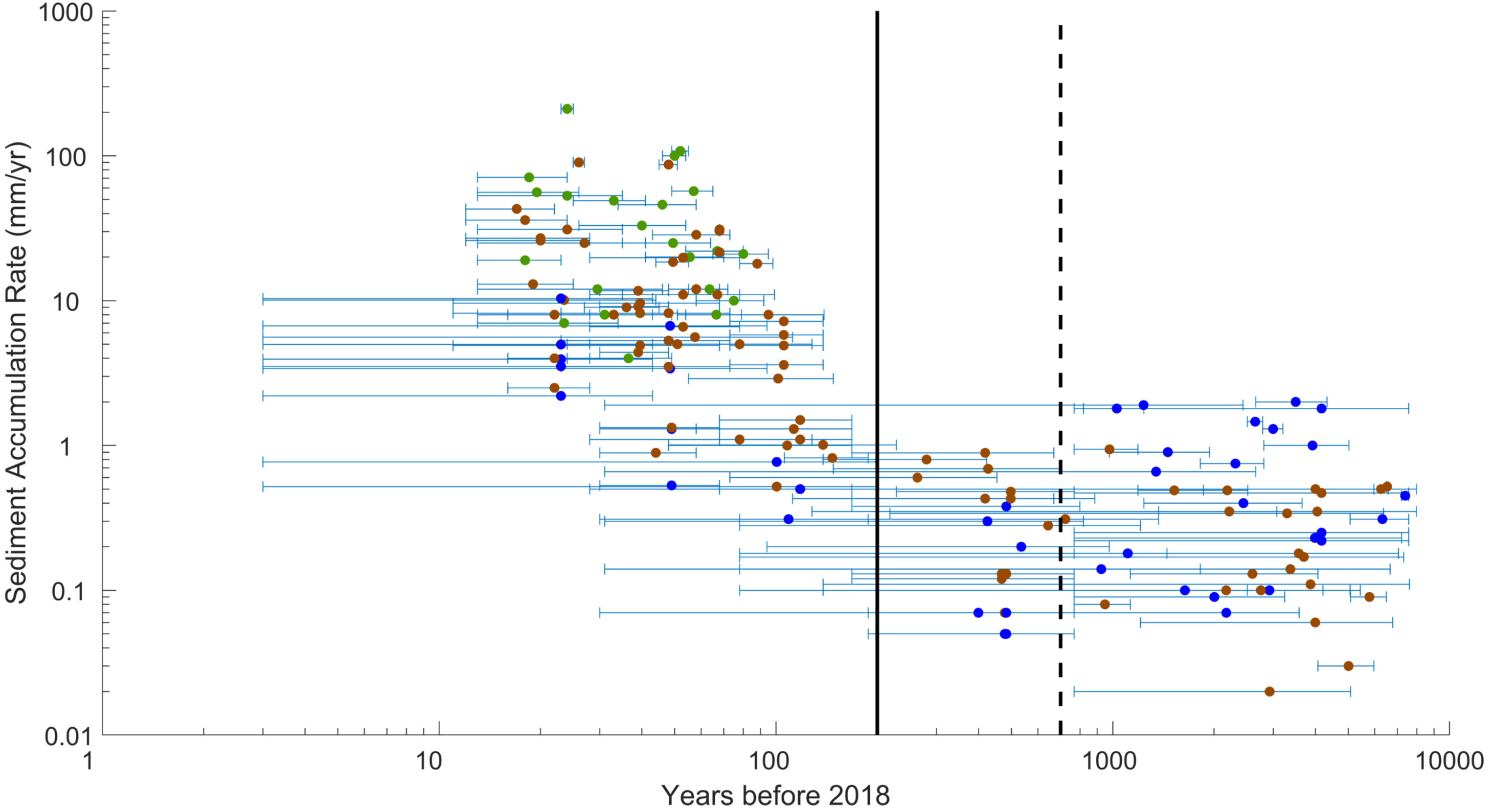

Figure 3.2 Historic sediment accumulation rates differentiated by contemporary environment in the Waikato region.

The error bars show the date range over which SAR is calculated and the dots show the average date. The colour of each dot shows the contemporary environment in which the core was collected: brown denotes intertidal; blue denotes subtidal; and green denotes mangroves. The solid black vertical line shows the approximate date of European settlement and the dashed black vertical line shows the approximate date of Polynesian settlement.

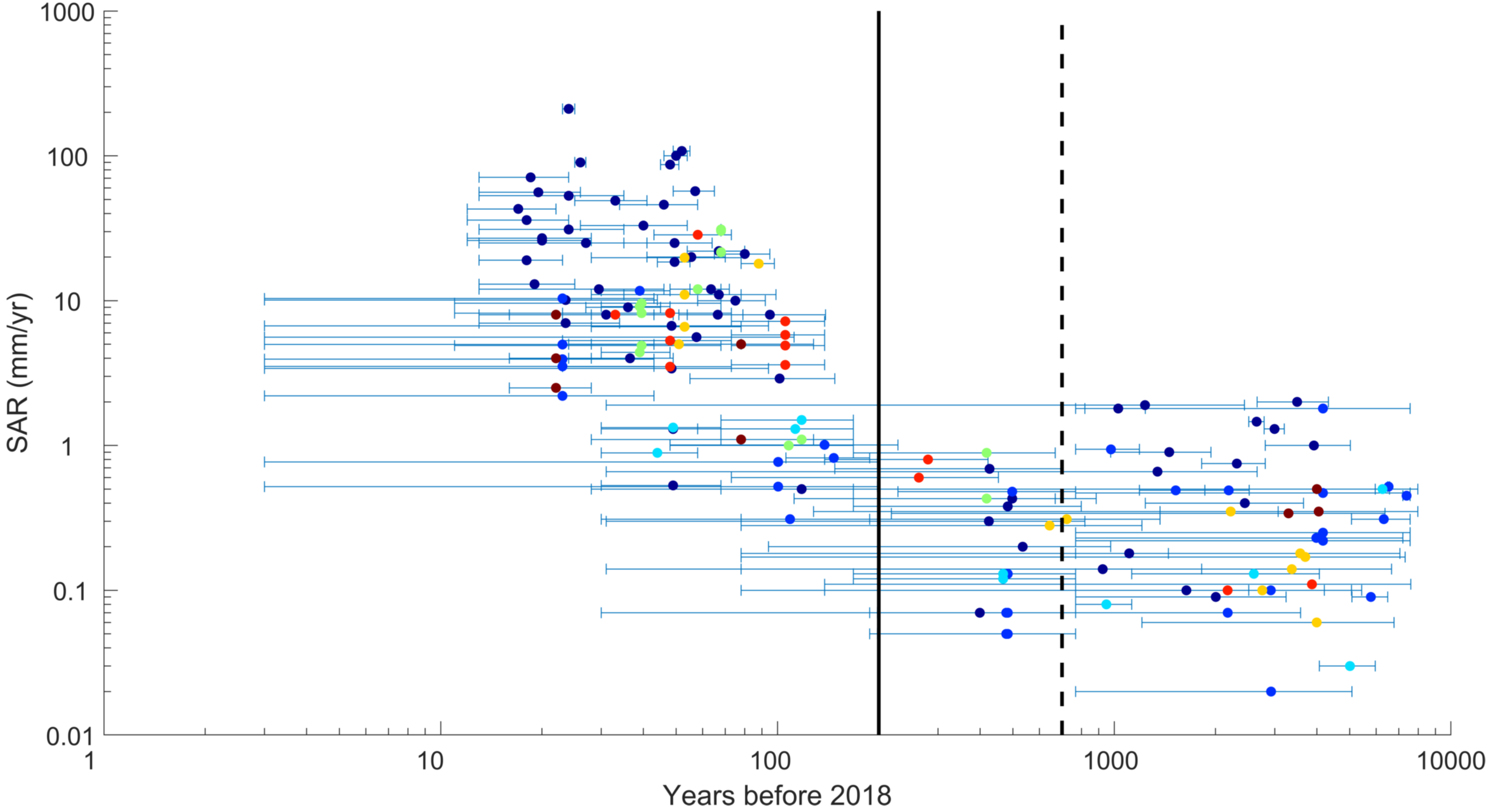

Figure 3.3 Historic sediment accumulation rates differentiated by estuaries within the Waikato region.

The error bars show the date range over which SAR is calculated and the dots show the average date. The colour of each dot shows the estuary in which the core was collected (see Figure 3.1 for estuary locations), dark blue denotes Firth of Thames, blue denotes Coromandel Harbour, cyan denotes Whangapoua, green denotes Whitianga, orange denotes Whangamata, red denotes Wharekawa and brown denotes Whaingaroa (Raglan). The solid black vertical line shows the approximate date of European settlement and the dashed black vertical line shows the approximate date of Polynesian settlement.

4 Discussion

There is a wide range of data on historic SAR in the Waikato, with 61 cores collected from 7 estuaries (Table 3.1, Figures 3.1 and 3.3). The majority of studies use more than one technique to assess SAR (Table 3.1) which increases the reliability of the information. The exception to this is Whitianga Harbour, with two studies: one study using only pollen analysis (McGlone, 1988) and the other only ^{210}Pb (Reeve, 2008). Comparison between these studies is difficult because they have been collected in different locations and at different times, with c. 20 years between them, in addition to differences in the time periods over which SAR have been calculated. The SARs estimated from these two studies are notably different and it is difficult to attribute these differences solely to spatial and temporal factors or to determine which study is more reliable. Such discrepancies reinforce the importance of using multiple dating techniques when measuring historic SAR in sediment cores and this should be adopted as standard practice.

The cores collected in the Waikato Region are dominated by measurements of more recent sedimentation, i.e. post human settlement (Table 3.1 and Figure 3.2), which is due to two main reasons. Firstly, more recently deposited sediments are easier to collect as they are closer to the current sediment surface. In areas of high contemporary sediment accumulation, e.g. the Firth of Thames with SARs of ~100 mm yr^{-1}, most sediment corers are not long enough to reach sediments deposited earlier than c. 200 years ago. Secondly the most widely applicable dating techniques (^{137}Cs and ^{210}Pb) can only be used for the recent historical period. To characterise baseline sedimentation rates, i.e., those sediments deposited before human settlement, a combination of ^{14}C and pollen analysis is required. Both of these depend on the identification of suitable material in the core which can be expensive and not always possible. However, these methods provide an indication of the sedimentation rates during pre-human catchment conditions, and thus provide critical information. If WRC collects further cores, pre-human sedimentation rates should be identified as a priority.

Inevitably the cores are also limited in their spatial extent. This limitation is due to the high cost of coring, the complexity of the different estuarine systems (e.g. dendritic with multiple embayments or arms) and the relatively large size of the Waikato coastal marine area. It is difficult to quantify the spatial limitations of these cores and to determine if the coverage is sufficient to establish background sediment rates but some general conclusions can be drawn about patterns and rates of historical sedimentation.

4.1 Causes of historical changes in sedimentation rates

Sedimentation occurs due to a combination of sufficient sediment supply and favourable hydrodynamics that allow the deposition of the supplied sediment in the coastal and estuarine environment. The amount of sediment supplied from the catchment will vary with natural processes such as fluctuations in rainfall (Grant, 1985) as well as anthropogenic influence such as vegetation clearance in the catchment (McGlone, 1989b). Patterns of deposition and erosion within an estuary will be modified by changes in sea level, changes to the wind and wave climate and even by the changes to the morphology following deposition of the sediment (Hunt et al., 2015).

The separation in time of natural and human influences is of relevance to the establishment of a baseline sedimentation rate. A suitable baseline sedimentation rate should not be influenced by anthropogenic activities whilst still being represented by a period of similar natural environmental conditions as the present day. For example, there is no point in using conditions from when the sea-level was much lower than present to establish a baseline, because it would be impossible to establish whether the lowered sea or anthropogenic change was the cause of different sedimentation rates. The sediment cores all show subtly different patterns due to the availability of dateable material within each core and therefore the dating and SAR averaging interval. Despite these limitations, there is a coherent general pattern of SAR and estuarine development which is common to most estuaries in the Waikato Region. In some cores, there is evidence of an initial elevated SAR which likely occurred in response to processes of early estuarine formation: in the Waikato Region sea levels increased following the last glaciation until reaching present day mean sea level prior to 7240 yr BP (Clement *et al*., 2016). Sea levels then rose a further 2m above present day sea levels at around 4000 yr BP before dropping to approximately present day levels by around 1000 yrs BP (Dougherty and Dickson, 2012; Clement *et al*., 2016). It is likely that this increased sea level resulted in increased accommodation space in unfilled estuaries that would have resulted in flood-dominant currents and a rapid filling from marine sediments as sea levels rapidly rose post-glaciation (e.g. Hume and McGlone, 1986; Hume and Dahm, 1992). The relatively small amount of catchment derived sediments would also have been retained within the estuary (Harpur, 2016). This infilling likely continued until the morphology stabilised at a steady rate of infilling in quasi-equilibrium with sediment input from the catchment. Depending on the rate of sediment input and the initial morphology of the estuarine basin, the timing at which the SAR stabilised would have varied. It is this lower steady rate of SAR that is of greatest relevance for determining a baseline sedimentation rate for an estuary. This reflects a period where SAR is no longer accelerated because of initial estuarine development and sea level rise, and is yet to accelerate as a result of catchment modification and increased sediment runoff from the land.

There is some evidence that sea level has continued to fluctuate over the last 1000 years in the South Pacific due to the end of the “Little Climatic Optimum” and the onset of the “Little Ice Age” (Nunn, 1998). This climatic transition may have resulted in an approximate drop in sea level of 0.75 m between 680 and 625 yr BP and a further drop of 0.4 m between 495 – 475 yr BP (Nunn, 1998; Nunn 2000a; Nunn 2000b), dates which coincide with the settlement of New Zealand by Maori. Although these changes of ~ 1 m are insignificant over geological time periods, they are significant in comparison to the hydrodynamic regime of a meso-tidal or micro-tidal estuary regime such as in the Waikato Region and therefore warrant consideration in the context of the identified sedimentation trends. Changes in sea level would directly influence the duration of inundation time during a tidal cycle with some areas that were periodically inundated during high tide becoming permanently dry except during extreme events. Changes in sea level can influence processes controlling sediment transport and deposition such as tidal propagation, estuarine circulation, estuarine salinity, tidal asymmetry, wave generation and the ability of waves to erode the seabed. A temporary increase in rainfall has also been associated with the transition period between the relatively dryer Little Climatic Optimum and Little Ice Age (Nunn, 1998) and this has been associated with historic catchment erosion events throughout the Pacific (Nunn, 2000a; Nunn, 2000b). Coastal environmental change as a result of the onset of the Little Ice Age has been theorised for a range of coastal environments throughout the Pacific (Nunn, 2000a; Nunn 2000b) but the impact on New Zealand estuarine environments and specifically rates of sedimentation are not known.

Following human settlement there is a general increase in SAR over time (Figure 3.2) and pollen analysis indicates that this increase occurs at the same time as successive catchment modification by firstly Maori and then by European settlers. Activities such as deforestation, mining, forestry and agriculture can enhance erosion of sediment within the estuary catchment and this sediment is then washed into rivers and deposited in the estuary. Maori cleared forest for agriculture throughout New Zealand using fire (King, 1984; McGlone, 1989b) although in the coastal areas of the Waikato Region the extent of deforestation appears to be only small (McGlone, 1983; McGlone, 1989b; Nunn, 1994; Harrison, 1998). The small extent of catchment clearance likely accounts for generally low levels of sedimentation during this time period. The increase in SAR is more marked following European settlement and this increase is related to the larger scale and extent of catchment clearance and modification following European settlement in the coastal areas of the Waikato region (Nunn, 1994; McGlone, 1983; McGlone, 1989b; Harrison, 1988). Deforestation (burning, driving dams, kauri gum digging), mining (deforestation, spoil movement), agriculture and exotic forestry have also contributed to enhanced sediment runoff during this time period with impacts varying both spatially and temporally throughout the region (Harrison, 1988; Jones, 2008).

An archetypal example of estuarine sedimentation through time is shown in the SAR recorded within the Whangapoua cores: with high initial SAR during early estuarine formation (~0.50 mm yr^{-1}), lower SAR pre-human settlement (~0.03 – 0.08 mm yr^{-1}), slightly elevated SAR post Polynesian settlement (~0.13 mm yr^{-1}) and highly elevated SAR post-European settlement (0.89 – 1.5 mm yr^{-1}) (Table 3.1). This example illustrates that the SAR pre-human settlement is the most relevant choice for a 'background' or baseline estimate of sedimentation rate. This sedimentation rate represents the period from which sea levels were relatively stable and therefore the wider oceanographic conditions were broadly equivalent with contemporary conditions and is representative of an unmodified catchment.

Exceptions to the general increase in SAR following human settlement have occurred with the lowest SAR measured during Polynesian settlement for the Firth of Thames and Coromandel Harbour (Table 3.1 and Figure 3.3). The reasons for this could be that the SAR averaging period pre-human settlement covers both the early estuarine sedimentation stage and the late stage and thus inclusion of the earlier period results in average SAR biased towards higher sedimentation rates. It is also possible that the Firth of Thames and Coromandel Harbour took longer to infill post glaciation and continued to infill at rapid rates up until around the time of Polynesian settlement. It is further conceivable that sedimentation rates during this period were influenced by the possible changes in sea level and rainfall experienced during the Little Ice Age although it is unclear why other estuaries in the Coromandel would not have been similarly affected. The largest reductions in SAR during Polynesian settlement compared to pre-human settlement occur in the data collected by Harpur (2016) in Coromandel Harbour although there is evidence of this of this phenomena recorded by other studies in Coromandel Harbour and the Firth of Thames (Naish, 1990; Hume and Dahm, 1992; Swales et al., 2016). Harpur (2016) notes that the SAR from the Polynesian epoch is based on limited data and therefore probably underestimates SAR during the Polynesian settlement epoch. Considering the uncertainty surrounding the cause and timing of the SAR within the region, it is conservative for baseline conditions of sedimentation to be considered as the lowest SAR period, irrespective of whether this occurs within the pre-human or Polynesian epoch.

4.2 Identification of suitable core records

Hydrodynamics and sediment transport processes differ over intertidal and subtidal areas (Green et al., 1997; Hunt et al., 2015). For this reason separate intertidal and subtidal baseline sedimentation rates have been derived based on cores collected in either contemporary intertidal (Table 4.1) or subtidal environments (Table 4.2).

Table 4.1 Summary of sediment cores used to formulate baseline rates in intertidal areas, bold italics signify the baseline value adopted.

Estuary name	Core ID	Early estuarine formation	Pre-human	Polynesian	Early European	Late European	Contemporary	Reference
Whaingaroa (Raglan Harbour)	Core 12B	***0.35 (post 7900 yr BP)***			1.1 (post 1890) 5.0 (post 1890)		2.5 (post 1990)	Swales et al. (2005a).
	Core 2B	ND	***0.34 (post 6300 yr BP)***	ND	ND	ND	ND	
	Core 10B	***0.5 (post 7900 yr BP)***					8 (post 1990)	
Coromandel Harbour	Core C1	0.52 (6500-6420 yr BP) 0.09 (6420-5010 yr BP)	***0.02 (5010-700 yr BP)***	0.07 (700 yr BP–1830 AD)	0.82 (1830-1988 AD)			Hume and Dahm (1992) (incorporates and supersedes analysis of same cores by McGlone (1989a))
	Core C4		0.94 (1120 - 6/800 yr BP) ***0.49 (2540-1790 yr BP)*** ***0.49 (1790-1120 yr BP)***	0.39-0.57 (6/800 – 160 yr BP)	1.01 (160 yr BP - ~1970 AD)		~11.7 (1970 – 1988 AD)	
	005		0.47 ± 0.03 (pre 700 yr BP) 0.25 ± 0.02 (pre 700 yr BP)	***0.13 ± 0.04 (700 yr BP – 1820 AD)***	0.52 ± 0.25 (1820 – 2015 AD)			Harpur (2016)
Whangapoua	W1A	0.50 (6500 – 5890 yr BP)	***0.03 (5890 – 4000 yr BP)***	0.13 (700 yr BP – 1850 AD)	1.3 (1850 – 1960 AD)	0.89 (1960 – 1988 AD)		Hume and Dahm (1992) (incorporates and supersedes analysis of same cores by McGlone (1988)).
	W2B	0.13 (4000 – 1060 yr BP)	***0.08 (1060 – 700 yr BP)***	0.12 (700 yr BP – 1850 AD)	1.5 (1850 – 1950 AD)	1.33 (1950 – 1988 AD)		
Wharekawa	WH3	***0.11 (7525 yr BP – 1880 AD)***			3.6 (1880 – 1945 AD)	8.2 (1945 – 1995 AD)		Swales and Hume (1995)

	WH5		***0.10 (4137 yr BP – 1880 AD)***		4.9 (1880 – 1945 AD)	5.3 (1945 – 1995 AD)	
Whangamata	Causeway	***0.06 (6710 – 1140 yr BP)***		0.28 (1140 yr BP – 1940 AD)		11 (1940 – 1990 AD)	Sheffield (et al., 1995).
	Sandflats		***0.35 (3000 – 1300 yr BP)***	0.31(1300 yr BP – 1940 AD)		6.6 (1940 – 1990 AD)	
	W1	***0.14 (6590 yr BP – 1940 AD)***				5 (1940 – 1994 AD)	Swales and Hume (1994)
	W2	***0.18 (6990 yr BP – 1940)***				5 (1940 – 1994 AD)	
	W3	***0.17 (7240 yr BP – 1940)***				5 (1940 – 1994 AD)	
	W4	***0.10 (5360 yr BP – 1940)***				5 (1940 – 1994 AD)	

Table 4.2 Summary of SAR used to formulate baseline rates in subtidal areas, bold italics signify the value adopted in the core record.

Estuary name	Core ID	Early estuarine formation	Pre-human	Polynesian	Early European	Late European	Contemporary	Reference
Coromandel Harbour	Core C2		0.07 (3510-700 yr BP)	***0.05 (700 yr BP-1830 AD)***	0.31 (1830-1988 AD) N/A			Hume and Dahm (1992) (incorporates and supersedes analysis of same cores by McGlone (1989a))
	CH1		0.25 ± 0.01 (pre 700 yr BP) 0.22 ± 0.04 (pre 700 yr BP)	***0.05 ± 0.05 (700 yr BP – 1820 AD)***			10.37 ± 1.8 (~1975-2015)	Harpur (2016).
	CH2						3.52 ± 0.62 (~1975-2015)	
	CH3	0.45 ± 0.08 (7500 – 7130 yr BP)	***0.23 ± 0.03 (7130 – 700 yr BP)***				4.98 ± 0.88 (~1975-2015)	
	CH5		***0.22 ± 0.01 (pre 700 yr BP)***				2.2 ± 0.66 (~1975-2015)	
	CH7	0.31 ± 0.01 (7500 – 5000 yr BP)	0.1 ± 0.02 (5000 – 700 yr BP)	***0.07 ± 0.07 (700 yr BP – 1820 AD)***	0.77 ± 0.26 (1820 - 2015)			
	CH10		1.8 ± 0.21 (pre 700 yr BP) ***0.22 ± 0.09 (pre 700 yr BP).***					
Firth of Thames	T1A		***0.09 (3170-700 yr BP)***	0.13 (700 yr BP–1850 AD)	0.50 (1850-1950 AD)	0.53 (1950 – 1988 AD)		Hume and Dahm (1992) (incorporates and supersedes analysis of same cores by McGlone (1989a)).
	T2A		0.18 (1380-700 yr BP)	***0.07 (700 yr BP – 1988 AD)***				
	T4	1.30 (3130 – 2720 yr BP) 1.46 (2720 – 2440 yr BP)	***0.10 (2440 – 700 yr BP)***	0.38 (730 yr BP – 1850 AD)	1.50 (1850-1950 AD)	1.3 (1950 – 1988 AD)		
	21	0.4 (3580 – 1170 yr BP)	1.8 (1170 – 750 yr BP)	***0.3 (750 – yr BP – 1987 AD)***				Naish (1990)

	31	1.9 (2370 yr BP – 1987AD)				
	40	2.0 (4260 – 2590 yr BP)	***0.66 (2590 yr BP – 1987 AD)***			
	37	1.0 (4960 – 2740 yr BP) 0.75 (2740 – 1750 yr BP)	***0.14 (1750 yr BP – 1987 AD)***			
	FT-4		0.9 (80/290 – 1037/42 AD)	***0.2 (1037/42 – 1924 AD)***	6.7 (1924 – 2015 AD)	Swales et al., 2016.

Contemporary measurements of sedimentation over intertidal areas exhibit a large variability in SAR between sampling locations (Pickrill, 1979; Hunt et al., 2016) (Figures 3.2). However, this magnitude of variability is a relatively recent phenomena and appears to have accompanied the large sediment influx and associated regime shifts that occurred following human modification of the catchment (Figure 3.2). Prior to catchment modification, although the relative variability in SAR over intertidal areas was still large (c. 25 times), the actual magnitude of the variability was very low (0.02 – 0.5 mm/yr, $\bar{x}$ = 0.21 mm/yr, s = 0.16 mm/yr) due to the small amount of sediment available in the system (Table 4.1).

Baseline rates of subtidal sedimentation are harder to estimate because subtidal cores that measure pre-human SAR have only been collected in Coromandel Harbour and the Firth of Thames (Table 4.2). The data in Coromandel Harbour shows that subtidal SAR is similar or slightly less than intertidal SAR. In the Firth of Thames we only have data to compare contemporary subtidal and intertidal SAR and this comparison also shows that subtidal SAR is less than intertidal SAR (Table 3.1, Figures 3.2 and 3.3). As for intertidal areas, the historic SAR is variable in a relative sense (c. 13 times) but the actual variability in SAR is very low (0.05 – 0.66 mm/yr, $\bar{x}$ = 0.18 mm/yr, s = 0.16 mm/yr) due to the low amounts of sediment supplied to the estuaries from the catchment pre-human influence.

4.3 Validation of approach

It is important to reiterate that the use of sediment cores to establish baseline sedimentation rates is problematic because, regardless of catchment condition, the contemporary estuarine and oceanographic environment where the core was collected is unlikely to be representative of the historic estuarine environment that existed during the time that the sediment was deposited. Significant amounts of sediment have been deposited since human settlement in New Zealand and deposition of sediment distorts the tide, modifies the propagation and development of waves and channelises flow. Areas that are now intertidal could have formerly been subtidal at the time that the sediment was deposited in the core. Furthermore there is evidence for changes in sea level that are comparable to the contemporary tidal range (Gibb, 1986; Nunn, 1998; Dougherty and Dickson, 2012; Clement et al., 2016) throughout the time period that the core record covers. The net result of these morphological and hydrodynamic changes through time is that the environment and the SAR observed in the core may not necessarily be representative of the contemporary environment and therefore may not be a suitable baseline SAR to use as a management target. However, as the overall magnitude of variability of historic pre-human SAR observed in both subtidal and intertidal cores is low and the cores have been collected in a range of morphological environments, it is possible to establish representative rates of pre human settlement SAR. Furthermore, the contrast in the relative variability of sedimentation rates pre and post human settlement, indicates that although the influence of natural variations in rainfall, sea level or estuarine morphology are important, the clearance of the catchments by humans appears to have had a proportionally a far greater impact on sedimentation rates within estuaries.

Overall, setting a baseline SAR based on the available core record depends on a single major assumption, that because sediment input was low pre-human settlement, regardless of the location within the estuary (and the spatial variability of hydrodynamic and morphological characteristics), the overall magnitude of sedimentation would have also been low and therefore similar to the SAR identified in the cores already collected. If this assumption is true, then it is possible to set a representative baseline SAR for the Waikato Region based on the existing core records already collected. This assumption can be tested by comparing the representative SAR calculated here with historical sedimentation rates calculated elsewhere in New Zealand in a range of different estuary types with differing catchment characteristics and estuarine hydrodynamics (Table 4.3).

Table 4.3 Summary of historic SAR in New Zealand estuaries outside of the Waikato.

Estuary name	Contemporary environment	Number of cores	Pre-human settlement SAR (mm/yr)		Reference	Notes
			Range	Average		
Mahurangi Estuary	Intertidal	2	0.3 – 0.6	0.4	Swales et al. (1997); Oldman et al. (2009)	
	Mangrove	1	0.8	0.8		
Wellington Harbour	Subtidal	6	0.11 – 0.9	NA	Goff (1997)	Excludes core SB-1.
Pauatahanui estuary	Subtidal	2	0.7 – 1.2	1	Swales et al. (2005b)	
Pakuranga Estuary	Intertidal	2	0.2 – 0.5	NA	Swales et al. (2002).	
Lucas Creek, Waitemata Harbour	Intertidal	Unknown	1.5	NA	Hume and McGlone (1986)	Includes early estuarine sedimentation and probably an overestimation
Pelorus Sound	Subtidal	6	0.2 - 0.85	0.5	Handley et al. (2017)	
Whangapoua Estuary (Great Barrier Island)	Intertidal	7	0.18 (± 0.09) - 0.39 (± 0.32)	NA	Ogden et al. (2006)	
Maungamaungaroa Estuary	Intertidal	2	0.04 – 0.14	0.01	Oldman and Swales (1999)	
Bay of Islands	Intertidal and subtidal	8	0.11 – 0.43	0.23	Swales et al. (2012)	

The intertidal sedimentation rates measured in estuaries outside of the Waikato Region typically range between 0.04 and 0.6 mm/yr and these sedimentation rates compare favourably with those recorded in the Waikato Region. Given the variations in catchment geology, estuary type, oceanographic conditions and climate in addition to the variety of water depths and estuarine environments sampled, this similarity validates the assumptions made here in selecting an appropriate baseline sedimentation rate.

5 Conclusions and recommendations

Pre-human SARs have been recorded in 16 intertidal locations within 5 estuaries (Whaingaroa (Raglan), Coromandel Harbour, Whangapoua, Wharekawa and Whangamata). In subtidal areas, SAR has been recorded at 15 locations in 2 estuaries (Coromandel Harbour and the Firth of Thames). Although the SAR pre-catchment clearance is variable, the magnitude of this variability is very low ($s = 0.16$ mm/yr).

Based on these results a generic baseline sedimentation rate of 0.2 mm/yr can be adopted for all estuaries in the Waikato region based on the average SAR across all cores (0.21 mm/yr in intertidal areas and 0.18 mm/yr in subtidal areas). This chosen SAR is an appropriate guideline based on an average of the lower values of recorded historic SAR in each core and therefore is consistent with the aspirational ethos of the Sea Change guidance.

Based on the historical baseline SAR and the Sea Change guideline sedimentation rate, contemporary SAR should therefore not exceed 2.2 mm/yr in the Waikato Region.

Theoretically further core data could refine this historic sedimentation rate for specific locations within estuaries, but in reality the practical value of this core data is limited in the context of setting a historic baseline SAR. Further coring is highly likely to reflect the trends identified here and therefore the considerable expenditure involved in collecting this data is not justified. The benefits of coring in the same place as a contemporary monitoring location are limited because the estuarine environment has changed through time. Changes include eustatic sea level, local morphology (due to sediment deposition) and water depth. These changes in water depths and morphology influence patterns of tidal propagation and wave generation, sediment transport rates and ultimately patterns of erosion and deposition. The result is that the contemporary estuarine environment differs greatly from that recorded in the sediment cores. Therefore the approach taken here derives representative baseline sedimentation rates from a range of cores collected in a variety of estuarine environments rather than trying to derive a specific sedimentation rate from a certain core at a particular geographical location.

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