Tauranga Harbour Sediment Study: Harbour bed sediments

NIWA Client Report: HAM2008-123
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Prepared for

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Executive Summary

Environment Bay of Plenty (EBOP) seeks to understand sedimentation in Tauranga Harbour in order to appropriately manage growth and development now and in the future and adapt management rules and practices appropriately and be able to make decisions concerning development of the harbour and catchment with full understanding of likely sedimentation effects. EBOP contracted NIWA to conduct the Tauranga Harbour Sediment Study to: (1) assess the relative contributions of catchment sediment sources surrounding the southern Tauranga Harbour, 2) assess the characteristics of significant sediment sources from the catchment, and (3) investigate the fate (dispersal and deposition) of catchment sediments in southern Tauranga Harbour.

This report is Technical Report C1 of the Tauranga Harbour Sediment Study. It documents the data discovery process for sediment grainsize statistics (including mean, sorting and skewness), sediment composition (percent mud <63 µm, sand 63 µm – 2 mm, and gravel >2 mm) and patterns of sediment accumulation rate in southern Tauranga Harbour. It provides the most comprehensive summary of those data for the harbour. These data are being used for: (1) choosing grainsizes to be simulated during the modelling component of the Tauranga Harbour Sediment Study, (2) initialising bed sediment composition for the harbour sediment-transport model and USC-3 sedimentation model, and (3) end-of-chain model validation of sedimentation rates predicted by the USC-3 model.

For the purpose of the modelling the southern Tauranga Harbour was divided into 26 subestuaries. Subestuaries are km-scale compartments of the harbour with common depth, hydrodynamic exposure and bed-sediment grainsize and are the fundamental units at which predictions are made by the USC-3 sedimentation model. They primarily include intertidal areas where fine sediments are deposited. The subestuaries were initially delineated on the basis of a conceptual understanding of harbour processes. This categorisation was refined following analysis of the sediment data. An extensive literature search identified 40 studies, some 26 of which contained potentially useful sediment data. The data, once screened for applicability and quality, identified about 300 samples with useful information on grainsize statistics and 600 samples with information on gravel/sand/mud percentage. The data were assimilated in ArcGIS along with hydrodynamic and geomorphologic information to describe and map the mean bed-sediment properties of each subestuary. This information is required to set up and run the harbour sediment-transport model and for initialising the USC-3 sedimentation model.

The sediment data were combined with a conceptual understanding of hydrodynamic, geomorphological and catchment processes that affect sedimentation, to group subestuaries into 11 categories. These categories identify areas of similar sediment types and geomorphology and where similar sediment processes (transport, dispersal and deposition, resuspension) of similar intensity (wave and tidal energy) occur. Categorisation is a first step towards translating the sediment data into initial conditions for the USC-3 sediment model.

Sediment accumulation rate determined for various locations in the harbour provides information on where sediments are building up and rates of sediment accumulation over the past 90 years. This information will be used to validate sediment accumulation predictions by the USC-3 model. There was little information available from existing studies, so 10 subestuaries were selected for coring. Coring was undertaken and sediments dated by radioisotope techniques. X-radiographs (x-rays) of the cores revealed the fine-scale sedimentary fabric of the sediments, providing information on depositional processes, sediment texture. Importantly, it also provided information on disturbance by animal burrowing (bioturbation) and/or physical stirring by waves. This information was also used to prioritise which cores to date and exactly where to take subsamples of sediment from the cores for radioisotope analysis. Sediment cores were dated using radioisotopes of caesium (^{137}Cs) and lead (^{210}Pb) and sediment accumulation rates calculated from the vertical concentration-activity profiles of ^{210}Pb and ^{137}Cs. Concentrations of the cosmogenic radioisotope berrylium (^{7}Be, with a ½ life of 53 days) were also measured in the core samples to provide information on the depth and intensity of sediment mixing in the surface-mixed layer, so as to identify those cores where the sediments were least likely to be disturbed by bioturbation and physical mixing (as mixing corrupts the sediment accumulation rate data derived from the dating). Detailed radioisotopic dating was undertaken on 6 cores. Sediment accumulation rates on tidal flats in the subestuaries ranged from 0.75 to 1.57 mm/yr over periods of 23 to 90 years.

The sediment accumulation rates measured in southern Tauranga Harbour are low compared to other estuaries on the east coast of Auckland, the Firth of Thames and Pauatahanui inlet where NIWA has done similar measurements. The low rates and evidence of deep mixing in the surface sediments of the cores indicate that large areas of the wave-exposed intertidal flats in the southern Tauranga Harbour are not long-term sinks for fine terrigenous sediments. Potential depositional environments for sediment include tidal flats, tidal creeks, sheltered bays, mangroves and saltmarsh habitats. Sediment is also exported from the harbour to the inner shelf. These hypotheses need to be tested and reconciled against the results from the modelling components of this study.

1. Introduction

1.1 Background

Environment Bay of Plenty (EBOP) seeks to understand sedimentation in Tauranga Harbour in order to appropriately manage growth and development now and in the future and adapt management rules and practices appropriately and be able to make decisions concerning development of the harbour and catchment with full understanding of likely sedimentation effects. This need stems from section 5 of the Tauranga Harbour Integrated Management Study (THIMS), which describes the many effects of sediments. Although these changes are to a large extent driven by historical events when there was little control on development, there is increasing public concern about sediment-related issues, and these are expected to escalate as the catchment continues to develop and climate change becomes increasingly felt. The THIMS recommended a review of the drivers and consequences of sedimentation, including analysis of sediment yields from all sources in the catchment, peak flow monitoring, projection of sediment yields under proposed development scenarios, assessment of sediment effects in the harbour including cumulative effects, analysis of current best practices, and recommendations on how to address the findings, including appropriate policy.

EBOP contracted NIWA to conduct the Tauranga Harbour Sediment Study. The study began in April 2007 and is scheduled to run for 3 years. The main aim of the study is to develop a model or models to be used to: (1) assess the relative contributions of the various sediment sources in the catchment surrounding southern Tauranga Harbour, (2) assess the characteristics of significant sediment sources, and (3) investigate the fate (dispersal and deposition) of catchment sediments in southern Tauranga Harbour. The project area is defined as the southern harbour, extending from Matahui Point to the harbour entrance at Mount Maunganui. The timeframe for predictions is 50 years from the present day (2001-2050).

1.2 Study outline and modules

The study consists of 6 modules:

Module A: Specification of scenarios – Defines land use and weather that are required for driving the various models. Three scenarios are defined in terms of landuse, which includes earthworks associated with any development, and weather. The weather is described in terms of magnitude and frequency of storms and wind climate, and needs to be specified to a degree that is sufficient for driving models. The third scenario incorporates anticipated effects of climate change.

Module B: Catchment sediment modelling - (1) Uses the GLEAMS model to predict time series of daily sediment yields from each subcatchment under each scenario. (2) Summarises these predictions to identify principal sources of sediment in the subcatchment; to compare sources of sediment under present-day landuse and under future development scenarios; and to assess sediment characteristics of significant sources. (3) Provides sediment loads to the USC-3 model for prediction of harbour sedimentation over decadal scales.

Module C: Harbour bed sediments - (1) Develops a description of the harbour bed sediments to provide sediment grainsize and composition information required for running the harbour sediment-transport model and for initialising the USC-3 model. (2) Provides information on sedimentation rates over the past 50 years for end-of-chain model validation.

Module D: Harbour modelling - (1) Uses the DHI FM (Fexible Mesh) hydrodynamic and sediment models and SWAN wave model to develop predictions of sediment dispersal and deposition at the “snapshot” or event scale, including during and between rainstorms and under a range of wind conditions. (2) Provides these event predictions to the USC-3 model for extrapolation of harbour sedimentation over decadal scales.

Module E: USC-3 model - Uses the USC-3 sedimentation model to make predictions of sedimentation, bed-sediment composition and linkages between sources and sinks at decadal scales, based on division of the catchment into subcatchments and the estuary into subestuaries. An end-of-chain model validation will consist of comparing USC-3 model predictions of annual-average sedimentation rate to measurements, where the measurements derive from Module C.

Module F: Assessment of predictions for management – Assesses and synthesises information developed in the modelling components of the study using an expert panel approach. It will address matters including: (1) Which catchments are more important as priority areas for focusing resources to reduce sedimentation in the harbour?, (2) What are the likely effects of existing and future urban development on the harbour?, (3) How can the appropriate regulatory agencies (EBOP, WBPDC and TCC) most effectively address sedimentation issues, and what management intervention could be appropriate? and (4) Are there any reversal methods, such as mangrove control and channel dredging, that may be effective?

1.3 This report

This report is Technical Report C1 of the Tauranga Harbour Sediment Study and completes Module C and Milestone 5. It documents the data discovery process for sediment grainsize statistics (including mean, sorting and skewness), sediment composition (percentage mud, sand and gravel) and patterns of sediment accumulation rate (SAR) in the southern Tauranga Harbour. It provides the most comprehensive summary of those data for the harbour. These three sets of data are required for: (1) choosing grainsizes to be simulated during the modelling component of the Tauranga Harbour Sediment Study, (2) initialising bed sediment composition for the harbour sediment-transport model and USC-3 model, and (3) end-of-chain model validation of USC-3 sedimentation rates.

This report describes the division of the southern harbour into 26 compartments with similar physical properties, called subestuaries. It details the data discovery process for surficial sediment grainsize statistics (mean, sorting and skewness) and sediment composition (percent mud <63 µm, sand 63 µm – 2 mm, and gravel >2 mm) for each subestuary. These data were compiled from existing literature and a careful selection process was undertaken to ensure only comparable data were included. The sediment data are then interpreted together with a conceptual understanding of hydrodynamic, geomorphological and catchment processes to group the 26 subestuaries into 11 categories. The categorisation process is a first step towards translating the sediment data into model initial conditions. Finally the data discovery for sediment accumulation rate data is documented. The data discovery found little useful information and so field work (coring and dating of tidal flat sediments) was undertaken. A description of the methods used to select core sites, the coring process and radioisotopic analysis and dating of the cores to determine sediment accumulation rates is provided along with the results of the analyses.

2. Subestuary definition

The southern Tauranga Harbour was split into 26 subestuaries for the purpose of the modelling (Fig. 1). Subestuaries are km-scale compartments with common depth, hydrodynamic exposure and bed-sediment grainsize and are the fundamental units at which predictions are made by the USC-3 sedimentation model (Green, 2007). They primarily include intertidal areas where fine sediments are deposited. They exclude deep channels where there are strong currents because fine sediment does not deposit in these environments. The subestuaries were initially delineated on the basis of a conceptual understanding of harbour processes and the criteria described above at a meeting between NIWA and EBOP in Tauranga in September 2007. This categorisation was refined following analysis of the sediment data described below.

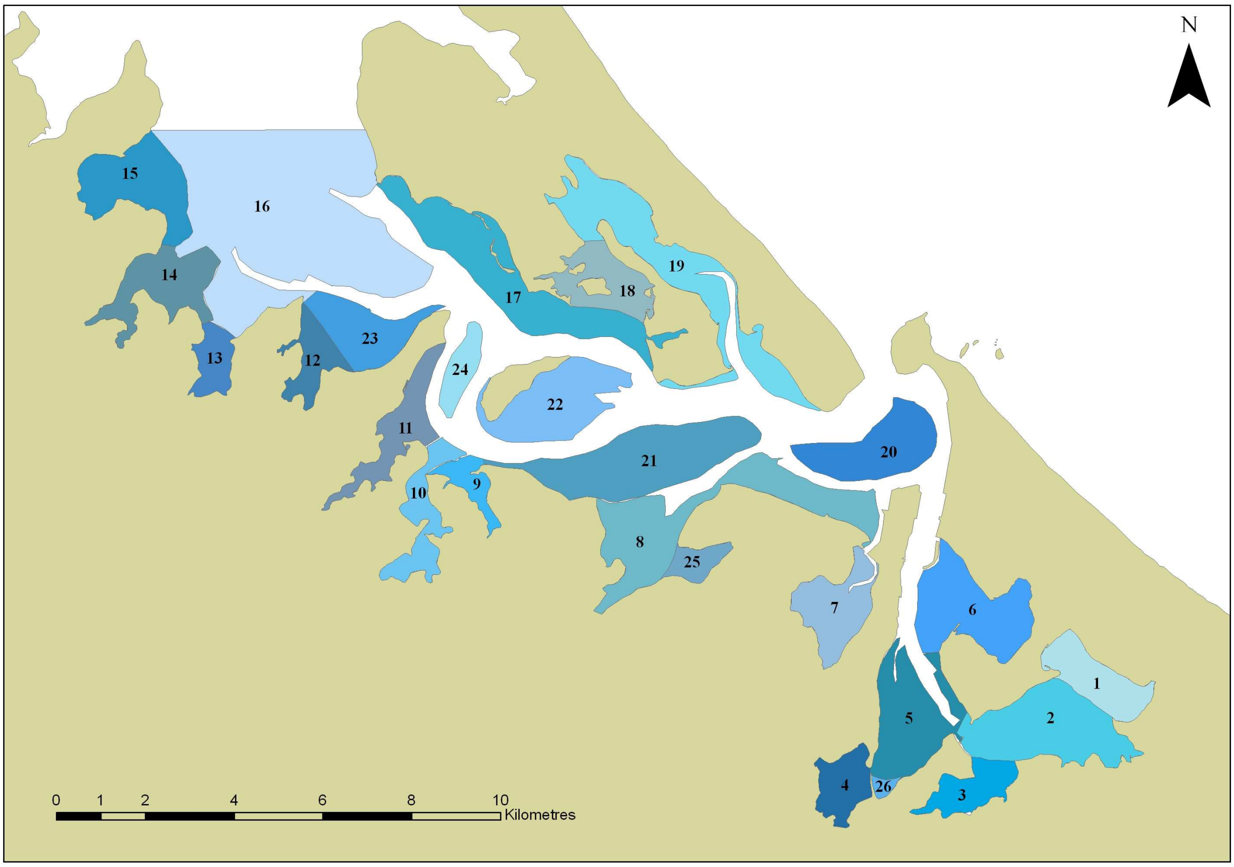

Figure 1: Southern Tauranga Harbour divided into 26 subestuaries.

2.1 Data discovery

An extensive literature search was undertaken to identify studies containing data on surface sediment grainsize statistics and sediment composition (percent gravel/sand/mud) in the southern Tauranga Harbour. Sources included Environment Bay of Plenty (EBOP) reports and monitoring records, student theses, published papers and unpublished reports. A total of 40 studies was reviewed (see Appendix 1), 26 of which contained data that were potentially useful for this study.

The data were assimilated in ArcGIS along with all available hydrodynamic and geomorphologic information. A selection process ensured chosen data were representative of a subestuary and comparable to other studies before being transferred to a Microsoft Access database for analysis. The results describe the mean properties of each subestuary.

2.2 Data selection and preparation

The grainsize statistics and composition data were wide ranging in terms of spatial extent and quality and were collected and analysed by a wide variety of methods. We screened the data carefully to ensure that only comparable data were assimilated into the database.

Data were excluded when:

1) There was a lack of information about collection methods or analysis techniques.

2) Samples fell outside subestuary boundaries (e.g., in deep channels).

3) Results appeared unrealistic considering the hydrodynamic environment they came from.

4) Only the mean grainsize was reported. All three grainsize statistics (mean, sorting and skewness) were needed in order to provide a complete picture of the sedimentation environment.

Data were included when:

1) Different sampling equipment was used in different studies (e.g., grab versus core), or the sediment was sampled to different depths, or different analysis techniques (such as sieving or laser measurements) were used, or when the sample was split before analysis.

2) Samples were collected a long time ago (sample collection dates ranged from 1976 to 2006, a 30-year time period) and there was the uncertainty that the sediment grainsize characteristics at the site may be different to that today.

3) Results from one study were very different to results from other studies in the same subestuary.

Samples from mid-tide level were selected as being most representative of a subestuary, particularly when there was large spatial variation in grainsize along or across a subestuary (due to hydrodynamic energy, or the presence of mangroves). Lone samples from very sheltered (causing the sediment to be finer than the subestuary average) or exposed (causing the sediment to be coarser than average) locations were not considered to be representative of a subestuary. In a few cases numerous samples from a subestuary (e.g., the studies by White, 1979, or Hope, 2002) provided an accurate picture of subestuary sediments.

Selection of data was facilitated by creating GIS shape files for each subestuary which contained the study name, location, and sediment data (composition and/or grainsize). The sample locations and sediment data were mapped in ArcGIS along with subestuary boundaries and on the hydrographic charts (to check channel and sand bank positions) and on high resolution colour aerial photographs (to check for mangroves or seagrass).

2.3 Studies selected for sediment description

Table 1 lists the 10 key studies used. The locations of the samples from those 10 studies are shown in Figure 2. Figure 3 distinguishes sites with grainsize statistics from those sites with composition data only.

Table 1: Studies used to describe surface sediment grainsize statistics and composition (gravel/sand/mud percent).

	Grainsize data type		
Data source	Composition	Mean grainsize	Full grainsize statistics (mean, sorting & skewness)
Davies Colley 1979	☑	☑	☑
Healy 1985	☑	☑	☑
Hope 2002	☑	☑	☑
McIntosh 1994	☑	☑	☑
Park 2003	☑	~	~
Park unpublished data	☑	☑	☑
Stokes 2008	☑	☑	~
Stokes unpublished data	☑	☑	~
Swales 2000	☑	☑	☑
White 1979	☑	☑	☑

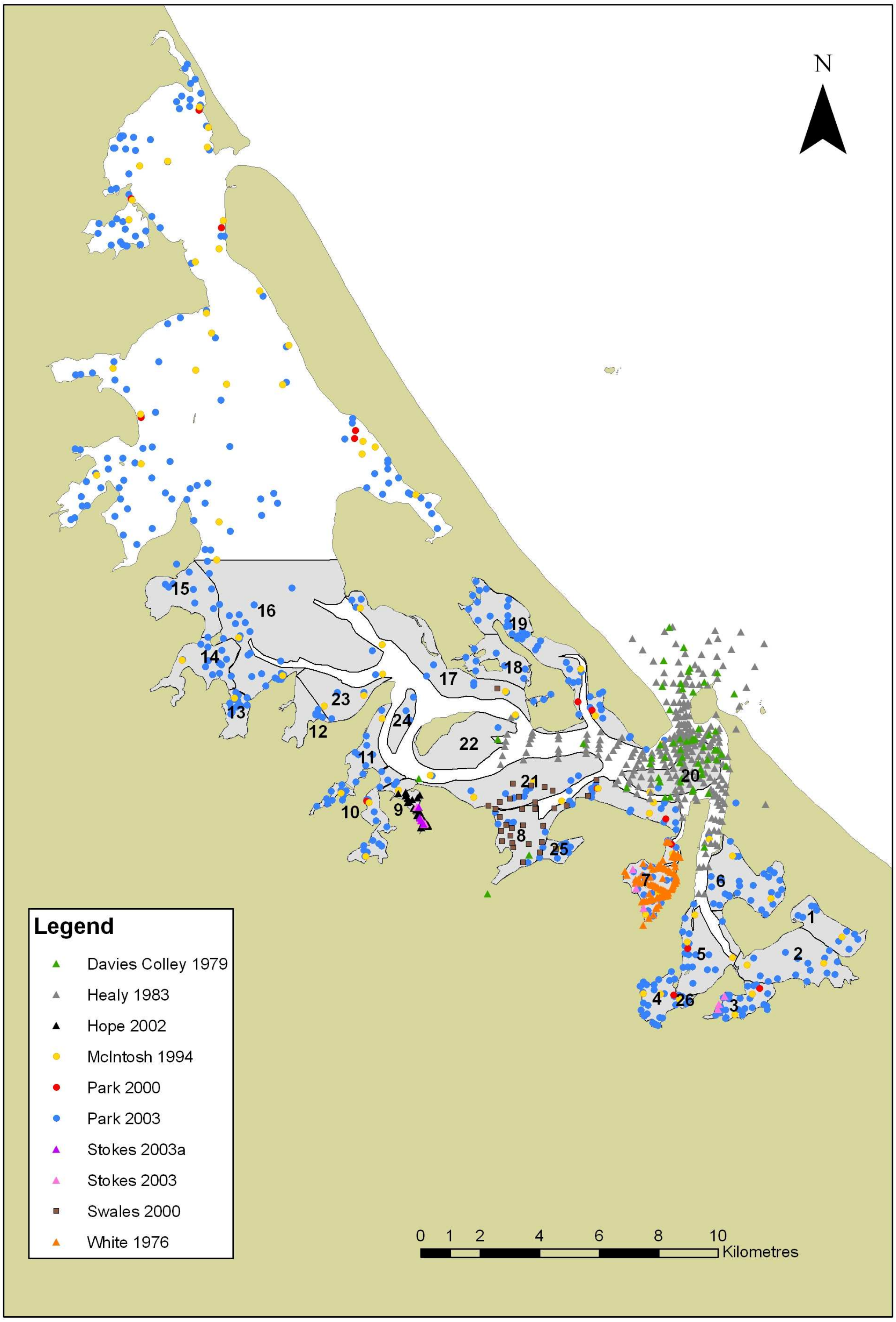

Figure 2: Sample locations of the 10 studies used to describe sediment grainsize and composition. All 10 studies had sediment composition (gravel/sand/mud percent) data, while only 7 provided full sediment grainsize statistics data. Figure 3 shows the distribution of sediment samples throughout the subestuaries.

To prepare data for analysis the grainsize sorting and skewness were calculated from percentile results using standard equations and grainsize units were converted from phi to millimetres (where necessary). In studies where percent mud or sand had been divided into finer fractions (e.g., very fine sand, fine sand, coarse sand etc.) the results were recombined to create the three composition fractions (i.e., mud <63 µm, sand 63 µm to 2 mm, gravel >2 mm) used in this study.

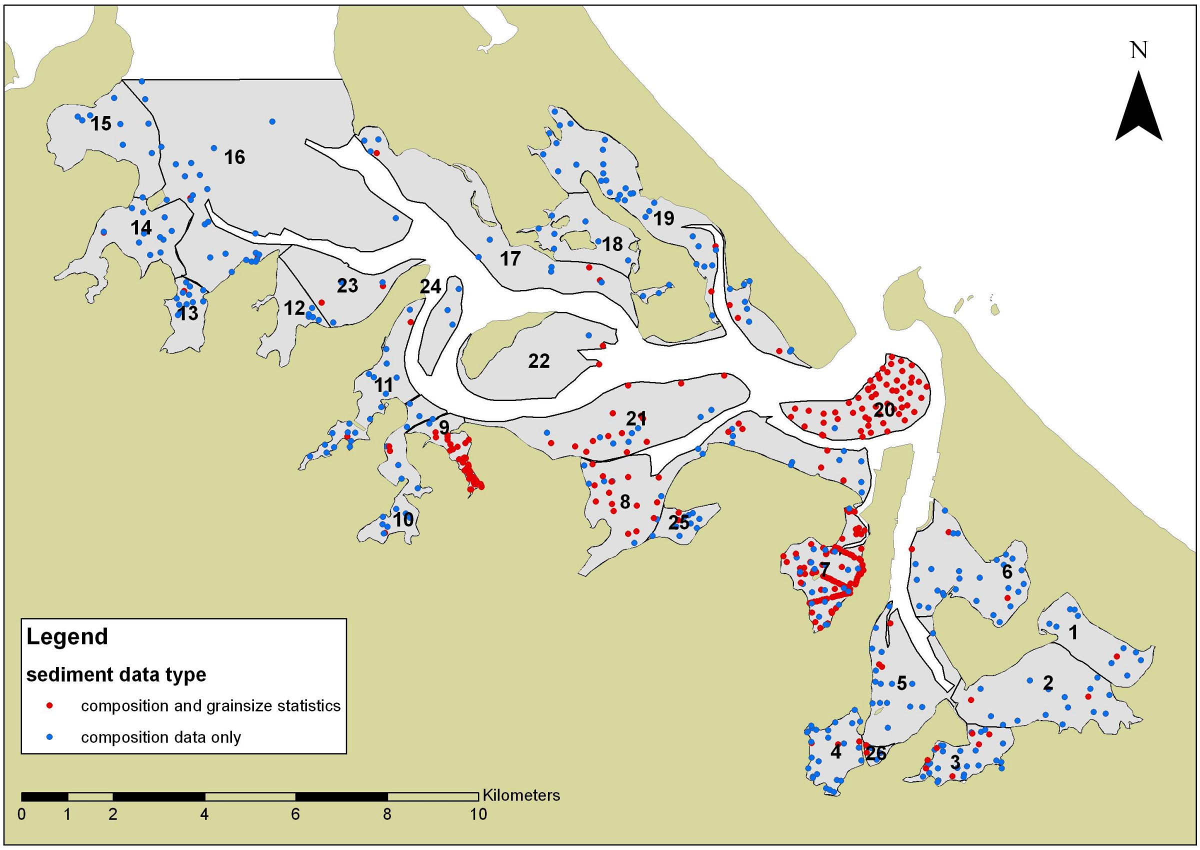

Figure 3: Sediment sample distribution according to data type. Green dots show samples with composition (gravel/sand/mud percent) data only. Blue dots show samples with grainsize statistics and composition data.

2.4 Analysis of grainsize statistics and composition data

ArcGIS shape files created for each data source (described above) contained the study name, location, and sediment data (composition and/or grainsize) in the form of attribute tables. These individual shape files were merged in ArcGIS to form a single shape file and attribute table that contained the sediment data from all 10 studies.

The merged attribute table was exported into Microsoft Access where queries were run to calculate the mean values of sediment grainsize and composition for each subestuary. Subestuary grainsize was calculated by taking the arithmetic mean of all of the grainsize data from within the boundaries of an individual subestuary. Subestuary sediment composition was calculated in the same way using all available composition data from each individual subestuary.

The mean sorting parameter and skewness for each subestuary were calculated in a similar manner to that above. A simplified four-tiered sorting parameter table was created by combining parts of the Folk and Ward sorting parameter table (Table 2).

Table 2: Simplified sorting parameter, based on Folk and Ward.

<table>
<tr><th>Phi units</th><th>Verbal classification for Folk and Ward sorting parameters</th><th>Phi units</th><th>Simplified sorting parameters for describing Tauranga samples</th></tr>
<tr><td><0.35</td><td>Very well sorted</td><td rowspan="2"><0.5</td><td rowspan="2">Well sorted</td></tr>
<tr><td>0.35 - 0.5</td><td>Well sorted</td></tr>
<tr><td>0.5 - 1.0</td><td>Moderately well sorted</td><td>0.5 - 1.0</td><td>Moderately sorted</td></tr>
<tr><td>1.0 - 2.0</td><td>Poorly sorted</td><td>1.0 - 2.0</td><td>Poorly sorted</td></tr>
<tr><td>2.0 - 4.0</td><td>Very Poorly sorted</td><td rowspan="2">>2.0</td><td rowspan="2">Very poorly sorted</td></tr>
<tr><td>>4.0</td><td>Extremely poorly sorted</td></tr>
</table>

2.5 Sediment grainsize and composition results

Table 3 provides further details of the information in Table 1. It lists the number of samples per study and per subestuary used for the sediment grainsize statistics and composition analysis. The number of samples varied widely between subestuary: in some cases there were no samples for calculating grainsize (subestuaries 12, 14 and 15) and only one sample for composition (e.g., subestuary 22), while in other cases there were over 90 samples (e.g., subestuary 7). There was a total of 619 samples for composition and 298 samples for statistics. Figure 2 shows that the greatest number of samples was collected in the vicinity of the Tauranga City/Port area.

Table 3: Number of grainsize statistics and composition samples used from each study, in each subestuary, to calculate the representative subestuary grainsize statistics and sediment composition.

Subestuary number	Number of samples used to calculate grainsize statistics	Study name
1	1	McIntosh 1994
1	3	Park 2003
2	2	McIntosh 1994
2	6	Park 2003
3	2	Park unreported data
3	2	McIntosh 1994
4	1	Park unreported data
4	1	McIntosh 1994
4	1	Park 2003
5	1	Park unreported data
5	2	McIntosh 1994
5	6	Park 2003
6	2	McIntosh 1994
6	18	Park 2003
7	1	Park unreported data
7	87	White 1979
7	3	McIntosh 1994
7	1	Park 2003
8	2	Park unreported data
8	3	McIntosh 1994
8	9	Park 2003
8	12	Swales 2000
9	33	Hope 2002
9	1	McIntosh 1994
10	1	Park unreported data
10	2	McIntosh 1994
10	1	Park 2003
11	2	McIntosh 1994
11	3	Park 2003
12	0	*nil*
13	1	McIntosh 1994
14	0	*nil*
15	0	*nil*
16	2	McIntosh 1994
16	3	Park 2003
17	2	McIntosh 1994
17	5	Park 2003
17	1	Swales 2000
18	1	Park2003
19	2	Park unreported data
19	1	McIntosh 1994
19	7	Park 2003
20	7	Davies Colley 1979
20	27	Healy 1985
20	1	McIntosh 1994
21	2	Healy 1985
21	2	McIntosh 1994
21	3	Park 2003
21	10	Swales 2000
22	1	Park2003
23	2	McIntosh 1994
24	2	Park 2003
25	1	McIntosh 1994
25	1	Park 2003
25	1	Swales 2000
26	1	Park unreported data
26	1	McIntosh 1994
26	2	Park 2003

Subestuary number	Number of samples used to calculate composition	Study name
1	1	McIntosh 1994
1	10	Park 2003
2	2	McIntosh 1994
2	15	Park 2003
3	2	Park unreported data
3	2	McIntosh 1994
3	18	Park 2003
3	12	Stokes unreported data
4	1	Park unreported data
4	2	McIntosh 1994
4	22	Park 2003
5	1	Park unreported data
5	2	McIntosh 1994
5	17	Park 2003
6	2	McIntosh 1994
6	27	Park 2003
7	1	Park unreported data
7	87	White 1979
7	4	McIntosh 1994
7	22	Park 2003
7	11	Stokes unreported data
8	2	Park unreported data
8	3	McIntosh 1994
8	21	Park 2003
8	14	Swales 2000
9	33	Hope 2002
9	1	McIntosh 1994
9	1	Park 2003
9	17	Stokes unreported data
9	3	Stokes 2008
10	1	Park unreported data
10	2	McIntosh 1994
10	16	Park 2003
11	2	McIntosh 1994
11	19	Park 2003
12	5	Park 2003
13	1	McIntosh 1994
13	12	Park 2003
14	1	McIntosh 1994
14	11	Park 2003
15	10	Park 2003
16	2	McIntosh 1994
16	26	Park 2003
17	2	McIntosh 1994
17	11	Park 2003
17	1	Swales 2000
18	7	Park 2003
19	2	Park unreported data
19	1	McIntosh 1994
19	35	Park 2003
20	7	Davies Colley 1979
20	27	Healy 1985
20	1	McIntosh 1994
20	1	Park 2003
21	2	Healy 1985
21	2	McIntosh 1994
21	8	Park 2003
21	9	Swales 2000
22	1	Park 2003
23	2	McIntosh 1994
23	3	Park 2003
24	3	Park 2003
25	1	McIntosh 1994
25	9	Park 2003
25	1	Swales 2000
26	1	Park unreported data
26	1	McIntosh 1994
26	4	Park 2003

Surface sediment grainsize statistics (mean, sorting and skewness) for each subestuary are presented in Table 4. Subestuaries 12, 14 and 15 had no suitable data available for calculating grainsize statistics. All subestuaries except number 13 had a mean grainsize of between 0.125 and 0.5 mm which equates to the Wentworth size classes of fine to medium sand, but in this study these grainsizes are simply defined as sand. Only subestuary 13 fell in the category of mud (< 0.063 mm).

The skewness and simplified sorting parameter are also presented in Table 4. Sorting was poor or very poor across most subestuaries, with the exceptions being subestuaries 8, 18, 20 and 22, which were moderately or well sorted, indicating that these are higher-energy environments.

Mean surface sediment composition results for each subestuary are presented in Table 5. All subestuaries are predominantly sand (generally >70%) and have very little gravel (generally < 5%). The result that best describes harbour bed sediments for this study is percent mud; firstly because this is a study about the fate of fine sediments, and secondly because percent mud gives a simple yet accurate indication about variability in sediment composition between subestuaries (ranging from 0.7% in subestuary 22% to 43.7% in subestuary 14). Therefore, the analysis in the following sections only refers to percent mud.

Figure 4 shows mean surface sediment grainsize, percent mud composition and simplified sorting parameter for each subestuary superimposed on the subestuaries map. An interpretation of these results is discussed in the next section.

2.6 Summary

The southern Tauranga Harbour was split into 26 subestuaries for the purpose of the modelling. Subestuaries are km-scale compartments of the harbour with common depth, hydrodynamic exposure and bed-sediment grainsize and are the fundamental units at which predictions are made by the USC-3 sedimentation model (Green, 2007). They primarily include intertidal area where fine sediments are deposited. The subestuaries were initially delineated on the basis of a conceptual understanding of harbour processes and the criteria described above at a meeting between NIWA and EBOP. This categorisation was refined following analysis of the sediment data.

An extensive literature search identified 40 studies, 26 of which contained potentially useful data. The data, once screened for applicability and quality, identified about 300 samples with useful information on grainsize statistics and about 600 samples with information on composition (gravel/sand/mud percentage). The data were assimilated in ArcGIS along with available hydrodynamic and geomorphologic information to describe and map bed-sediment properties of each subestuary.

Table 4: Mean surface sediment grainsize statistics results for each subestuary.

Subestuary number	Number of samples used to calculate grainsize statistics	Mean grainsize (mm)	Standard deviation ± (mm)	Mean skewness	Mean sorting	Sorting parameter
1	4	0.273	0.035	0.259	1.121	Poorly sorted
2	8	0.324	0.103	0.152	1.049	Poorly sorted
3	4	0.270	0.070	0.095	1.783	Poorly sorted
4	3	0.335	0.056	0.154	1.274	Poorly sorted
5	9	0.403	0.186	0.010	1.213	Poorly sorted
6	20	0.321	0.104	0.246	1.038	Poorly sorted
7	92	0.156	0.104	0.170	1.437	Poorly sorted
8	26	0.299	0.134	0.316	0.940	Moderately sorted
9	34	0.272	0.115	0.358	1.770	Poorly sorted
10	4	0.281	0.044	0.162	1.793	Poorly sorted
11	5	0.185	0.025	0.277	1.064	Poorly sorted
12	0	~	~	~	~	~
13	1	0.061	~	-0.180	4.574	Very poorly sorted
14	0	~	~	~	~	~
15	0	~	~	~	~	~
16	5	0.179	0.089	-0.070	1.254	Poorly sorted
17	8	0.402	0.144	-0.046	1.075	Poorly sorted
18	1	0.321	~	0.397	0.967	Moderately sorted
19	10	0.315	0.060	0.330	1.098	Poorly sorted
20	35	0.346	0.121	-0.194	0.876	Moderately sorted
21	17	0.244	0.088	-0.040	1.158	Poorly sorted
22	1	0.235	~	0.113	0.458	Well sorted
23	2	0.308	0.070	0.040	1.263	Poorly sorted
24	2	0.326	0.220	0.290	1.448	Poorly sorted
25	3	0.290	0.112	0.081	1.147	Poorly sorted
26	4	0.287	0.079	0.149	1.636	Poorly sorted

Table 5: Mean surface sediment composition results for each subestuary.

Subestuary number	Number of samples used to calculate composition	% Mud (< 63 µm)	% Sand (63 µm - 2 mm)	% Gravel (> 2mm)
1	11	13.95	85.36	0.69
2	17	6.89	92.04	1.07
3	41	31.14	68.25	0.61
4	29	30.32	68.22	1.46
5	20	9.80	87.56	2.69
6	29	8.13	91.16	0.71
7	126	20.84	77.62	0.66
8	40	3.50	94.04	2.43
9	55	35.74	63.84	0.07
10	19	22.26	75.05	2.69
11	21	23.69	75.67	0.62
12	5	6.27	92.87	0.86
13	12	48.10	49.35	2.55
14	12	43.68	54.59	1.73
15	9	27.17	72.29	0.54
16	26	14.47	83.55	1.98
17	14	3.36	94.73	1.89
18	7	10.84	88.89	0.28
19	43	8.53	90.32	1.16
20	36	0.27	96.71	2.96
21	21	4.43	90.49	5.04
22	1	0.70	99.30	0.01
23	5	4.30	92.84	2.86
24	3	14.07	80.74	5.19
25	11	10.80	88.50	0.72
26	6	14.29	83.80	1.91

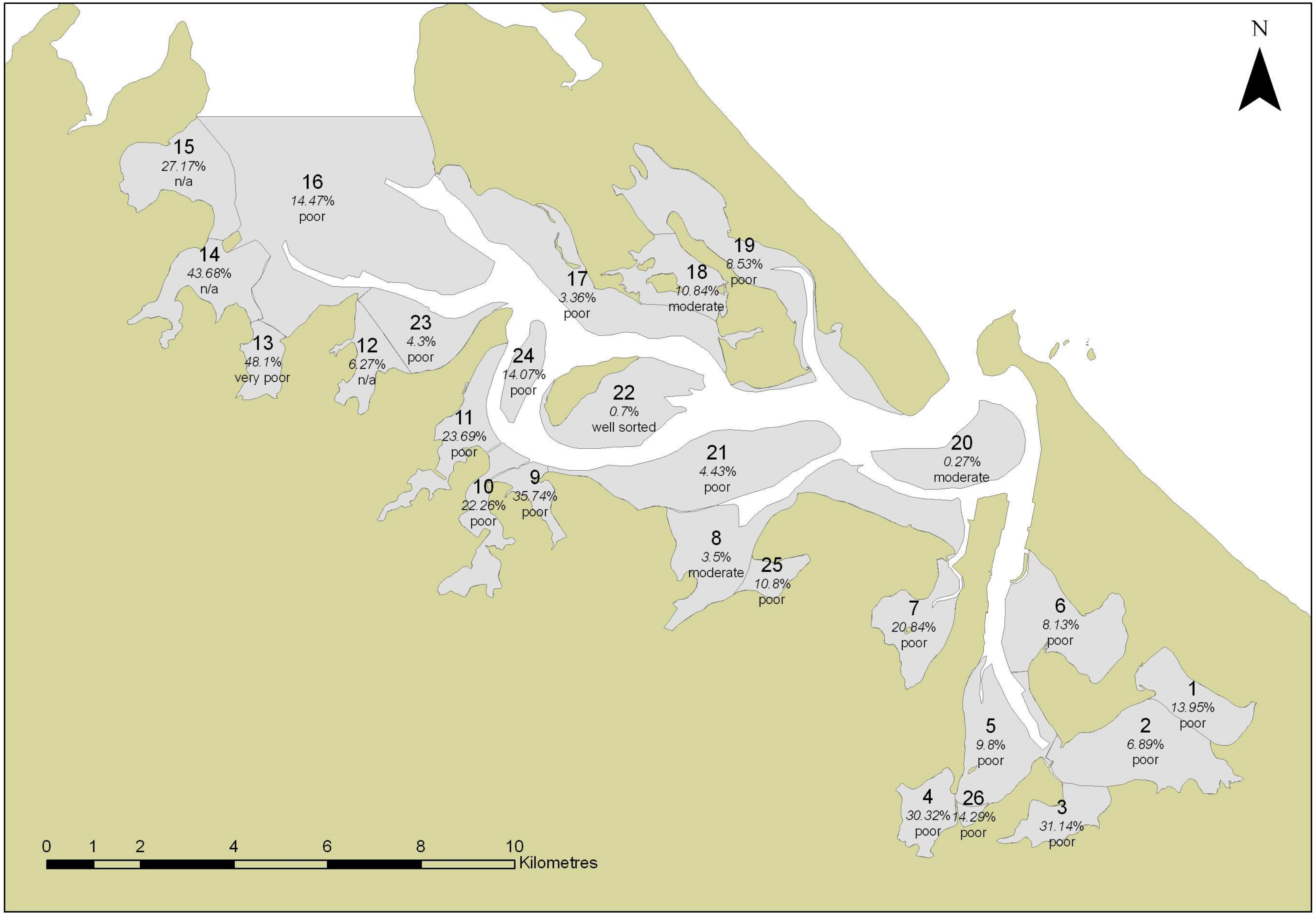

Figure 4: Subestuaries showing subestuary number (large font and bold) along with the mean grainsize, percentage mud and simplified sorting parameter.

3. Categorising subestuary types

This section describes how the sediment data were combined with a conceptual understanding of hydrodynamic, geomorphological and catchment processes that affect sedimentation, to group subestuaries into 11 categories. Categorisation is a first step towards translating the sediment data into initial conditions for the model.

3.1 Sediment data considerations

When mapped, the mean grainsize of the 26 subestuaries followed the patterns we would have expected given our conceptual understanding of the environment. Our analysis determined that grainsize composition (especially percent mud) gave better resolution of the differences between subestuary environments than mean grainsize. Reasons for this were: 1) percent mud had been determined at many more sites (about 600) than mean grainsize (about 300), 2) there was better spatial coverage for percent mud than for grainsize statistics (subestuaries 12, 14 and 15 had no suitable data available for calculating grainsize but all subestuaries had composition data) and 3) during the data selection process percent mud showed less variability between studies compared to mean grainsize. Skewness and a simplified sorting parameter were also used to verify trends and patterns during the categorisation process.

3.2 Processes affecting sediment regimes

Factors that affect the processes controlling sediment erosion, transport and dispersal include geomorphology (estuary shape and aspect, and the geometry of banks and shoals) and hydrodynamics (exposure to wind-wave and tidal current energy). The influences of these processes on sediment transport were gauged by examining bathymetry charts and ArcGIS maps of subestuary locations and sediment data results (percent mud, mean grainsize and sorting).

Another major factor controlling sediment transport and dispersal is the volume of freshwater arriving in the form of catchment runoff. Figure 5 shows a simplified drainage network for the catchment of Tauranga Harbour. This was used to examine the relative size of the subcatchments, and their entry points into the harbour, in order to consider the likely effects of freshwater discharge on the hydrodynamics and thus the sediment transport. Most of the subcatchments drain the hills to the west (Kaimai-Mamaku) and the south (Welcome Bay) of the harbour. These areas are generally covered with forest, horticulture and agriculture with some urban pockets. In contrast, the subcatchments on the northeast (Mount Maunganui) side of the harbour constitute a small percentage of the total catchment area, are low lying, smaller and generally urbanised.

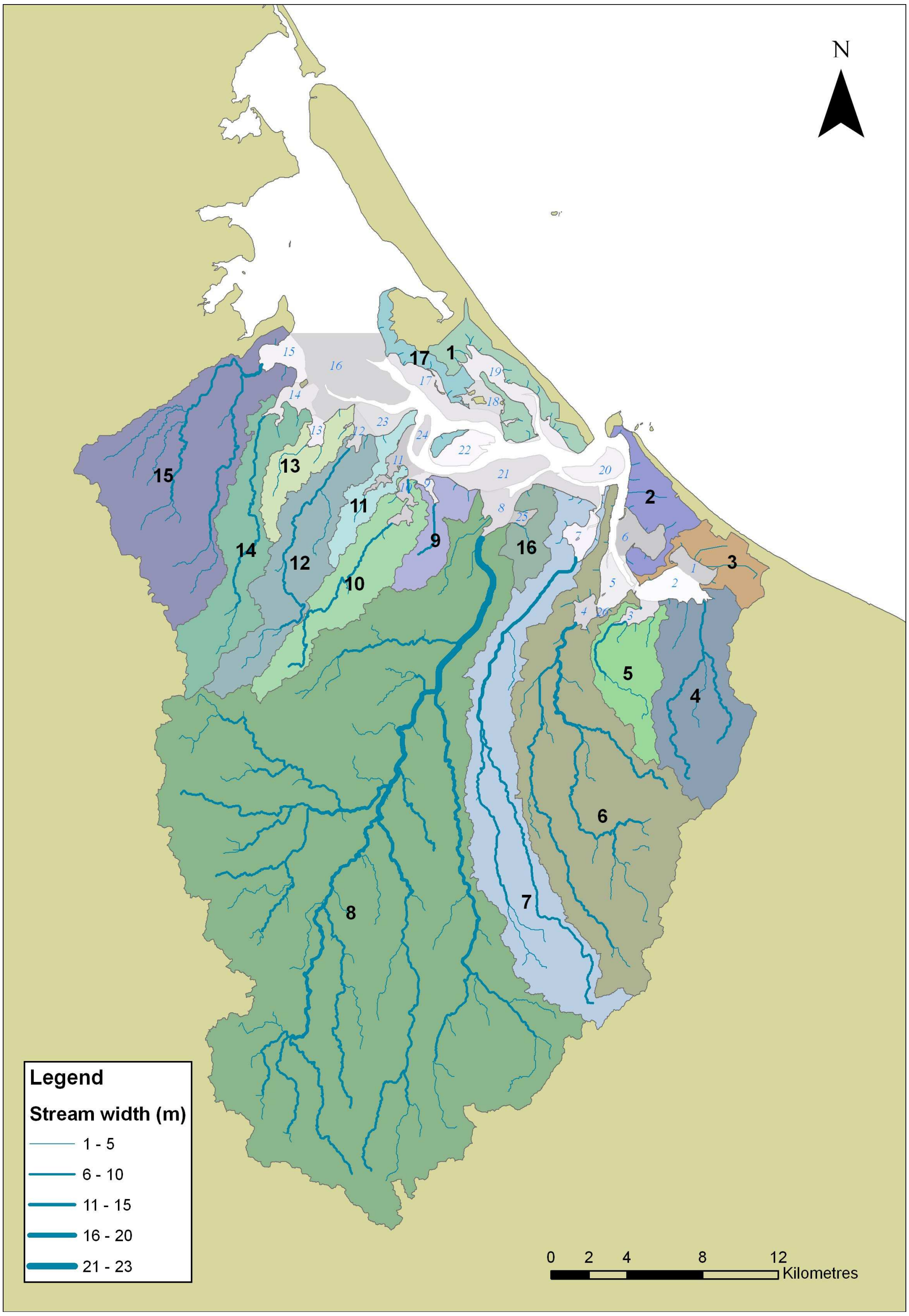

Figure 5: Simplified drainage network for the catchment of Tauranga Harbour. The numbers are those used to identify catchments in the catchment component of the Tauranga Harbour Sediment Study.

3.3 Category descriptions

Table 6 lists the various factors (sediment, hydrodynamic, geomorphologic and catchment information) considered in subdividing the 26 subestuaries into 11 categories. Figure 6 shows the 11 categories along with their mean grainsize, percentage mud composition and simplified sorting parameter.

The categories are described as follows. Hunters Creek and Hunters Creek Transition categories are low energy with medium mud content (8.5 – 10.8%). They were designated as distinct categories due to their separation from the mainland catchment. Mid Harbour has no direct catchment input but is semi-exposed with medium mud content (14.0%). Open Harbour Banks is very exposed with low mud content (0.3 – 4.4%) and no direct catchment input. Open Silty Embayments are medium energy and low-medium mud content (3.5 – 8.1%). They are divided into East and West due to differences in wave climate and catchment inputs. Whereas the East has a flat urban catchment, the West has a large hilly catchment. Sheltered Muddy Embayments are sheltered (low wave energy) environments with high mud content (10.8 – 48.1%) and all lie on the western shore (West) with large hilly catchments except for subestuary 1 which is on the eastern shore (East) and which has a flat urban catchment. Southern Harbour Open and Southern Harbour Transition categories are wide with medium wave energy and medium mud content (6.9 and 9.8%). The Southern Harbour Transition category has no immediate catchment, hence its name, while the Southern Harbour Open has a hilly catchment and large river input. The Upper Harbour Transition category is a large, wide, and exposed with medium mud content (14.5%) and no immediate catchment input.

3.4 Summary

The sediment data were combined with a conceptual understanding of hydrodynamic, geomorphological and catchment processes that affect sedimentation, to group subestuaries into 11 categories. These categories identify areas of similar sediment types and geomorphology and where similar sediment processes (transport, dispersal and deposition, resuspension) of similar intensity (wave and tidal energy) are presumed to occur.

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Table 6: Geomorphological, hydrodynamic and catchment factors used in the subestuary categorisation process.

Category	Subestuary number	Percent mud	Geomorpholocial factors			Hydrodynamic energy factors		Catchment factors	
			Subestuary shape (narrow/open)	Subestuary position on harbour shore	Subestuary exposure	Wave exposure	Tidal currents	Maximum stream order	Catchment size
Hunters Creek	**19**	8.5	narrow	north	sheltered	low	medium	n/a	n/a
Hunters Creek Transition	**18**	10.8	open	north	sheltered	low	low	n/a	n/a
Mid Harbour	**24**	14.0	open	mid harbour	semi-exposed	medium	high	nil	nil
Open Harbour Banks	**17**	3.4	open	north	exposed	medium	high	nil	nil
	20	0.3	open	mid harbour	exposed	high	high	nil	nil
	21	4.4	open	mid harbour	exposed	high	high	nil	nil
	22	0.7	open	mid harbour	exposed	high	high	nil	nil
Open Silty Embayment – east	**6**	8.1	open	east	sheltered	medium	medium	3	small
Open Silty Embayment – west	**8**	3.5	open	west	exposed	medium	medium	5	large
	12	6.3	open	west	semi-exposed	medium	medium	3	small
	23	4.3	open	west	exposed	high	low	nil	nil
Sheltered Muddy Embayment - east	**1**	14.0	open	east	sheltered	low	low	3	Small
Sheltered Muddy Embayment – west	**3**	31.1	narrow	west	sheltered	low	low	3	medium
	4	30.3	narrow	west	sheltered	low	low	4	medium
	7	20.8	narrow	west	sheltered	low	low	3	medium
	9	35.7	narrow	west	semi-exposed	medium	low	3	small
	10	22.3	narrow	west	sheltered	low	low	3	small
	11	23.7	combination	west	semi-exposed	medium	low	2	small
	13	48.1	narrow	west	sheltered	medium	low	2	small
	14	43.7	combination	west	semi-exposed	medium	low	3	small
	15	27.2	combination	west	semi-exposed	medium	low	4	medium
	25	10.8	narrow	west	sheltered	low	low	n/a	n/a
	26	14.3	narrow	west	sheltered	low	low	na/	n/a
Southern Harbour – open	**2**	6.9	open	south and east	semi-exposed	medium	low	4	medium
Southern Harbour – Transition	**5**	9.8	open	south and east	semi-exposed	low	medium	nil	nil
Upper Harbour - Transition	**16**	14.5	open	mid harbour and north	exposed	high	medium	nil	nil

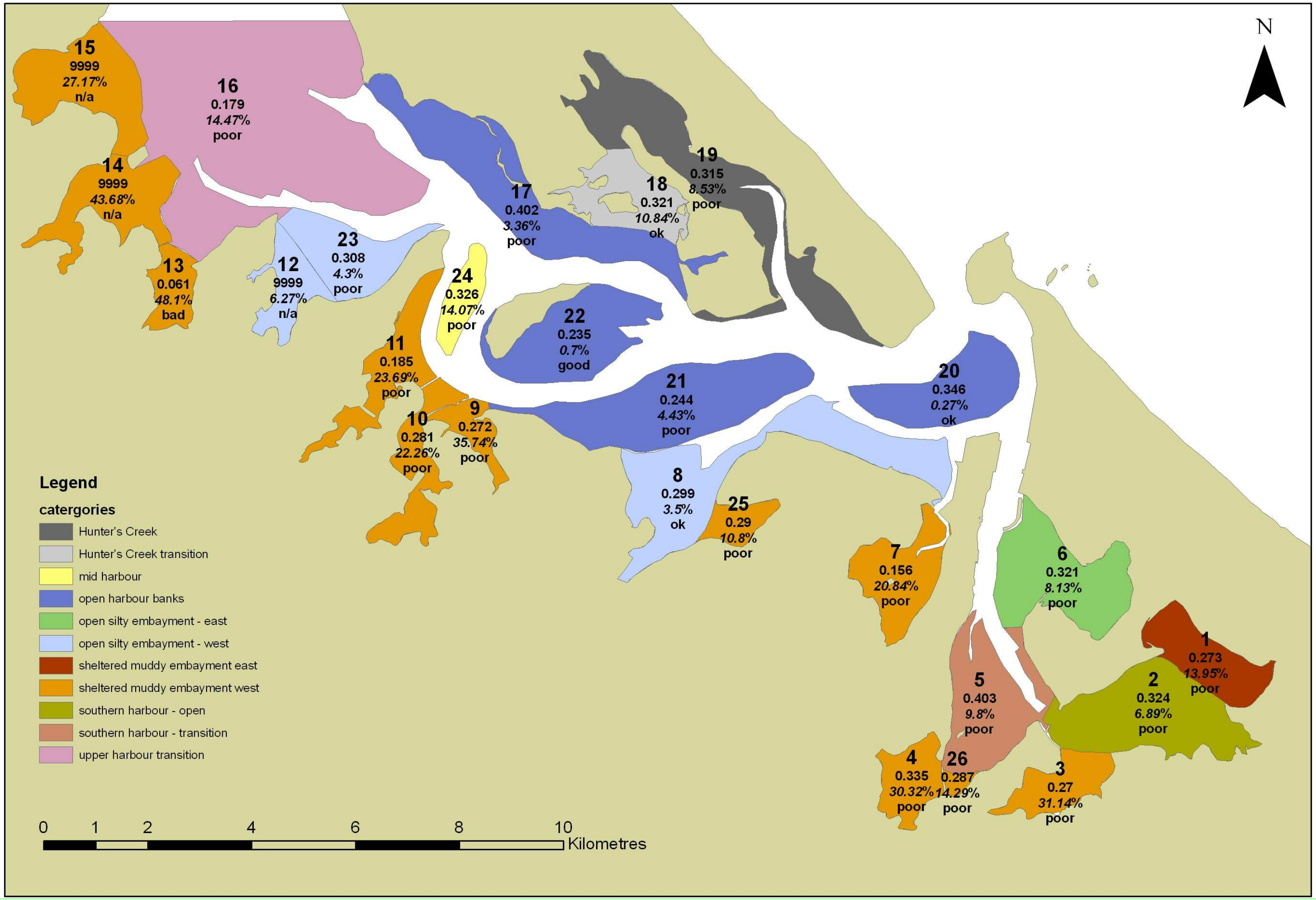


Figure 6: Subestuary map showing subestuary number (large font and bold) above mean grainsize, percentage mud and simplified sorting parameter results for each subestuary. The 11 categories are identified by colour coding and defined in the legend.

4. Sediment accumulation rate

Measurements of sediment accumulation from the harbour provide information on where sediments are building up and rates of sediment accumulation over the past 50 years, which will be used to validate sediment accumulation predictions by the USC-3 model. Our literature research revealed little information on sediment accumulation rate (SAR). The core sites were selected, coring undertaken and sediments examined by x-radiograph and dated by radioisotopic techniques to determine sediment accumulation rate.

4.1 Existing sediment accumulation rate data

We located 13 studies that potentially contained information on SAR. Twelve of these studies revealed little useful information for the reasons summarised in Table 7. The study by Burggraaf et al. (1994) on sediment contaminants in Waikareao Estuary (subestuary 7) detected the organochlorine DDT at 50 mm depth, which provides an estimated average sedimentation rate of about 0.9 mm/yr since the last use of DDT (to control grass grubs on pasture) in about 1950.

Unfortunately, data from the surveys of intertidal flat profiles at 26 locations by EBOP (Figure 7) in 2003 and 2007 did not provide suitable data to derive SAR. The surveying method used had a resolution of about 40 mm, which was too large to resolve the centimetre or two change in bed elevation that probably took place in the 4 years between the two surveys. However, as more surveys are completed over a longer time period, these data will have greater resolution and be valuable records of sediment accumulation over large parts of the harbour.

Table 7: Studies investigated as a source of sediment accumulation rate data.

Source	Description	Why not used
Barnett 1985	No data in Barnett reports (all data for the Tauranga study is in the Healy and Black reports)	No data
Beamsley and Black 2003	Sediment flux inferred from sediment trap and SSC data	Rates inferred and dataset too short
Black 1984	Data from Healy report	Data from Healy report
Burggraaf et al. 1994	Journal paper looking at DDT, DDE, DDD contaminants in surface sediments from Tauranga harbour. Simple calculation for sedimentation rate on pg 295. Calculation based on levels of different contaminants found at different depths within the sediment (e.g. DDT found 50 mm down sediment profile), and likely time of contaminant use (e.g. DDT, c.1950). This gives an approximate sediment accumulation rate of 0.9 mm/yr since 1950.	n/a
EBOP surveys 2003 - 2007	Surveyors measured intertidal flat level at 20+ sites in Tauranga harbour in 2003 and again in 2007	Survey results not yet accurate enough
Davies-Colley 1976	Sediment discharge inferred from Bagnold's bedload formula	Dataset too short
Davis and Healy 1993	Interpretation of the late Quaternary stratigraphy of southeastern Tauranga harbour based largely on >70 bore holes and radiometric dating, supplemented by high resolution seismic survey and scuba observations.	Dates not detailed enough to infer SAR
Healy 1985	Sub bottom seismic profiles	No dates associated with profiles
Hope 2002	4 x 40 cm cores in Waikaraka estuary	Dating results not reliable
Perano 2000	Sediment flux inferred from sediment trap and SSC data	Rates inferred and dataset too short
Stokes et al. 2008	Erosion pins and Surface Elevation Table methodologies	Data set too short
Stokes unpublished results 2003-2005	Cores	Results not yet available
Swales et al. 2000	12 x 3 m deep cores around Wairoa River to determine key lithological properties	No dating done on cores

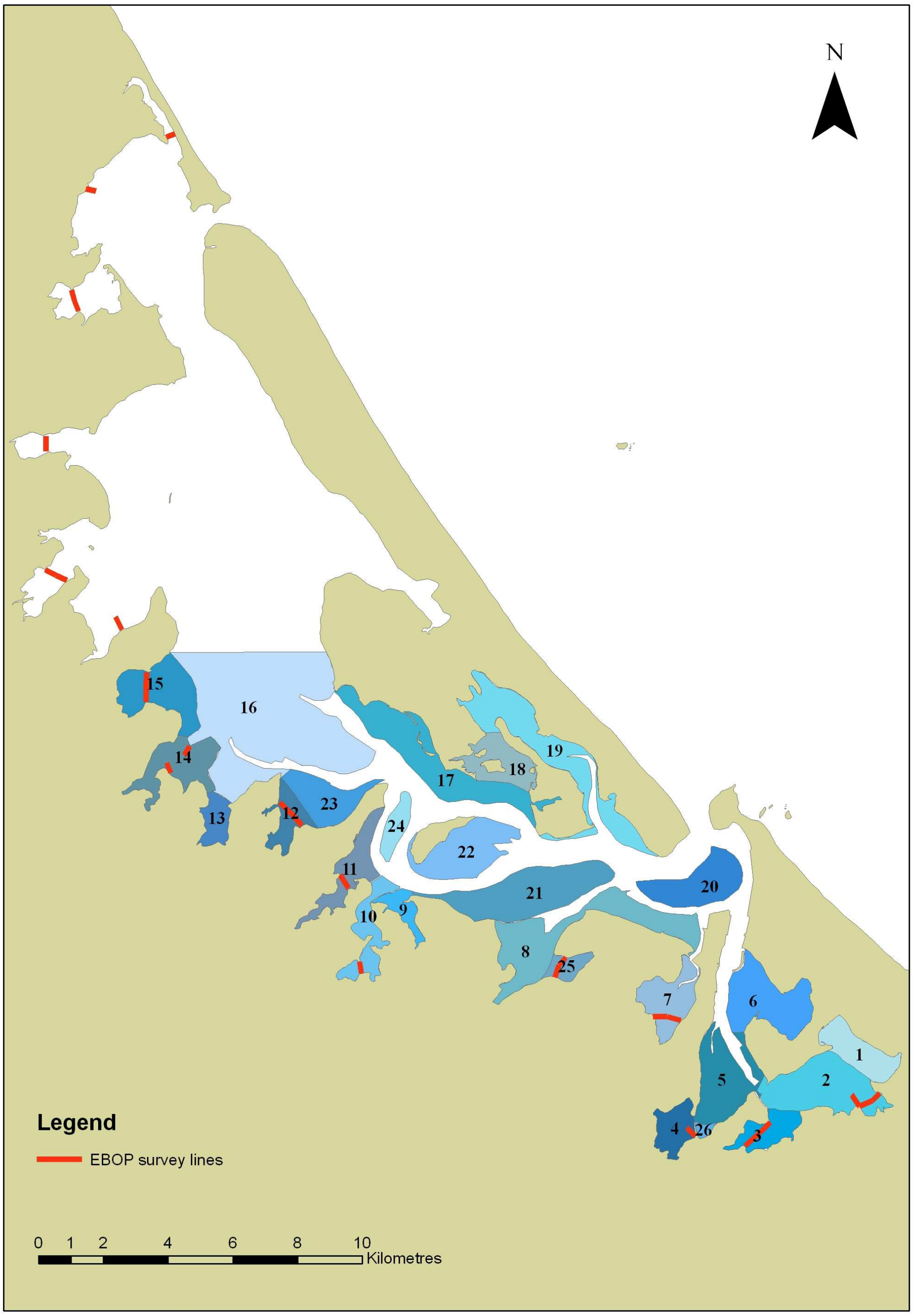


Figure 7: The 26 locations (survey profile lines) where EBOP surveyed the intertidal flats in 2003 and 2007 to monitor level change and sediment accumulation.

4.2 Selection of core sites

High-resolution colour aerial photographs along with various other catchment and estuary information were examined from the 26 subestuaries to select core locations that would provide representative sediment accumulation rates. Table 8 lists considerations undertaken in choosing the 10 subestuaries for coring. Criteria for selection also required that the core sites be characterised by a uniform (not patchy depositional regime and that the sediments should contain >3% mud (for successful radioisotope analysis), be away from meandering estuary channels, stream inputs, areas of physical or biological reworking and mangroves or seagrass beds. A GPS location was determined for each site, but the exact position was chosen in the field on the day of the coring. All sites ended up being located close to the original selection sites, apart from the site in subestuary 15 which was moved to a location one kilometre away where it was more easily accessible by boat. This resulted in the core being taken in the western corner of subestuary 16, near subestuary 14. A tenth core intended for subestuary 21 was not taken as the area was clearly very active and sandy and would not have yielded useful SAR results. SAR core locations are shown in Figure 8 and Table 9.

Table 8: Criteria considered in selecting core locations.

	Subestuary	Cored	Reasoning
1	Speedway	-	*Sewerage treatment pond upstream may input particles into estuary*
2	Rangataua Bay	☑	Outflow for subcatchment 104; open south harbour example
3	Welcome Bay	-	*In same subcatchment as subestuary 2; mangroves; to be represented by SAR from subestuary 4*
4	Waimapu Estuary	☑	Outflow for large subcatchment (106); sheltered muddy embayment example; data can represent subestuary 3
5	Tauranga City foreshore	-	*Transition area; no direct subcatchment drainage*
6	Waipu Bay	☑	Unusual geomorphology; likely depositional area; represents west facing open silty embayment; outflow for urban subcatchment 125
7	Waikareao	-	*SAR given by Burggraaf 1994 paper*
8	Mouth of Wairoa River	☑	Outflow for Wairoa river subcatchment (108)
9	Waikaraka	-	*Obstruction upstream will likely affect sediment supply; to be represented by SAR from subestuary 10*
10	Te Puna	☑	Representative of subestuaries 9,10 and 11, of which 10 has the largest subcatchment
11	Mangawhai Bay	-	*To be represented by SAR from subestuary 10*
12	Mouth of Waipapa River	-	*To be represented by SAR from subestuary 23*
13	Pahoia Beach Road	-	*To be represented by SAR from subestuary 15*
14	Mouth of Wainui River	-	*To be represented by SAR from subestuary 15*
15	Mouth of Aongatete River	☑	Represents subestuaries 13, 14 and 15, where 15 has the largest subcatchment
16	Middle-harbour sandbanks	-	*May be too hydrodynamically active*
17	Matakana Island	☑	West facing open harbour bank; land and channel provide physical boundaries
18	Rangiwaea Island	-	*To be represented by SAR from subestuaries 17 and 19*
19	Hunters Creek	☑	Possible sink; separate hydrodynamics
20	Centre Bank	-	Too hydrodynamically active; low percent mud
21	Oikimoke Point	☑	Represents 20 and 22; open harbour bank where 21 has highest percent mud
22	Sandbank east of Motuhoa Island	-	Too hydrodynamically active; low percent mud
23	West of Omokoroa Peninsula	☑	Open silty embayment; represents subestuary 12 and 23; subcatchment 112 outflow
24	Sandbank east of Omokoroa Peninsula	-	Too hydrodynamically active; channels either side
25	Matua	-	To be represented by SAR from subestuary 8; same subcatchment as subestuary 8; small
26	Waimapu causeway	-	No direct subcatchment drainage; small

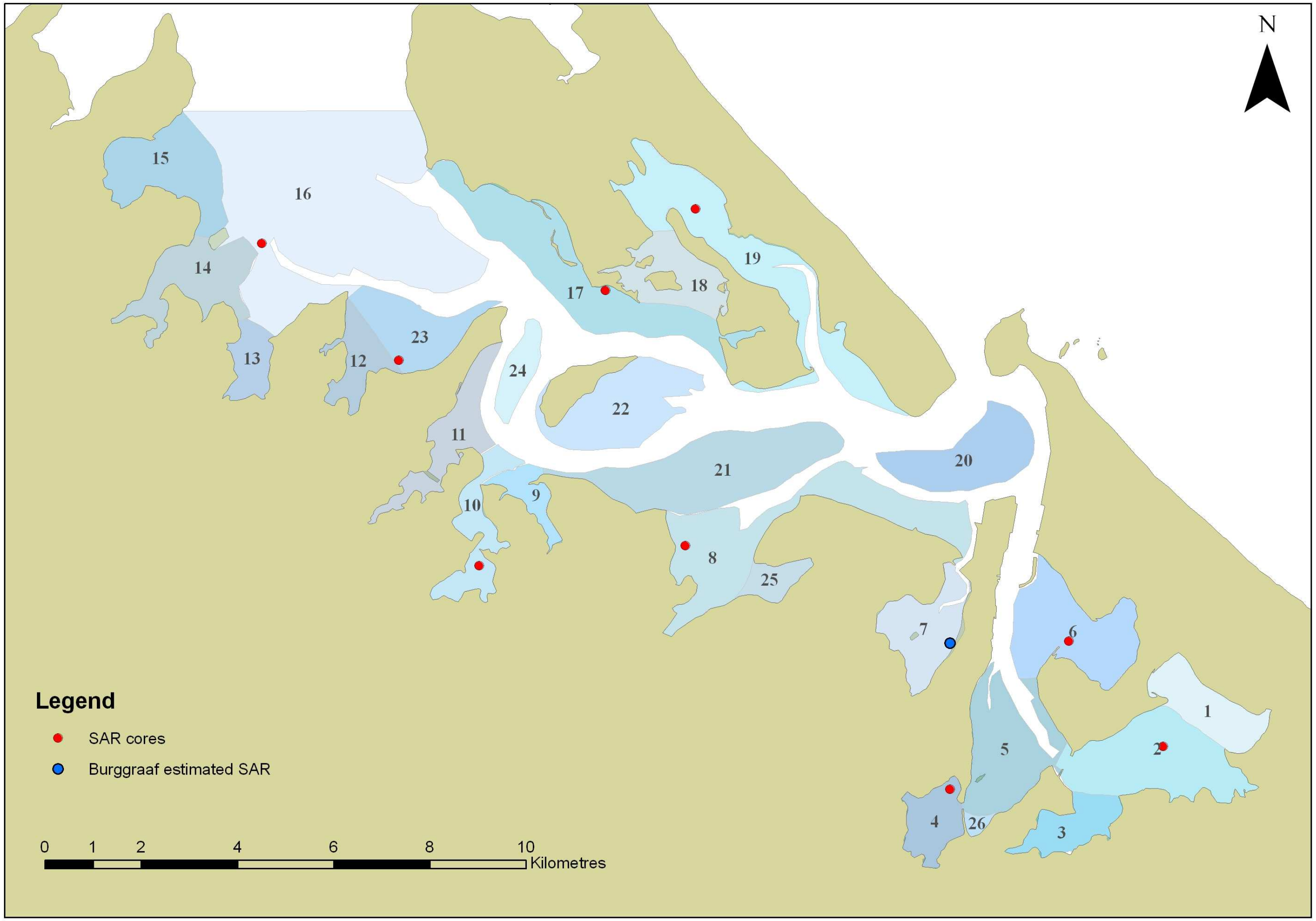


Figure 8: Locations of SAR core sites in the 26 subestuaries and the site (in subestuary 7) where Burggraaf determined SAR based on DDT in the core.

Table 9: Locations cored to determine sediment accumulation rate

Subestuary	NZMG (Northing)	NZMG (Easting)
2	-37.70398	176.21188
4	-37.71337	176.16197
6	-37.68500	176.18878
8	-37.66968	176.09770
10	-37.67493	176.04890
16	-37.61593	175.99557
17	-37.62253	176.07675
19	-37.60675	176.09732
23	-37.63688	176.02872

4.3 Field methods

Two replicate PVC cores (50 cm deep by 10 cm diameter) were collected at each site at low tide. The cores were driven carefully into the sand, avoiding compaction as much as possible, and were dug out using a spade.

Attempts at collecting sediment slabs using rectangular section Perspex trays for x-ray imaging were unsuccessful as the sediment was too firm and sandy, so a third PVC core was taken for x-ray imaging instead.

Photos of the site and sediment surface were taken as well as a photo of the sediment profile that had been cut away with a spade. Field notes and photos are documented in Appendix 2. The cores were capped, taped and kept horizontal during transport to avoid compaction. A core from each site was also archived.

4.4 X-radiographs of cores

X-radiographs (x-rays) of the cores were undertaken to show fine-scale sedimentary fabric of sediments and to provide information on depositional processes, sediment texture, and whether the sediment column had been disturbed by animal burrowing (bioturbation) and/or physical processes within the surface-mixed layer (SML) depth. This information was also used to prioritise which cores to date and exactly where to take subsamples of sediment for radioisotopic analysis. X-ray images of cores are shown in Appendix 2.

The cores were sectioned longitudinally, photographed and then trimmed to provide a 2 cm thick longitudinal slab. The slabs were x-rayed using a Phillips Model Macrotank 205 X-ray generator with Kodak AA400 film (50 kV, 5 mA, 1.1 min) (see Appendix 2 for more details on x-ray processing).

The x-radiographs show the cores are characteristic of the mixed silt and sands deposited on estuarine intertidal flats. Lower-density material such as plant fragments and/or fine-grained muds show up as darker grey–black areas. Cockle-shell valves (*Austrovenus stutchburyi*) are abundant in most of the cores (Appendix 2). The higher-density carbonate shell material, along with quartz sand layers, appear white in the x-radiographs. A description of each of the cores follows.

Core 2 was collected from Rangataua Bay (subestuary 2, Fig. 8). The x-radiographs show that sediments are composed of homogenous silty-sand to 25 cm depth, where there is a sharp contact with a shell layer containing abundant shell valves and fragments of cockle (Appendix 2). The SML extends to about 6 cm depth, where a contact with lower-density silts occurs. There is little intact lamination or bedding above the shell layer. The numerous mm-scale vertical tubes infilled with mud are indicative of the burrowing action of worms. The dark areas within the shell layer are consistent with muds and/or sediments with high water content.

Core 4 was collected from Waimapu Estuary (subestuary 4, Fig. 8). The x-radiographs show that sediments are composed of a surface layer of shell-rich sand overlaying a low-density mud layer below 10 cm depth. Shell material is rare in the top most 5 cm of the core (Appendix 2). The mud layer has a mottled appearance with numerous dark patches and tubes of low-density material. There is little evidence of intact bedding, which is consistent with sediment mixing by animals.

Core 8 was collected from the wave-exposed intertidal flats of the Wairoa Estuary near Oikimoke Point (subestuary 8, Fig. 8). The x-radiograph indicates that the top of the core is composed of a homogenous sandy mud or water-logged fine sand. A sharp contact with an underlying cockle-shell layer occurs at 15 cm depth. The dark areas within the shell layer indicate water and/or mud-filled voids. There is little evidence of intact bedding. This is most likely the result of sediment mixing related to the feeding and burrowing activities of animals. This is indicated by the mottled appearance of the sediment, which occurs when sediments of different textures are incompletely mixed. By comparison, physical mixing of intertidal-flat sediments, most commonly by waves, results in fine-scale laminations, due to sediment resuspension, sorting and redeposition.

Core 16 was collected from wave-exposed intertidal flats east of Te Hopai Island (subestuary 16, Fig. 8). The x-radiograph indicates a high-density fine-sand layer to ~10 cm depth overlaying lower-density muddy sand. There is some evidence of bedding towards the base of the surface sand layer, at 7–9 cm depth. This is indicated by fine mm-scale horizontal laminations in the sediment. There is also evidence of weak bedding in the muddy sand unit below 10 cm depth. A sharp contact with a cockle-shell layer with fine sand occurs at 37 cm depth.

Core 19 was collected from intertidal flats near Paeroa Point in the Hunters Creek Inlet, which separates Rangiwaea and Matakana Islands (subestuary 8, Fig. 8). The x-radiograph indicates a high-density silty fine-sand layer to about 7 cm depth overlaying a lower-density sandy-mud. There is bedding visible in the lower part of the surface sand layer. The sandy mud unit below 7 cm contains numerous mm-scale, mud-filled vertical burrows formed by worms. There is also some evidence of bedding, as shown by fine laminations at 15–20 cm depth. Cockle-shell valves and fragments are rare throughout this core. This is consistent with the worm-dominated muddy sediments found at this site.

Core 23 was collected from intertidal flats west of Omokoroa Peninsula (subestuary 12, Fig. 8). A relatively high-density silty fine-sand layer occupies the top 4 cm of the core. A thin layer of sand at the base of the unit is indicative of sediment sorting by wave resuspension/re-deposition. This surface layer overlies a sandy shell layer extending from 4–35 cm depth. A sandy-mud unit occurs below 35 cm. There is little evidence of intact bedding in this core.

4.5 Dating cores and determining sediment accumulation rate

Sediment cores were dated using the radioisotopes caesium-137 (^{137}Cs, ½ life 30 years) and lead-210 (^{210}Pb, ½ life 22.3 years). SAR was calculated from the vertical concentration-activity profiles of ^{210}Pb and ^{137}Cs. Concentrations of the cosmogenic radioisotope beryllium-7 (^{7}Be, ½ life 53 days) were also measured in the core samples. ^{7}Be is particle reactive and tends to be concentrated in aquatic systems, making it a useful sediment tracer in fluvial-marine systems at seasonal timescales (Sommerfield et al. 1999). More detail about radioisotope analysis and the formation and significance of surface-mixed layers in estuarine sediments are described in Appendix 3.

In the present study the ^{7}Be was used to provide information on the depth and intensity of sediment mixing in the surface-mixed layer . The ^{7}Be was also used to select cores for further radioisotope dating analyses in order to identify those cores where the sediments were least likely to be disturbed by bioturbation and physical mixing (as mixing corrupts the sediment accumulation rate data derived from the dating).

Sedimentation rates calculated from cores are annual-average rates which are usually expressed as mm/year. More detail about SAR analysis is described in Appendix 3.

On the basis of the information provided by the x-radiographs (in particular the surface mixing) sediment cores from subestuaries 2, 4, 8, 16, 19 and 23 were selected for radioisotopic analysis. Sediment samples from the top most 10 cm of each core (i.e., 0.5, 2.5, 6.5 and 9.5 cm depths) were analysed within one month of collection to analyse for the short-lived ^{7}Be to determine the depth and intensity of sediment mixing in the SML. ^{210}Pb and ^{137}Cs were also measured. In the second phase of analyses, samples below 10 cm depth (19–20, 29–30, 39–40 and 49–50 cm) were taken to determine the maximum depths of ^{210}Pb and ^{137}Cs in the cores. In addition, surface samples (0–1 cm depth) from cores 6, 10 and 17 were analysed to determine radioisotope surface concentrations.

4.6 Sediment accumulation rates

Sediment accumulation rates were estimated for several cores from depth profiles of ^{210}Pb. ^{137}Cs was not detected in any of the cores, meaning time-averaged SAR could not be determined from the maximum depth of ^{137}Cs in the sediment column as has been applied in a number of North Island estuaries. This result is notable given the ubiquitous nature of ^{137}Cs in the environment (Appendix 3). ^{137}Cs concentrations in estuarine sediments have substantially reduced since the atmospheric deposition peak in the mid 1960s, due to radioactive decay. Furthermore, ^{137}Cs deposition was substantially less in the southern hemisphere than in the northern hemisphere. Today, ^{137}Cs concentrations in estuarine sediments are typically less than 1 Becquerel (Bq) per kilogram (1 Bq = 1 radioactive decay per second), so that they are getting close to minimum detectable concentrations. By comparison, ^{210}Pb concentrations in surface sediments are typically 10 Bq kg^{-1} or more. Thus, the most likely explanation for being unable to detect ^{137}Cs in Tauranga Harbour sediments is that original deposition and accumulation of ^{137}Cs was low due to sediment reworking and dispersal, and the low mud content of the sediments was not conducive to ^{137}Cs accumulation. Today the small amounts of ^{137}Cs have decayed below minimum detectable concentrations. This also means that we have no independent method to check the SAR estimates derived from the ^{210}Pb concentration profiles.

^{7}Be was detected in each of the cores to 3–10 cm depths and these concentration profiles were also analysed. These ^{7}Be data provide information about sediment mixing and were also used to interpret the ^{210}Pb profiles. Figure 9 presents the ^{7}Be concentration profiles for the Tauranga sediment cores. In the absence of sediment mixing, the maximum ^{7}Be depth due solely to sedimentation would be less than 1–2 mm, based on the short ^{7}Be half-life and typical SAR of several mm per year. The presence of ^{7}Be to 3–10 cm depth in the cores indicates that ^{7}Be-labelled sediments are being mixed into the surface-mixed layer over short time scales (i.e., ≤ 100 days) by biological and/or physical processes. The ^{7}Be profiles can be classified into two types. Type (I) profiles are well mixed (i.e., uniform ^{7}Be concentrations with depth) and have complete sediment mixing within the SML (cores 2, 8 and 16). Type (II) profiles have exponential ^{7}Be decay profiles and show a reduction in mixing intensity with depth (cores 4, 19 and 23). In both cases, the presence of ^{7}Be to several cm depth, and absence of bioturbation structures in the SML, is consistent with wave- or tidal current-driven sediment re-suspension/re-deposition over days–months.

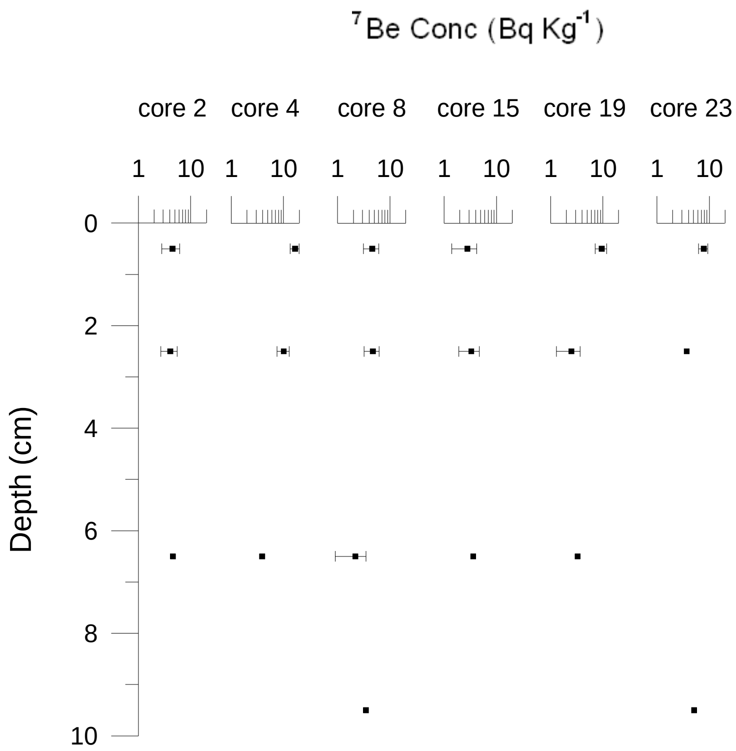
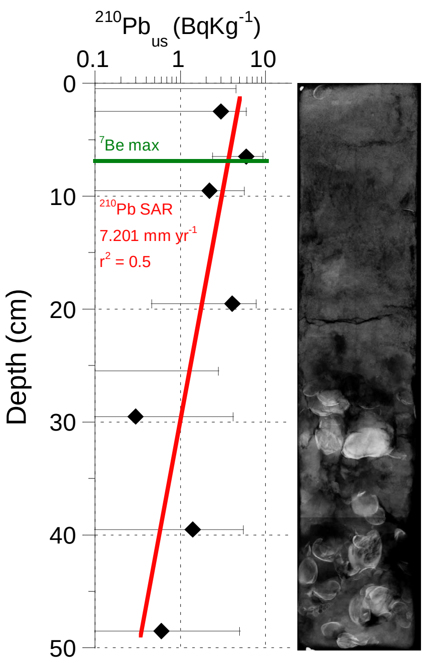


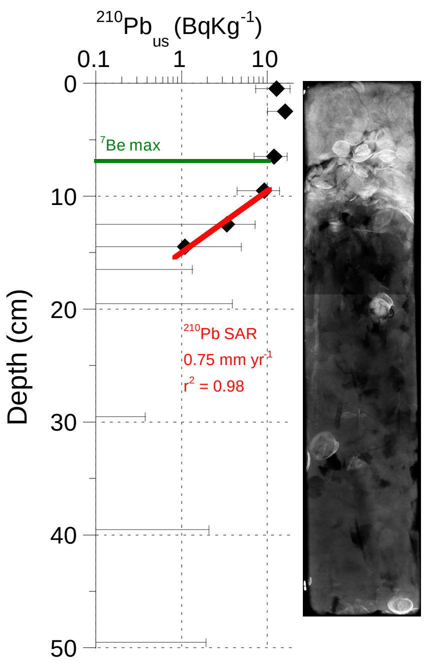
Figure 9: ^{7}Be concentration profiles for the Tauranga sediment cores.

The depths of the ^{7}Be SML in cores taken from Tauranga Harbour are deep in comparison to other North Island estuaries. For example, maximum depths of ^{7}Be SML were ≤ 5 cm in intertidal-flat sediments of the Central Waitemata Harbour, Firth of Thames, Pauatahanui Inlet (Porirua) and Okura Estuary (Swales et al. 2005; Swales et al. 2007a; Swales et al. 2007b; Swales et al. 2008).

^{210}Pb concentrations in the SML of 5–15 Bq kg^{-1} are typical of North Island estuaries. Because of the relatively deep surface mixing indicated by the ^{7}Be data the temporal resolution of the ^{210}Pb dating will be reduced. Figures 10a-f present the ^{210}Pb concentration data and fitted regressions that are used to estimate time-averaged SAR. Typically, regressions are fitted to the ^{210}Pb profile in the accumulation zone below the SML, indicated by the x-radiograph and/or ^{7}Be data. In Tauranga Harbour sediments ^{210}Pb profiles display considerable scatter and the maximum depth of ^{210}Pb in most of the cores is less than 20 cm. This is shallow in comparison with recent studies in other North Island estuaries where ^{210}Pb profiles extend to 50 cm depth or more. This implies low accumulation rates in southern Tauranga Harbour sediments.



a)



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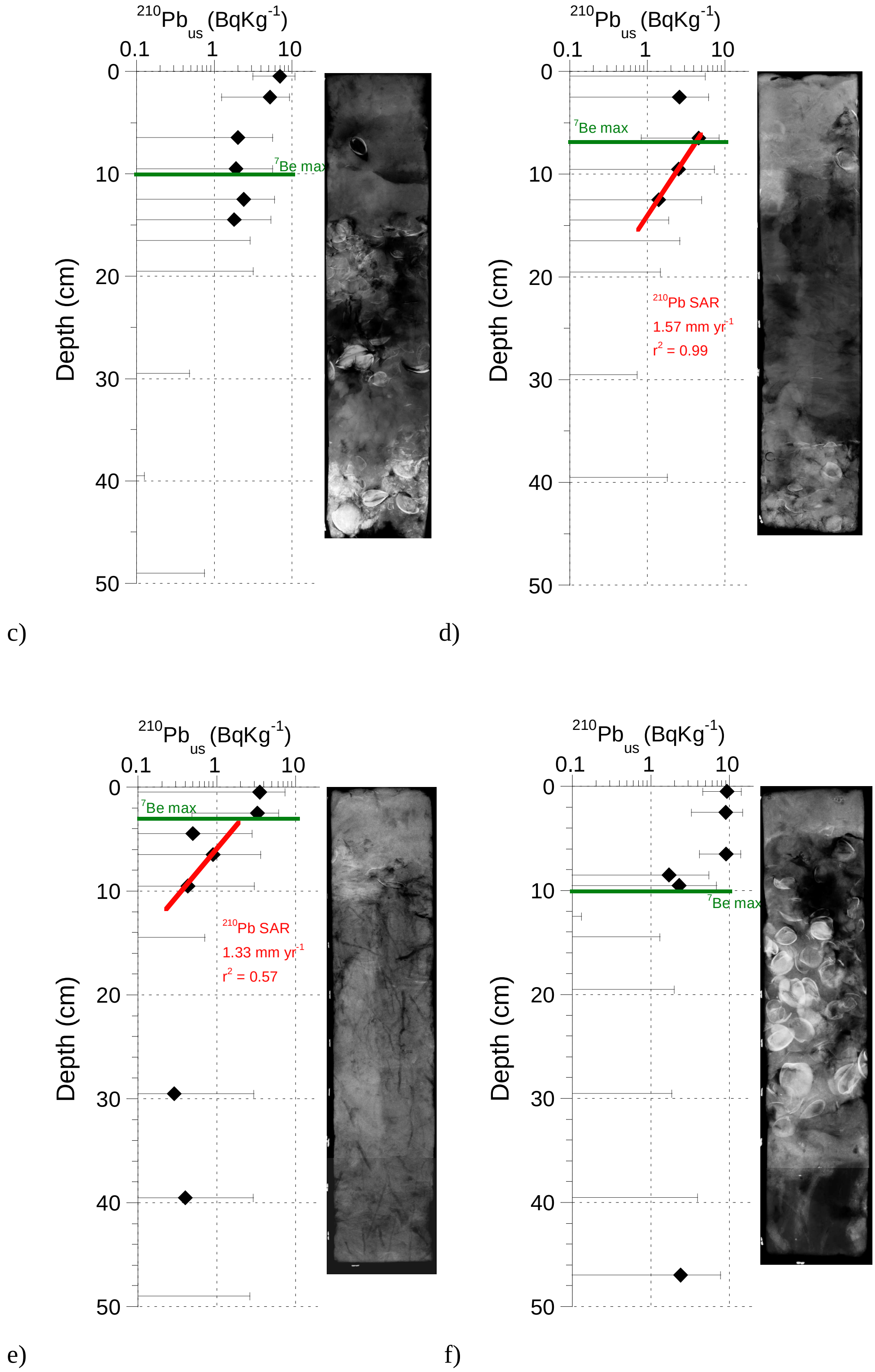

Figure 10a-f: The $^{210}Pb_{us}$ profiles and x-radiographs for SAR cores 2, 4, 8, 15, 19 and 23.

Core 2 (subestuary 2)

The ^{210}Pbprofile in core 2 displays considerable scatter (Fig. 10a). The coefficient of determination (r^2) of 0.5 for the regression fit is poor. The fit also includes data from the ^{7}Be SML, so that the estimated SAR of 7.2 mm yr^{-1} has considerable uncertainty.

Core 4 (subestuary 4)

At core site 4, the presence of the SML to 7 cm depth is indicated by relatively uniform ^{210}Pb concentrations (Fig. 10b). The regression fit to the ^{210}Pb data below the SML yields a SAR of 0.75 mm yr^{-1} (r^2 = 0.98, n = 3). The data points available (i.e., 3) are the minimum number for the regression fit. This accumulation zone occurs in the low-density mud layer immediately below the surficial shell-rich sand layer in the top most 10 cm of the core. These results indicate low inputs of sediments to the Waimapu Estuary (subestuary 4, Fig. 8), with deep mixing of surface sediment, most likely due to wave re-suspension. This physical sorting process will winnow fine silts from the SML. The residence time of sediment in the SML before it is removed by burial can be estimated from the ^{210}Pb SAR as D/SAR, where D is the SML thickness. For core 4 this gives a residence time of 70 mm/0.75 mm yr^{-1} = 90 years. Thus, core 4 indicates that sediments trapped in Waimapu Estuary will remain in the SML for almost a century before being removed by burial.

Core 8 (subestuary 8)

At core site 8, the ^{7}Be SML extends to 10 cm depth, with the maximum depth of ^{210}Pb being 15 cm. As a result, the ^{210}Pb data show considerable scatter and there are limited data below the SML (Fig. 10c). Therefore it was not possible to estimate a SAR for this site. These data are consistent with a highly wave-exposed intertidal flat, with negligible long-term accumulation of fine sediments. While fine terrigenous sediments might be deposited in the immediate aftermath of storms, the unconsolidated deposits can be eroded by waves and tidal currents, dispersed and settled in depositional environments elsewhere in the harbour.

Core 16 (subestuary 16)

At core site 16, the ^{7}Be SML extends to 7 cm depth, with the maximum depth of ^{210}Pb being less than 15 cm (Fig. 10d). The regression fit to the ^{210}Pb data below the SML yields a SAR of 1.57 mm yr^{-1} (r^2 = 0.99 n = 3). The data points available (i.e., 3) are the minimum number for the regression fit. The accumulation zone occurs in the transition between the higher-density fine-sand layer and the underlying lower-density muddy sand. The absence of ^{210}Pb below 12 cm depth suggests that most of this mud unit was deposited more than 100 years ago. The deep, intense mixing of the SML indicated by the x-radiograph and the uniform ^{7}Be concentration profile is consistent with a wave-exposed intertidal flat environment. The residence time of sediment in the SML before it is removed by burial is 70 mm/1.57 mm yr^{-1} = 45 years.

Core 19 (subestuary 8)

At core site 19, the ^{7}Be SML extends to 3 cm depth, with the maximum depth of ^{210}Pb being 40 cm (Fig. 10e). The regression fit to the ^{210}Pb data below the SML to 10-cm depth yields a SAR of 1.33 mm yr^{-1} (r^2 = 0.57 n = 3). The data points available (i.e., 3) are the minimum number for the regression fit. The accumulation zone occurs in the silty fine-sand and sandy-mud layers of the near-surface sediments. The high ^{210}Pb concentrations below 30 cm are likely due to downward mixing of more recent ^{210}Pb-labelled sediments. This is consistent with the x-radiograph which shows numerous mm-scale, mud-filled worm burrows in the sediment below the SML. The exponential decay in the ^{7}Be concentration profile indicates that mixing intensity reduces rapidly with depth in the sediment column. This is consistent with a more sheltered intertidal flat environment, as found in the Hunters Creek Inlet. The residence time of sediment in the SML before it is removed by burial is 30 mm/1.33 mm yr^{-1} = 23 years.

Core 23 (subestuary 12)

At core site 23 the ^{7}Be SML extends to 10 cm depth, with the maximum depth of ^{210}Pb being 48 cm (Fig. 10f). The uniform ^{7}Be and ^{210}Pb concentrations in the SML indicate intense physical sediment mixing at time-scales of ~100 days or less. The absence of ^{210}Pb between 10 cm and 40 cm depth coincides with the sandy-shell layer, which suggests that ^{210}Pb-labelled fine sediments are absent. As described for core 8, the radioisotope data are consistent with a wave- and tidal current-exposed intertidal flat where long-term accumulation of fine sediments is negligible.

4.7 Comparison of sedimentation rates with other North Island estuaries

The radioisotope data for Tauranga Harbour are relatively poor compared to those we have determined for some other North Island estuaries. For this reason have only 3 reliable SAR estimates based on radioisotopes for Tauranga Harbour (along with the single SAR based on the DDT marker in Waikareo Estuary). The lack of resolution in the radioisotope data is due to: (1) deep, intense physical mixing of sediments which means that the temporal resolution of the cores is reduced, (2) absence of ^{137}Cs in sediments so that we have no dating method independent of the ^{210}Pb data, and (3) low rates of fine-sediment accumulation on intertidal flats consistent with wave-driven sediment re-suspension, which exacerbates sediment-mixing effects. This is an interesting finding in itself as it suggests that there are low net rates of accumulation of fine sediments on the intertidal flats (at least in the places we cored) due to reworking by waves and currents and burrowing organisms.

By way of comparison, Figure 11 shows an example of the sedimentation record preserved in a sub-tidal basin at Karepiro Bay (North Shore, Auckland) where long-term accumulation of fine terrigenous sediments has been occurring over the last century (Swales et al. 2008). In this example the ^{210}Pb dating is supported by an independent ^{137}Cs SAR estimate. Furthermore, the ^{210}Pb data shows a smooth exponential decay with depth, with a robust fit to the data (r^2 = 0.88, n = 9), providing a high degree of confidence in the SAR estimate.

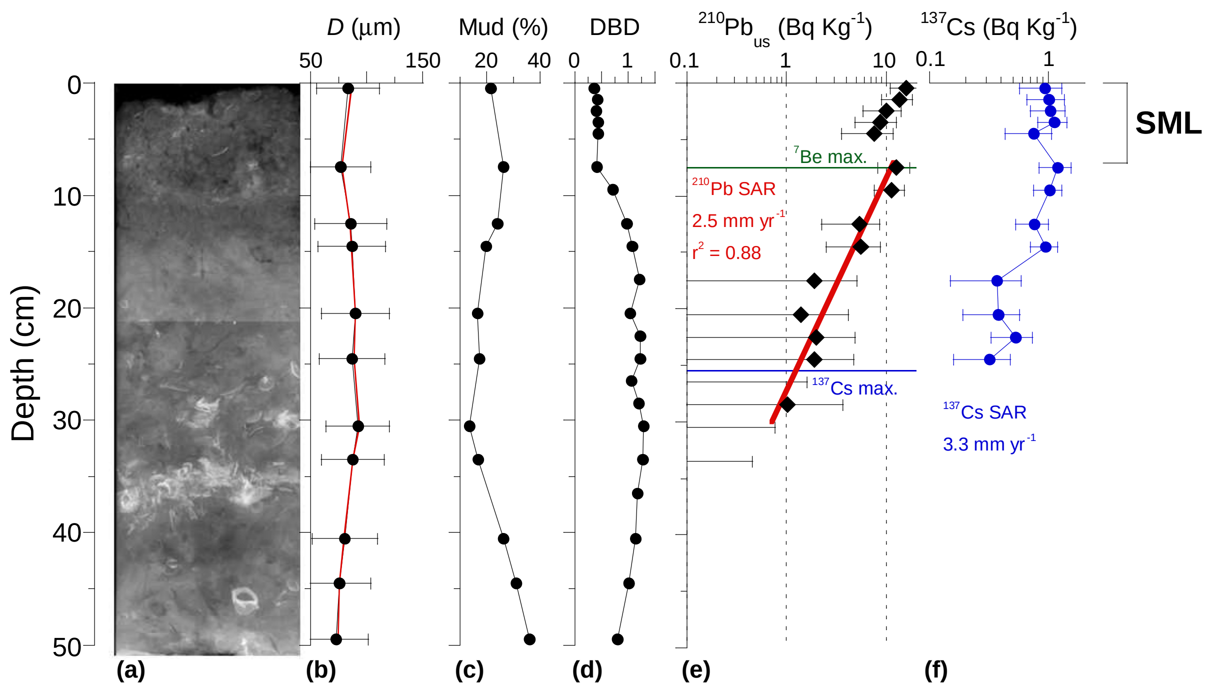

Figure 11: Core KPO-1 (Karepiro Bay subtidal) sediment profiles: (a) x-radiograph; (b) mean (black) and median (red) particle diameters, with 1 std dev plotted; (c) mud content (% volume); (d) dry-bulk sediment density (g cm^{-3}); (e) unsupported ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and co-efficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be and ^{137}Cs depths; (f) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR. Note: ^{137}Cs SAR accounts for rapid mixing in the surface mixed layer. Source: Swales et al. (2008).

In Tauranga Harbour, annual-average SAR of 0.75–1.57 mm yr^{-1} on intertidal flats over the last 50–100 years is low in comparison to other North Island estuaries where similar methods have been applied. In making this comparison it is important to distinguish between the various depositional environments found in estuaries: (1) tidal creeks, (2) intertidal flats, and (3) subtidal flats in the main bodies of estuaries. In the tidal creeks of the Auckland Region, SAR has typically averaged ~20 mm yr^{-1} over the last 50 years or so (e.g., Oldman and Swales, 1999; Swales et al. 2002a). Rapid infilling of these tidal creeks is a consequence of increased soil erosion associated with land development, close proximity to catchment outlets and estuarine processes that favour fine-sediment deposition.

Beyond the tidal creeks (which account for a small proportion of the estuary area) terrigenous sediments accumulate on intertidal and subtidal flats. Studies in Auckland's east-coast estuaries show that sedimentation has typically occurred more rapidly on intertidal (average 4.7 mm yr^{-1}) than on subtidal (average 2.9 mm yr^{-1}) flats (Swales et al. 2002b). Although, in the Central Waitemata Harbour, SAR was similar on intertidal (average 3.2 mm yr^{-1}) and subtidal (average 3.3 mm yr^{-1}) flats (Swales et al. 2007b). In the Pauatahanui Inlet (Porirua), rates of estuary infilling are similar to Auckland estuaries, with SAR averaging 2.4 mm yr^{-1} over the last century (Swales et al. 2005). In the Firth of Thames, several tens of millions of tonnes of fine sediment have been delivered by rivers over the last century, so that sedimentation has been extremely rapid even on highly wave-exposed intertidal flats. Radioisotope data show that SAR has averaged ~25 mm yr^{-1} since at least the 1930s (Swales et al. 2007a). This study also shows how mangroves influence the sedimentation process, with 3–5 fold increases in SAR following mangrove colonisation.

4.8 Summary

Sediment accumulation rate determined for various locations in the harbour provide information on where sediments are building up and rates of sediment accumulation over the past 90 years. This information will be used to calibrate sediment accumulation predictions by the USC-3 sedimentation model.

A literature search identified only one useful measurement of sediment accumulation rate. That was 0.9 mm/yr (over 58 years) for the Waikareo Estuary (subestuary 7).

Because there was little information available from existing studies, 10 subestuaries were selected for coring. Coring was undertaken, and sediments were dated by radioisotope techniques. X-radiographs (x-rays) of the cores were undertaken to show fine-scale sedimentary fabric and provide information on depositional processes, sediment texture, and whether the sediment column had been disturbed by animal burrowing (bioturbation) and/or physical processes such as wave stirring of the seabed. This information was also used to prioritise which cores to date and exactly where to take subsamples of sediment from the cores for radioisotope analysis. Sediment cores were dated using the radioisotopes ^{137}Cs and ^{210}Pb. Sediment accumulation rates were calculated from the vertical concentration-activity profiles of ^{210}Pb and ^{137}Cs. Concentrations of the cosmogenic radioisotope ^{7}Be (½ life 53 days) were also measured in the core samples to provide information on the depth and intensity of sediment mixing in the surface-mixed layer and to identify those cores where the sediments were least likely to be disturbed by bioturbation and physical mixing (as mixing corrupts the SAR data derived from the dating). Detailed radioisotope dating was undertaken on 6 cores. Sediment accumulation rates so derived were 0.75 mm/yr over 90 years (Waimapu Inlet, subestuary 4), 1.57 mm/yr over 45 years (Te Hopai Estuary, subestuary 16), and (Hunters Creek, subestuary 8) 1.33 mm/yr over 23 years. These rates are low compared to other estuaries on the east coast of Auckland, the Firth of Thames and Pauatahanui Inlet (Wellington).

The low rates of sediment accumulation and the radioisotope evidence of deep mixing in the cores indicate that large areas of the wave-exposed intertidal flats in southern Tauranga Harbour are not long-term sinks for fine terrigenous sediments. There is evidence of reworking of deposited sediment (by waves and tides stirring the seabed) which remobilises sediment, which is then dispersed away from the original deposition site more widely about the harbour. Potential depositional environments for that sediment include tidal flats, tidal creeks, sheltered bays, mangroves and saltmarsh habitats. Sediment is also exported from the harbour to the inner shelf. These hypotheses need to be tested and reconciled against the results from the modelling components of this study.

5. Acknowledgements

We thank Stephen Park and his colleagues for extracting survey and sediment data from EBOP records for our use. Sanjay Wadhwa assisted with the GIS work. Anna Altenberger and Rod Budd assisted with the field work and coring, and Ron Ovenden processed the cores. University of Waikato staff Terry Healy, Debra Stokes, Kyle Spiers provided sediment data from their records. We thank Richard Gorman and Malcolm Green of NIWA for reviewing the report. We thank the Auckland Regional Council (Monitoring & Research Group) for permission to reproduce the Karepiro Bay sediment core data.

6. References

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Oldman, J.W. & Swales, A. (1999). Maungamaungaroa estuary numerical modelling and sedimentation. NIWA Client Report ARC70224.

Sommerfield, C.K.; Nittrouer, C.A. & Alexander, C.R. (1999). ^{7}Be as a tracer of flood sedimentation on the Northern California margin. *Continental Shelf Research 19*: 335–361.

Swales, A.; Williamson, R.B.; Van Dam, L.F.; Stroud, M.J.; McGlone, M.S. (2002a). Reconstruction of urban stormwater contamination of an estuary using catchment history and sediment profile dating. *Estuaries 25(1)*: 43–56.

Swales, A.; Hume, T.M.; McGlone, M.S.; Pilvio, R.; Ovenden, R.; Zviguina, N.; Hatton, S.; Nicholls, P.; Budd, R.; Hewitt, J.; Pickmere, S.; Costley, K. (2002b). Evidence for the physical effects of catchment sediment runoff preserved in estuarine sediments: Phase II (field study). ARC Technical Publication 221. NIWA Client Report HAM2002-067.

Swales, A.; Bentley, S.J.; McGlone, M.S.; Ovenden, R.; Hermansphan, N.; Budd, R.; Hill, A.; Pickmere, S.; Haskew, R.; Okey, M.J. (2005). Pauatahanui Inlet: effects of historical catchment landcover changes on estuary sedimentation. NIWA Client Report HAM2004-149 for Wellington Regional Council and Porirua City Council.

Swales, A.; Bell, R.G.; Ovenden, R.; Hart, C.; Horrocks, M.; Hermansphan, N.; Smith, R.K. (2007a). Mangrove-habitat expansion in the southern Firth of Thames: sedimentation processes and coastal-hazards mitigation. NIWA Client Report HAM2006-138 for Environment Waikato.

Swales, A.; Stephens, S.; Hewitt, J.E.; Ovenden, R.; Hailes, S.; Lohrer, D.; Hermansphan, N.; Hart, C.; Budd, R.; Wadhwa, S.; Okey, M.J. (2007b). Central

Waitemata Harbour Study. Harbour Sediments. NIWA Client Report HAM2007-001 for Auckland Regional Council.

Swales, A.; Gibbs, M.; Ovenden, R.; Budd, R. & Hermansphan, N. (2008). Sedimentation in the Okura – Weiti – Karepiro Bay system. NIWA Client Report HAM2008-153.

Valette-Silver, N.J. (1993). The use of sediment cores to reconstruct historical trends in contamination of estuarine and coastal sediments. *Estuaries* 16(3B): 577–588.

7. Appendix 1: Sediment grainsize statistics and composition data.

All studies located during the review.

Reference	Sediment character (grainsize and composition): sediment data	Sediment character: data used	Sediment character: why not	Sedimentation rate (SAR): rate data	Sedimentation rate (SAR): data used	Sedimentation rate (SAR): why not	
Barnett, A.G. and Gregorius, B.H. 1984 Tauranga Harbour Study Report. Numerical modelling of the proposed harbour crossing. Water quality centre job report No. WT319/1	☒	n/a		☒	n/a		1
Barnett, A.G. and Bell, R.G. 1984. Tauranga Harbour Study Report. Hydrodynamic model results for the Tauranga harbour ship handling report. Water quality centre job report No. WT319/2	☒	n/a		☒	n/a		2
Barnett, A.G. 1984. Tauranga Harbour Study. Model studies of alternative Tauranga harbour bridge configurations. Consultant report WT319/3.	☒	n/a		☒	n/a		3
Barnett, A.G. 1985. Tauranga harbour study. Studies of the new Murray-North harbour bridge proposal. Consultant report No. WT319/4.	☒	n/a		☒	n/a		4
Barnett, A.G. 1985. Tauranga Harbour Study. Tauranga harbour tridge - impact on tidal flows. Consultant report No. WT319/5	☒	n/a		☒	n/a		5
Barnett, A.G. 1985. Tauranga Harbour Study. Part 1: OVERVIEW	☑	☒	data in healy report	☒	n/a		6
Barnett, A.G. 1985. Tauranga Harbour Study. Part 3: Hydrodynamics	☑	☒	data in healy report	☒	n/a		7
Beamsley, B and Black K. 2003. Opureora (Matakana Ferry) Channel Dredging: Field data collection. Report prepared for: Boffa Miskell Ltd on behalf of EBOP. Report Number 2003.1400.1 ASR Ltd.	☑	☒	subtidal	☑	☒	inferred from settling velocities	8
Bell, R.G., 1991. Port of Tauranga model study (deepened shipping channel proposal), Port of Tauranga Limited, Mt Maungauni .DSIR report 6127/1,	☒	n/a		☒	n/a		9
Bell, R.G., 1994. Port of Tauranga model study: Sulphur point whaft extensions , Port of Tauranga Ltd., Mt Maunganui. NIWA report POT002/1.	☒	n/a		☒	n/a		10
Black, K.P., 1984. Sediment Transport. Tauranga Harbour Bridge.Part IV: TEXT	☑	☒	data is from Healy field study	☑	☒	data is from Healy field study	11
Black, K.P., 1984. Sediment Transport. Tauranga Harbour Bridge.Part IV: FIGUES AND TABLES	☑	☒	data is from Healy field study	☑	☒	data is from Healy field study	12
Burggraaf, S., Langdon, A.G., and Wilkins, A.L., 1994. Organochlorine contaminants in sedments of Tauranga Harbour, New Zealand. NZJMFR, 28(3): 291-298.	☑	☒	not comparable	☑	☑		13
Burggraaf, S, Wilkins, A.L., Langdon, A.G., Kim N.D. 1997. Heavy metals and organic hydrocarbons in sediments from the waikareao estuary, Tauranga Harbour, New Zealand. Bulletin of Environmental Contamination and Toxicology. 58:871-878.	☑	☒	same grain size data as from 1994 paper	☒	n/a		14
Dahm, J. 1983. The geomorphic development, bathymetric stability and sediment dynamics of Tauranga Harbour. MSc thesis, Department of Earth Sciences, University of Waikato, Hamilton	☑	☒	not in subestuary	☒	n/a		15
Davies-Colley, R.J., 1976. Sediment dynamics of Tauranga Harbour and the Tauranga Inlet. MSc thesis, University of Waikato.	☑	☑		☑	☒	inferred from settling velocities	16
Davies-Colley, R.J. and Healy, T.R. 1978. Sediments and hydrodynamics of the Tauranga Entrance to Tauranga harbour. N.Z. Journal of Marine and Freshwater Reaserach 12(3): 225-36.	☑	☒	not in subestuary, entrance data	☒	n/a		17
Davis, R.A. and Healy, T.R. 1993. Holocene coastal depositional sequences on a tectonically active setting: southeastern Tauranga harbour, New Zealand. Sedimentary Geology, 84: 57-69.	☒	n/a		☑	☒	no dates for cores	18
de Lange, W.P., 1988. Wave climate and sediment transport within Tauranga Harbour, in the vicinity of Pilot Bay. D.Phil. Thesis, University of Waikato, Hamilton, New Zealand	☑	☒	not in subestuary	☒	n/a		19

EBOP Surveys - Sedimentation Site Monitoring Data	☒	n/a		☑	☒	rates not accurate enough	20
Healy, T.R. 1985.Tauranga Harbour Study Part ii: Field data collection programme	☑	☑		☑	☒	no dates done on cores	21
Healy, T.R. 1985.Tauranga Harbour Study Part V: Morphological study	☑	☒	same data as field data collection report	☒	n/a		22
Hope, H.M., 2002. Sediment Dynamics of Waikaraka Estuary, a small, semi-encolsed estuarine system in the upper reaches of a developed harbour. M.Sc. Thesis. University of Waikato, New Zealand.	☑	☑		☑	☒	rates not accurate enough	23
Lelieveld, S.D. et al 2004 New Zealand Journal of Marine and Freshwater Research, Vol 38: 115 - 128.	☑	☒	not in subestuary	☒	n/a		24
Kruger and Healy 2006 Mapping the morphology of a dredged ebb tidal delta, tauranga harbour, nz. Journal of coastal research. 22. 3. 720-727.	☑	☒	not in subestuary	☒	n/a		25
Matheson, F.E. and Schwarz, A.-M. 2007. Growth responses of Zostera capricorni to estuarine sediment conditions. Aquatic botany.	☒	n/a	no data for Tauranga	☒	n/a		26
McIntosh, J., 1994. Tauranga Harbour Regional Plan Environmental Investigations; Water and sediment quality of Tauranga Harbour. EBOP 94/10. ISSN 1172-5850	☑	☑		☒	n/a		27
Park, S.G. 2000. Benthic macrofauna monitoring. EBOP environmental report 2000/15. ISSN 1172-5850	☑	☑		☒	n/a		28
Park, S.G., 2003. Marine sediment and contaminants survey (2001-03) of Tauranga Harbour. EBOP, 2003/20	☑	☑		☒	n/a		29
Perano, Katrina.M. 2000. Sediment transport on intertidal falts in atide-dominated environment, Wairoa Estuary, Tauranga, New Zealand.M.Sc thesis, University of Waikato, Hamilton	☑	☒	same data as Heybridge study	☑	☒	inferred from settling velocities	30
Roper, D. 1990.Benthos associated with an estuarine outfall, Tauranga Harbour, New Zealand. New Zealand Journal of Marine and Freshwater Research, Vol. 24: 487-498.	☑	☒	not in subestuary	☒	n/a		31
Stokes, D.J., Healy, T.R. and Cooke, P.J. 2008. Surface Elevation Changes and Sediment Characteristics of Intertidal Surfaces Undergoing Mangrove Expansion, and Mangrove Removal, Waikaraka Estuary, Tauranga Harbour, New Zealand. Xxxxxxxxxxxxxx	☑	☑		☑	☒	cores not yet processed, RSET data not over long enough time period	32
Stokes, Debra. Unpublished sediment grain size data. Excel spread sheet	☑	☑		☒	n/a		33
Stokes, Debra. Draft Report for EBOP. Tauranga mangrove managemetn monitoring programme. September 2007.	☑	☒	Grain size already given in Stokes unpublished	☑	☒	same data as Stokes 2008, RSET data not over long enough time period	34
Surman, M., Clarke, R. and Carter, M. 1999. Tauranga Harbour sediment source survey. Environment BOP Operations report 98/13. EBOP.	☒	n/a	stream data	☒	n/a	stream stuff	35
Swales, A., Hume, T., Gorman, T., Perano, K., MacDonald, I., Budd, R. Liefting, R. 2000. Invertigations For Te Tawa Marina, Tauranga Harbour: Sedimentary aspects of navigation channel alighment and dredging. HDL90203, NIWA, Hamilton	☑	☑	n/a	☑	☒	no dates done on cores	36
Tian, F. 1998. Accumulation of Resin Acids in Sediments Adjacent to a log handling area, Tauranga Harbour, New Zealand. Bull. Evniron. Contam. Toxicol. 60:441-447.	☒	n/a		☒	n/a		37
Wallingford Report. 1963. Wallingford Hydraulics Research Station of Berkshire, England.	☒	n/a		☒	n/a		38
White, J. 1979. Recent Sediments of Waikareao Estuary, Tauranga, New Zealand. M.Sc. Thesis. University of Waikato, New Zealand.	☑	☑		☒	n/a		39
Williams, B.L. 1984. Tauranga Harbour Effluent Dispersion Study. Consultant report No. WT402.	☒	n/a		☒	n/a		40

Sediment grainsize mean, sorting and skewness results per study per subestuary.

subestuary	study name	number of samples to calculate mean	mean (mm)	stdev	number of samples to calculate sorting and skewness	mean sorting	mean skewness
1	McIntosh 1994	1	0.236	n/a	1	1.254	0.280
	Park 2003	3	0.286	0.030	3	1.077	0.252
2	McIntosh 1994	2	0.399	0.136	2	0.917	-0.015
	Park 2003	6	0.298	0.090	6	1.093	0.208
3	Park unpublished data	2	0.291	0.015	2	1.780	0.430
	McIntosh 1994	2	0.248	0.112	2	1.786	-0.240
	Stokes unpublished data	12	1.133	0.469	0	n/a	n/a
4	Park unpublished data	1	0.395	n/a	1	1.341	0.042
	McIntosh 1994	1	0.325	n/a	1	1.038	0.210
	Park 2003	1	0.285	n/a	1	1.443	0.210
5	Park unpublished data	1	0.468	n/a	1	1.095	-0.105
	McIntosh 1994	2	0.359	0.170	2	1.503	0.090
	Park 2003	6	0.407	0.219	6	1.136	0.003
6	McIntosh 1994	2	0.252	0.100	2	0.796	0.155
	Park 2003	18	0.329	0.104	18	1.065	0.256
7	Park unpublished data	1	0.341	n/a	1	1.554	0.543
	White 1979	87	0.147	0.091	87	1.444	0.164
	McIntosh 1994	3	0.363	0.239	3	1.397	0.257
	Park 2003	1	0.141	n/a	1	0.858	0.114
	Stokes unpublished data	11	0.990	0.706	0	n/a	n/a
8	Park unpublished data	2	0.346	0.094	2	1.559	0.560
	McIntosh 1994	3	0.259	0.058	3	0.825	0.110
	Park 2003	9	0.318	0.121	9	0.858	0.286
	Swales 2000	12	0.287	0.165	12	0.928	0.350
9	Hope 2002	33	0.272	0.116	33	1.772	0.377
	McIntosh 1994	1	0.252	n/a	1	1.688	-0.290
	Stokes unpublished data	17	0.768	0.452	0	n/a	n/a
	Stokes 2008	3	0.162	0.044	0	n/a	n/a
10	Park unpublished data	1	0.295	n/a	1	1.760	0.384
	McIntosh 1994	2	0.300	0.048	2	1.987	-0.060
	Park 2003	6	1.938	1.506	1	1.437	0.386
11	McIntosh 1994	2	0.202	0.031	2	0.976	0.040
	Park 2003	3	0.173	0.017	3	1.123	0.434
12	nil	0	n/a	n/a	0	n/a	n/a
13	McIntosh 1994	1	0.061	n/a	1	4.574	-0.180
	Park 2003	3	2.441	2.823	0	n/a	n/a
14	Park 2003	1	0.961	n/a	0	n/a	n/a
15	Park 2003	1	1.010	n/a	0	n/a	n/a
16	McIntosh 1994	2	0.146	0.166	2	2.176	-0.275
	Park 2003	4	0.769	1.136	3	0.639	0.066
17	McIntosh 1994	2	0.255	0.029	2	0.717	0.105
	Park 2003	5	0.495	0.084	5	1.144	-0.010
	Swales 2000	1	0.232	n/a	1	1.450	-0.530
18	Park 2003	1	0.321	n/a	1	0.967	0.397
19	Park unpublished data	2	0.277	0.003	2	1.853	0.353
	McIntosh 1994	1	0.180	n/a	1	1.045	0.320
	Park 2003	7	0.345	0.030	7	0.890	0.325
20	Davies-Colley 1979	7	0.344	0.125	7	0.889	-0.253
	Healy 1985	27	0.349	0.123	27	0.884	-0.187
	McIntosh 1994	1	0.278	n/a	1	0.574	0.030
21	Healy 1985	2	0.349	0.209	2	1.075	0.100
	McIntosh 1994	2	0.206	0.059	2	1.853	0.330
	Park 2003	3	0.287	0.056	3	0.987	0.491
	Swales 2000	10	0.217	0.060	10	1.087	-0.301
22	Park 2003	1	0.235	n/a	1	0.458	0.113
23	McIntosh 1994	2	0.308	0.070	2	1.263	0.040
24	Park 2003	2	0.326	0.220	2	1.448	0.290
25	McIntosh 1994	1	0.199	n/a	1	1.300	0.090
	Park 2003	1	0.258	n/a	1	1.201	0.304
	Swales 2000	1	0.415	n/a	1	0.940	-0.150
26	Park unpublished data	1	0.351	n/a	1	1.511	0.191
	McIntosh 1994	1	0.225	n/a	1	2.199	-0.290
	Park 2003	2	0.287	0.103	2	1.417	0.347

Sediment composition results per study per subestuary.

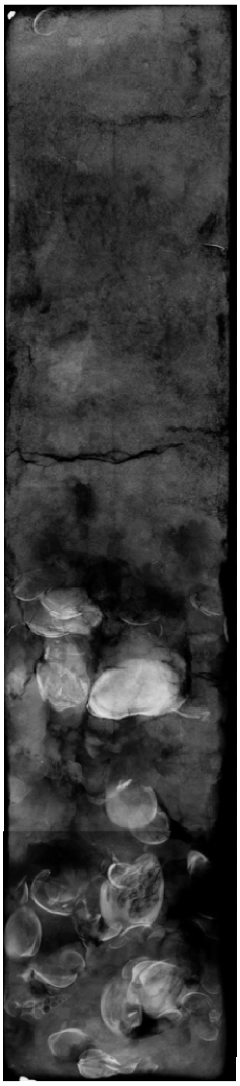
subestuary	study name	number of samples used to calculate composition	percent mud (<63 µm)	percent sand (63 µm - 2 mm)	percent gravel (> 2 mm)
1	McIntosh 1994	1	7.00	91.00	2.00
	Park 2003	10	14.64	84.79	0.56
2	McIntosh 1994	2	1.50	96.50	2.00
	Park 2003	15	7.61	91.44	0.95
3	Park unpublished data	2	8.37	90.46	1.18
	McIntosh 1994	2	11.00	86.50	2.50
	Park 2003	18	23.11	76.19	0.72
	Stokes unpublished data	12	44.03	55.97	0.00
4	Park unpublished data	1	0.00	99.20	0.80
	McIntosh 1994	2	12.00	84.00	4.00
	Park 2003	22	29.69	69.39	0.92
5	Park unpublished data	1	2.97	97.03	0.00
	McIntosh 1994	2	6.00	87.50	7.00
	Park 2003	17	10.65	87.07	2.34
6	McIntosh 1994	2	2.50	95.50	2.00
	Park 2003	27	8.54	90.84	0.61
7	Park unpublished data	1	0.82	97.58	1.60
	White 1979	87	18.68	80.83	0.36
	McIntosh 1994	4	6.50	86.00	7.50
	Park 2003	22	12.97	86.08	0.94
	Stokes unpublished data	11	62.55	37.54	0.00
8	Park unpublished data	2	0.90	96.40	2.71
	McIntosh 1994	3	1.67	96.67	1.67
	Park 2003	21	4.68	94.18	1.14
	Swales 2000	14	2.55	92.94	4.49
9	Hope 2002	33	22.35	77.64	0.00
	McIntosh 1994	1	11.00	86.00	3.00
	Park 2003	1	1.02	98.34	0.64
	Stokes unpublished data	17	65.65	33.29	0.00
	Stokes 2008	3	33.33	66.33	0.00
10	Park unpublished data	1	11.19	88.35	0.46
	McIntosh 1994	2	9.50	84.50	6.00
	Park 2003	16	24.55	73.04	2.41
11	McIntosh 1994	2	6.50	92.50	1.00
	Park 2003	19	25.50	73.90	0.58
12	Park 2003	5	8.16	90.99	0.85
13	McIntosh 1994	1	36.00	49.00	15.00
	Park 2003	12	49.10	49.39	1.52
14	McIntosh 1994	1	22.00	78.00	0.00
	Park 2003	11	48.12	49.99	1.89
15	Park 2003	10	27.17	72.27	0.56
16	McIntosh 1994	2	22.50	75.00	2.50
	Park 2003	26	14.74	82.67	1.83
17	McIntosh 1994	2	0.50	97.50	2.00
	Park 2003	11	3.42	95.46	1.10
	Swales 2000	1	8.50	81.10	10.38
18	Park 2003	7	10.84	88.89	0.28
19	Park unpublished data	2	8.17	90.97	0.87
	McIntosh 1994	1	2.00	93.00	5.00
	Park 2003	35	8.64	90.17	1.20
20	Davies Colley 1979	7	0.69	96.14	3.21
	Healy 1985	27	0.18	96.62	3.11
	McIntosh 1994	1	0.00	100.00	0.00
	Park 2003	1	0.00	100.00	0.00
21	Healy 1985	2	0.00	96.65	0.29
	McIntosh 1994	2	8.00	83.50	8.50
	Park 2003	8	7.13	88.97	3.92
	Swales 2000	9	1.64	92.04	6.31
22	Park 2003	1	0.70	99.30	0.01
23	McIntosh 1994	2	5.00	92.00	3.00
	Park 2003	3	3.74	93.58	2.69
24	Park 2003	3	14.07	80.74	5.19
25	McIntosh 1994	1	9.00	90.00	1.00
	Park 2003	9	12.14	87.52	0.35
	Swales 2000	1	0.48	95.81	3.70
26	Park unpublished data	1	13.56	86.01	0.43
	McIntosh 1994	1	12.00	84.00	4.00
	Park 2003	4	15.05	83.21	1.75

8. Appendix 2: Sediment coring core field notes and x-radiographs.

Core 2 - subestuary 2

Site description: Sand, ripples, few shells on top. Thick black smelly layer of sand below. Bottom layer is soft, fine, grey clay with lots of big dead shells.

← 0 cm (surface)



← 50 cm (Depth below surface)

Core 2 was collected from Rangataua Bay (subestuary 2, Fig. 8). The x-radiographs show that sediments are composed of homogenous silty-sand to 25 cm depth, where there is a sharp contact with a shell layer containing abundant shell valves and fragments of cockle. The surface-mixed layer (SML) extends to about 6 cm depth, where a contact with lower-density silts occurs. There is little intact lamination or bedding above the shell layer. The numerous mm-scale vertical tubes infilled with mud are indicative of the burrowing action of worms. The dark areas within the shell layer are consistent of muds and/or sediments with high water content.

Core 4 - subestuary 4

Site description: Firm near shore but got muddier and muddier as we walked toward site. Got too soft to walk. Muddy, burrows, sparse shell on surface. Mud lower down in core too. Grey soft clay layer with large dead shells/hash at bottom.

← 0 cm

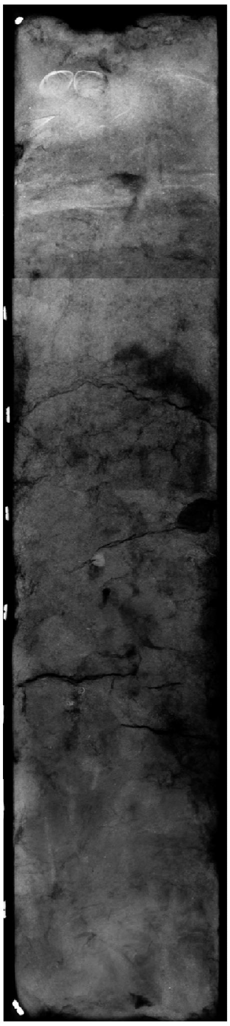
← 45 cm

Core 4 was collected from Waimapu Estuary (subestuary 4, Fig. 8). The x-radiographs show that sediments are composed of a surface-layer of shell-rich sand over-laying a low-density mud layer below 10 cm depth. Shell material is rare in the top-most 5 cm of the core. The mud layer has a mottled appearance with numerous dark patches and tubes of low-density material. There is little evidence of intact bedding, which is consistent with sediment mixing by animals.

Core 6 - subestuary 6

Site description: Firm sand, ripples, few shells. Sandy lower down in core as well. No clay/mud. Seagrass beds 200-300 m away.

← 0 cm



← 50 cm

No description of core 6 as it was not selected for SAR analysis.

Core 8 - subestuary 8

Site description: Firm and sandy on top. Shell hash layer below. Clay layer with shell below that.

← 0 cm

← 45 cm

Core 8 was collected from the wave-exposed intertidal flats of the Wairoa River mouth near Oikimoke Point (subestuary 8, Fig. 8). The x-radiograph indicates that the top of the core is composed of a homogenous sandy-mud or water-logged fine-sand. A sharp contact with an underlying cockle-shell layer occurs at 15 cm depth. The dark areas within the shell layer indicate water and/or mud-filled voids. There is little evidence of intact bedding. This is most likely the result of sediment mixing related to the feeding and burrowing activities of animals. This is indicated by the mottled appearance of the sediment, which occurs when sediments of different textures are incompletely mixed. By comparison physical mixing of intertidal-flat sediments, most commonly by waves, results in fine-scale laminations, due to sediment re-suspension, sorting and re-deposition.

Core 10 - subestuary 10

Site description: Thin soft muddy layer on the top covering a moderately firm brown sand/mud mix with some cockles and macomona. Thick layer of black sand below. Grey clay with layers of dead shells. Then layer of grey clay only. Mangroves on upper shore.

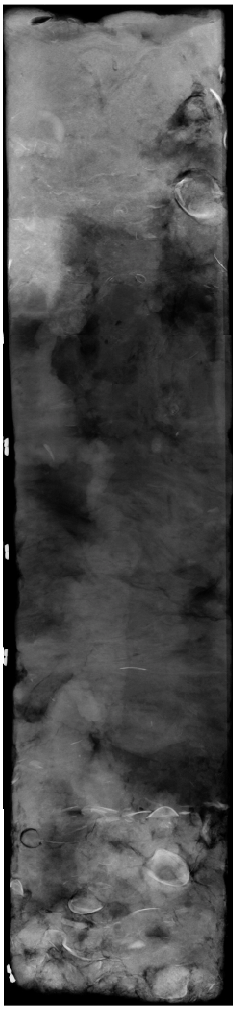
← 0 cm

← 45 cm

No description of core 10 as it was not selected for SAR analysis.

Core 16 - subestuary 16

Site description: Very difficult to navigate to correct site. Couldn’t get up small channels. Had to pick new site that we could access by boat. Took core in subestuary 16. Firm sand on top, mud lower down. Hole filled with water so couldn’t take cross section photo. Took spade full of sand and got photo of top section only – top layer oxic sand, then black anoxic sand beneath. Can’t see mud layer in photo but it was there. Seagrass at channel edge. Mangroves fringe shoreline.



← 0 cm

← 45 cm

Core 16 was collected from wave-exposed intertidal flats east of Te Hopai Island (subestuary 16, Fig. 8). The x-radiograph indicates a relatively high-density fine-sand layer to ~10 cm depth overlaying lower-density muddy sand. There is some evidence of bedding towards the base of the surface sand layer, at 7–9 cm depth. This is indicated by fine mm-scale horizontal laminations in the sediment. There is also evidence of weak bedding in the muddy sand unit below 10 cm depth. A sharp contact with a cockle-shell layer with fine sand occurs at 37 cm depth.

Core 17 - subestuary 17

Site description: Firm sand with shells on surface. Narrow shore. Lots of water in sand, hard to dig out cores. Seagrass bed nearby.

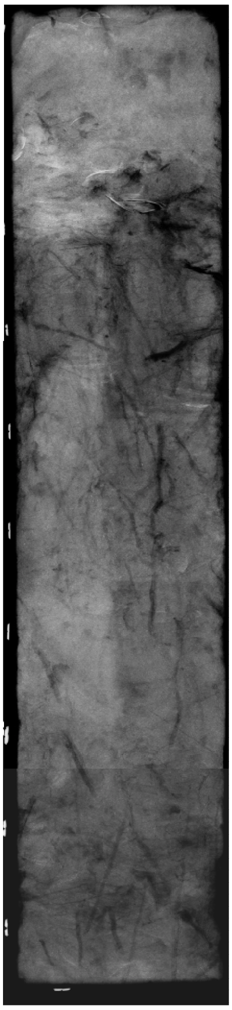
← 0 cm

← 45 cm

No description of core 17 as it was not selected for SAR analysis.

Core 19 - subestuary 8

Site description: Hard sand with ripples. Firm brown sand at top then thick black layer of sand. Seagrass fringe along channel. Mangroves on upper shore.



← 0 cm

← 45 cm

Core 19 was collected from intertidal flats near Paeroa Point in the Hunters Creek Inlet, which separates Rangiwaea and Matakana Islands (subestuary 8, Fig. 8). The x-radiograph indicates a relatively high-density silty fine-sand layer to ~7 cm depth overlaying a lower-density sandy-mud. Bedding in the lower part of the surface sand layer. The sandy mud unit below 7 cm, contains numerous mm-scale, mud-filled vertical burrows formed by worms. There is also some evidence of bedding, as shown by fine laminations at 15–20 cm depth. Cockle-shell valves and fragments are rare throughout this core. This is consistent with the worm-dominated muddy sediments found at this site.

Core in subestuary 21 – No core taken

Firm sand with ripples which broke the coring hammer. As this site was near site #8 (~1.5 km), and had similar physical characteristics (layer of shell hash then mud) it seemed likely long term deposition would be similar. No core taken. Large dense sea grass beds in area.

No site photo.

No core.

No x-radiograph.

No sand photo.

Core 23 - subestuary 12

Site description: Moderately firm sand/mud mix underfoot, thin soft muddy layer on top, except in middle of larger seagrass patches where sand/mud up to ankles. Thick black sand layer below. Layer of dead shells in grey clay. Then layer of grey clay only. Many large seagrass bed in the area.

← 0 cm

← 45 cm

Core 23 was collected from intertidal flats west of the Omokoroa Peninsula (subestuary 12, Fig. 8). A relatively high-density silty fine-sand layer occupies the top 4-cm of the core. A thin layer of sand at the base of the unit is indicative of sediment sorting by wave resuspension/re-deposition. This surface layer overlies a sandy shell layer extending from 4 cm to 35 cm depth. A sandy-mud unit occurs below 35 cm. There is little evidence of intact bedding in this core.

9. Appendix 3: Sediment core dating methodology.

X-ray digitising procedure

The x-rays films were digitised as follows. Films were illuminated using a Kaiser Prolite 5000 high-frequency 5000°K lightbox. A Nikon D1x digital SLR camera with 60mm f2.8D microNikkor lens (ISO 125, f6.3 or f7.1 aperture) was used to image the films. File format is black and white RGB-tif files with 3008 x 1960 pixels. The images were cropped and in some cases duplicated and image and contrast adjustments made using the Adobe Photoshop software.

In x-ray images relatively high density objects such as carbonate shells and sands appear white. Lower density organic material (e.g., plant fragments) and/or fine-grained muds are identified as darker grey–black areas.

Sediment Mixing

Biological and physical processes, such as the burrowing and feeding activities of animals and/or sediment resuspension by waves (Fig. A3.1), mix the upper sediment column (Bromley, 1996). As a result, sediment profiles are modified and this limits the temporal resolution of dating. Various mathematical models have been proposed to take into account the effects of bioturbation on ^{210}Pb concentration profiles (e.g., Guinasso and Schink, 1975).

Biological mixing has been modelled as a one-dimensional particle-diffusion process (Goldberg and Kiode, 1962) and this approach is based on the assumption that the sum effect of 'random' biological mixing is integrated over time. In estuarine sediments exposed to bioturbation, the depth profile of unsupported ^{210}Pb typically shows a two-layer form, with a surface layer of relatively constant unsupported ^{210}Pb concentration overlying a zone of exponential decrease. In applying these types of models, the assumption is made that the mixing rate (i.e., diffusion co-efficient) and mixing depth (i.e., surface-mixed layer, SML) are uniform in time. The validity of this assumption usually cannot be tested, but changes in bioturbation process could be expected to follow changes in benthic community composition.

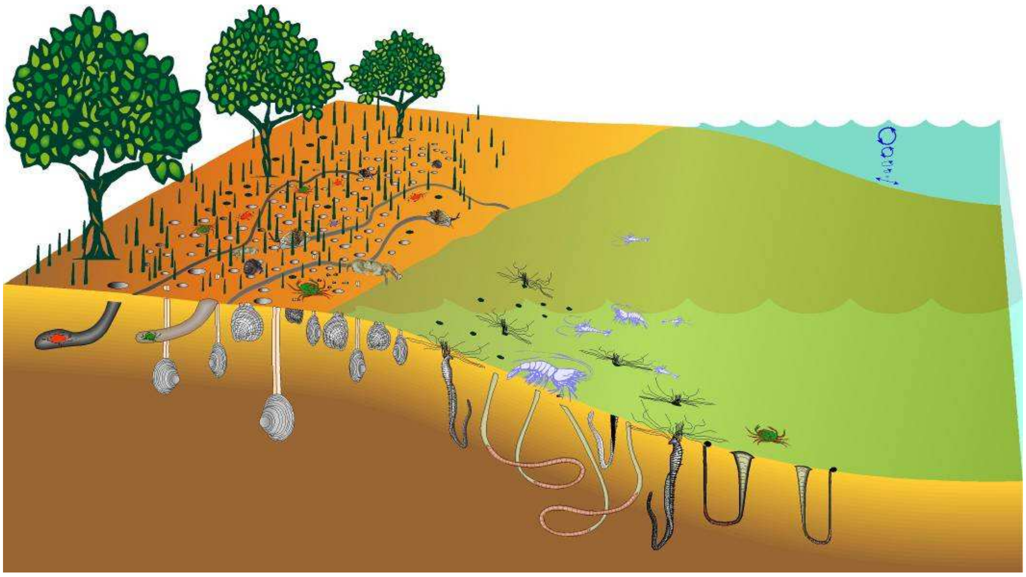


Figure A3.1: Biological and physical processes, such as the burrowing and feeding activities of animals and/or sediment resuspension by waves, mix the upper sediment column. As a result, sediment profiles are modified and limit the temporal resolution of dating. The surface mixed layer (SML) is the yellow zone.

Radioisotope dating

Sediment cores are dated using the radioisotopes caesium-137 (^{137}Cs, ½ life 30 years) and lead-210 (^{210}Pb, ½ life 22.3 years). SAR are calculated from the vertical concentration-activity profiles of ^{210}Pb and ^{137}Cs. Concentrations of the cosmogenic radioisotope berrylium-7 (^{7}Be, $t_{1/2}$ 53 days) were also measured in the core samples. ^{7}Be is particle reactive and tends to be concentrated in aquatic systems, making it a useful sediment tracer in fluvial-marine systems at seasonal timescales (Sommerfield et al. 1999). In the present study, ^{7}Be is used to provide information on the depth and intensity of sediment mixing in the surface-mixed layer (SML).

Sediment dating using several independent methods offsets the limitations of any one approach. This is important when interpreting sediment profiles from estuaries because of the potential confounding effects of sediment mixing by physical and biological processes. Sediment mixing by physical and biological processes in the surface mixed layer (SML) results in uniform radioisotope concentrations. Because of differences in ^{7}Be and ^{210}Pb decay rates, these radioisotopes provide quantitative information about the depth and rate of sediment mixing. This is important when considering the fate of fine-sediments in estuaries.

Radioisotope activity concentrations expressed in S.I. units of Becquerel (disintegration s^{-1}) per kilogram (Bq kg^{-1}) were determined by gamma-spectrometry. For simplicity, we will refer to the activity concentrations of ^{137}Cs and ^{210}Pb as concentrations. Dry samples (~50 g) were counted for 23 hrs using a Canberra Model BE5030 hyper-pure germanium detector. The unsupported or excess ^{210}Pb concentration ($^{210}Pb_{us}$) was determined from the ^{226}Ra ($t_{1/2}$ 1622 yr) assay after a 30-day ingrowth period for ^{222}Rn ($t_{1/2}$ 3.8 days) gas in samples embedded in epoxy resin. Gamma spectra of ^{226}Ra, ^{210}Pb and ^{137}Cs were analysed using Genie2000 software.

The uncertainty ($U_{2\sigma}$) of the $^{210}Pb_{us}$ concentrations was calculated as:

$$U_{2\sigma} = \sqrt{(^{210}\mathrm{Pb}_{2\sigma})^2 + (^{226}\mathrm{Ra}_{2\sigma})^2} \quad (1)$$

where $^{210}Pb_{2\sigma}$ and $^{226}Ra_{2\sigma}$ are the two standard deviation uncertainties in the total ^{210}Pb and ^{226}Ra concentrations at the 95% confidence level. The main source of uncertainty in the measurement of radioisotope concentrations relates to the counting statistics (i.e., variability in the rate of radioactive decay). This source of uncertainty is reduced by increasing the sample size. The $U_{2\sigma}$ values are presented in section 4 with the radioisotope concentration data.

The $^{210}Pb_{us}$ profiles in cores are used to determine: (1) time-averaged SAR from regression analysis of natural log-transformed data; (2) $^{210}Pb_{us}$ inventory (*A*, Bq cm^{-2}) and; (3) mean annual supply rate (*P*, Bq cm^{-2} yr^{-1}) based on the ^{210}Pb decay co-efficient (*k*, 0.0311 yr^{-1}). These data were compared with the ^{210}Pb atmospheric flux (0.005 Bq cm^{-2} yr^{-1}) measured by NIWA at Auckland. SAR are also estimated from ^{137}Cs profiles based on the maximum depth of ^{137}Cs in each core, which include corrections for sediment mixing in the surface layer indicated by ^{7}Be profiles. In NZ, ^{137}Cs deposition from the atmosphere was first detected in 1953 (Matthews, 1989).

^{137}Cs dating

^{137}Cs was introduced to the environment by atmospheric nuclear weapons tests in 1953, 1955–1956 and 1963–1964. Peaks in annual ^{137}Cs deposition corresponding to these dates are the usual basis for dating sediments (Wise, 1977; Ritchie and McHenry, 1989). Although direct atmospheric deposition of ^{137}Cs into estuaries is likely to have occurred, ^{137}Cs is also incorporated into catchment soils, which are subsequently eroded and deposited in estuaries (Fig. A3.2). In New Zealand, 137Cs deposition was first detected in 1953 and its annual deposition was been measured at several locations until 1985. Annual ^{137}Cs deposition can be estimated from rainfall using known linear relationships between rainfall and Strontium-90 (^{90}Sr) and measured ^{137}Cs/^{90}Sr deposition ratios (Matthews, 1989). Experience in Auckland estuaries shows that ^{137}Cs profiles measured in estuarine sediments bear no relation to the record of annual ^{137}Cs deposition (i.e., 1955–1956 and 1963–1964 ^{137}Cs-deposition peaks absent), but rather preserve a record of direct and indirect (i.e., soil erosion) atmospheric deposition since 1953 (Swales et al. 2002). The maximum depth of ^{137}Cs occurrence in sediment cores (corrected for sediment mixing) is taken to coincide with the year 1953, when ^{137}Cs deposition was first detected in New Zealand. We assume that there is a negligible delay in initial atmospheric deposition of ^{137}Cs in estuarine sediments (e.g., ^{137}Cs scavenging by suspended particles) whereas there is likely to have been a time-lag (i.e., < 1 yr) in ^{137}Cs inputs to estuaries from topsoil erosion, which would coincide with the occurrence of floods.

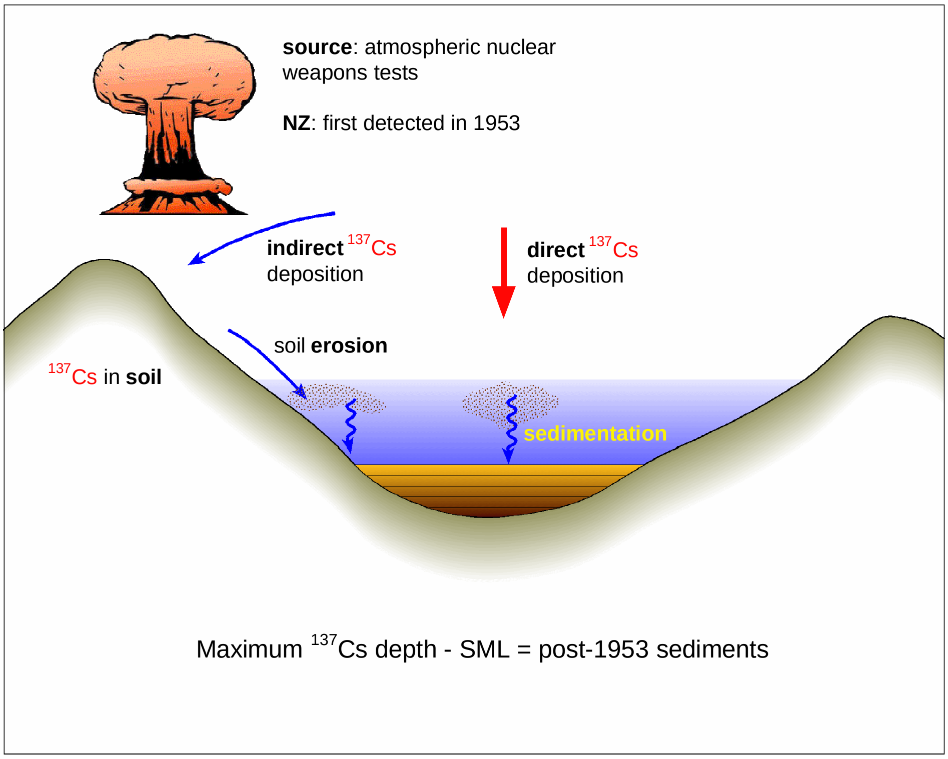


Figure A3.2: ^{137}Cs pathways to estuarine sediments.

If a surface mixed layer (SML) is evident in a core, as shown by an x-ray image and/or a tracer profile (e.g., ^{7}Be, ^{210}Pb) then ^{137}Cs is likely to have been rapidly mixed through the SML. Therefore, to calculate time-averaged sedimentation rates, the maximum depth of ^{137}Cs occurrence is reduced by the maximum depth of the SML.

Uncertainty in the maximum depth of ^{137}Cs is due to: (1) the depth interval between sediment samples and (2) minimum detectable concentration of ^{137}Cs, which is primarily determined by sample size and counting time. The 1963–1964 ^{137}Cs deposition peak was about five-times than the deposition plateau that occurred between 1953 and 1972. Thus, depending on the sample size, there is uncertainty in the age of the maximum ^{137}Cs depth (i.e., 1953–1963). To reduce this uncertainty, we have maximised the sample mass that is analysed (section 3).

^{210}Pb dating

^{210}Pb (half-life 22.3 yr) is a naturally occurring radioisotope that has been widely applied to dating recent sedimentation (i.e., last 150 yrs) in lakes, estuaries and the sea (Fig. A3.3). ^{210}Pb is an intermediate decay product in the uranium-238 (^{228}U) decay series and has a radioactive decay constant (k) of 0.03114 yr^{-1}. The intermediate parent radioisotope radium-226 (^{226}Ra, half-life 1622 years) yields the inert gas radon-222 (^{222}Rn, half-life 3.83 days), which decays through several short-lived radioisotopes to produce ^{210}Pb. A proportion of the ^{222}Rn gas formed by ^{226}Ra decay in catchment soils diffuses into the atmosphere where it decays to form ^{210}Pb. This atmospheric ^{210}Pb is deposited at the earth surface by dry deposition or rainfall. The ^{210}Pb in estuarine sediments has two components: supported ^{210}Pb derived from *in situ* ^{222}Rn decay (i.e., within the sediment column) and an unsupported ^{210}Pb component derived from atmospheric fallout. This unsupported ^{210}Pb component of the total ^{210}Pb concentration in excess of the supported ^{210}Pb value is estimated from the ^{226}Ra assay (see below). Some of this atmospheric unsupported ^{210}Pb component is also incorporated into catchment soils and is subsequently eroded and deposited in estuaries. Both the direct and indirect (i.e., soil inputs) atmospheric ^{210}Pb input to receiving environments, such as estuaries, is termed the unsupported or excess ^{210}Pb.

The concentration profile of unsupported ^{210}Pb in sediments is the basis for ^{210}Pb dating. In the absence of atmospheric (unsupported) ^{210}Pb fallout, the ^{226}Ra and ^{210}Pb in estuary sediments would be in radioactive equilibrium, which results from the substantially longer ^{226}Ra half-life. Thus, the ^{210}Pb concentration profile would be uniform with depth. However, what is typically observed is a reduction in ^{210}Pb concentration with depth in the sediment column. This is due to the addition of unsupported ^{210}Pb directly or indirectly from the atmosphere that is deposited with sediment particles on the bed. This unsupported ^{210}Pb component decays with age (k = 0.03114 yr^{-1}) as it is buried through sedimentation. In the absence of sediment mixing, the unsupported ^{210}Pb concentration decays exponentially with depth and time in the sediment column. The validity of ^{210}Pb dating rests on how accurately the ^{210}Pb delivery processes to the estuary are modelled, and in particular the rates of ^{210}Pb and sediment inputs (i.e., constant versus time variable).

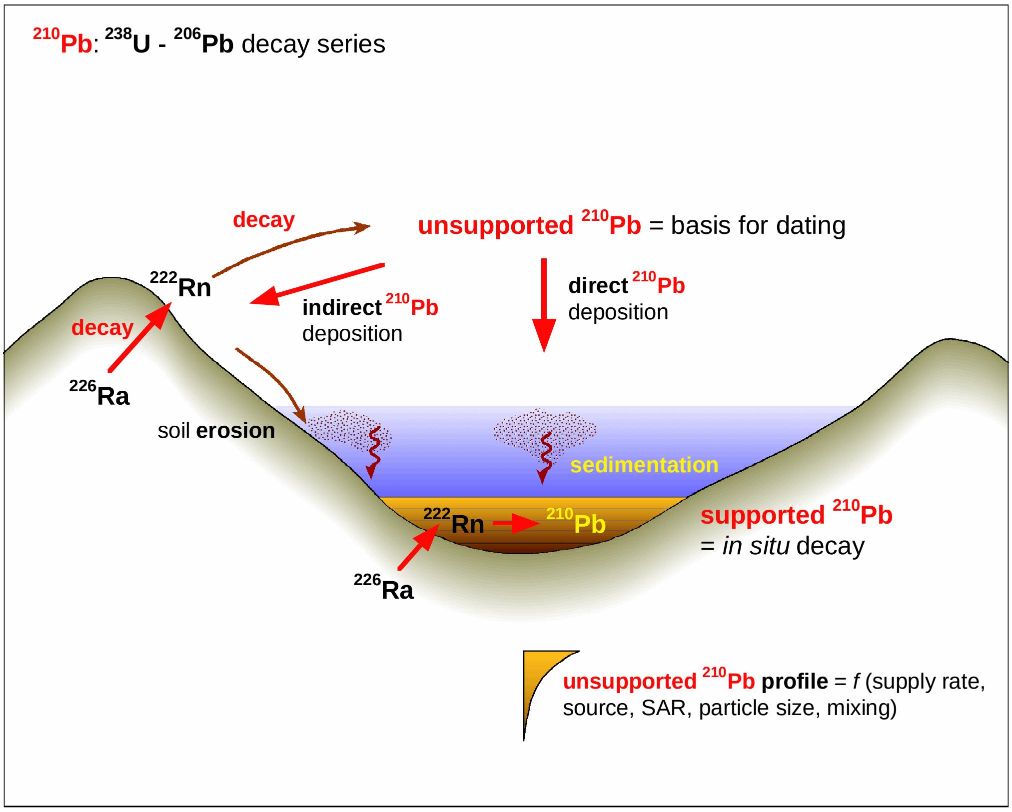


Figure A3.3: ^{210}Pb pathways to estuarine sediments.

^{210}Pb budget

The quantity of unsupported ^{210}Pb in sediment cores is often referred to as the ^{210}Pb inventory, *A*(o). This inventory provides important information about the long-term fate of fine-sediments in receiving environments such as estuaries. ^{210}Pb is delivered to the Earth's surface as dry deposition or with rainfall. The latter appears to be more important (Matthews, 1989). ^{210}Pb are delivered to estuaries directly (by atmospheric deposition) and indirectly (attached to eroded soil particles). Once in the estuary, radioisotopes are scavenged by fine-sediment particles suspended in the water column, which then may be deposited on the bed (Swales et al. 2002).

The mean annual ^{210}Pb atmospheric flux (P_{atmos}) can be estimated from the inventory of unsupported ^{210}Pb in the sediment column, which is denoted by *A*(o) (Bq cm^{-2}). This is estimated from the dry bulk density and unsupported ^{210}Pb concentration in sediment samples. The mean annual supply rate of unsupported ^{210}Pb (*P*, Bq cm^{-2} yr^{-1}) is then calculated as:

$$P = kA(\text{o}) \qquad (6)$$

where *k* is the decay constant for ^{210}Pb (0.03114 years). Note that unsupported ^{210}Pb is the atmospheric component of ^{210}Pb in sediments, as ^{210}Pb is also produced by in situ decay of parent radioisotopes present in sediments (Appendix 2).

Comparison of the A(o) and P estimates derived from cores with the average annual ^{210}Pb atmospheric flux (P_{atmos}) can be used to evaluate long-term fine-sediment fate at a given core site:

$P > P_{atmos}$ indicates fine sediment is preferentially being deposited over time scales of decades.

$P < P_{atmos}$ indicates that fine sediment is being removed from and/or is not accumulating at a site.

The ratio P / P_{atmos} is termed the concentration factor (C).

The atmospheric ^{210}Pb flux has been measured at monthly intervals by NIWA since June 2002 at a rainfall station in Howick. Monthly ^{210}Pb fluxes show substantial variability (0.0001–0.002 Bq cm^{-2} mo^{-1}), whereas annual ^{210}Pb fluxes show much less variability (0.0049–0.0056 Bq cm^{-2} yr^{-1}). This is an important result because constant ^{210}Pb supply at annual–decadal time scales is a key assumption of the ^{210}Pb dating method. The average annual ^{210}Pb flux of 0.0051Bq cm^{-2} yr^{-1} (2003–2007) is used here to calculate C.

Sediment accumulation rates (SAR)

Sedimentation rates calculated from cores are **net average sediment accumulation rates (SAR)**, **which are usually expressed as mm yr^{-1}**. These SAR are net values because cores integrate the effects of all processes, which influence sedimentation at a given location. At short time scales (i.e., seconds–months), sediment may be deposited and then subsequently resuspended by tidal currents and/or waves. Thus, over the long term, sedimentation rates derived from cores represent net or cumulative effect of potentially many cycles of sediment deposition and resuspension. However, less disrupted sedimentation histories are found in depositional environments where sediment mixing due to physical processes (e.g., resuspension) and bioturbation is limited. The effects of bioturbation on sediment profiles and dating resolution reduce as SAR increase (Valette-Silver, 1993).

Net sedimentation rates also mask the fact that sedimentation is an episodic process, which largely occurs during catchment floods, rather than the continuous gradual process that is implied. In large estuarine embayments, such as the Firth, mudflat sedimentation is also driven by wave-driven resuspension events. Sediment eroded from the mudflat is subsequently re-deposited elsewhere in the estuary.

Although sedimentation rates are usually expressed as a sediment thickness deposited per unit time (i.e., mm yr^{-1}) this statistic does not account for changes in dry sediment mass with depth in the sediment column due to compaction. Typically, sediment density (ρ = g cm^{-3}) increases with depth and therefore some workers prefer to calculate dry mass accumulation rates per unit area per unit time (g cm^{-2} yr^{-1}). These data can be used to estimate the total mass of sedimentation in an estuary (tonnes yr^{-1}) (e.g., Swales et al. 1997). However, the effects of compaction can be offset by changes in bulk sediment density reflecting layering of low-density mud and higher-density sand deposits. Furthermore, the significance of a SAR expressed as mm yr^{-1} is more readily grasped than a dry-mass sedimentation rate in g cm^{-3} yr^{-1}. For example, the rate of estuary aging due to sedimentation (mm yr^{-1}) can be directly compared with the local rate of sea level rise.

Time-averaged SAR were estimated from the unsupported ^{210}Pb ($^{210}Pb_{us}$) concentration profiles preserved in cores. The rate of $^{210}Pb_{us}$ concentration decrease with depth can be used to calculate a net sediment accumulation rate. The $^{210}Pb_{us}$ concentration at time zero (C_0, Bq kg^{-2}), declines exponentially with age (t):

$$C_{\mathrm{t}} = C_0 e^{-kt} \qquad (2)$$

Assuming that within a finite time period, sedimentation (S) or SAR is constant then $t = z/S$ can be substituted into Eq. 2 and by re-arrangement:

$$\frac{\ln\left[\frac{C_t}{C_0}\right]}{z} = -k/S \qquad (3)$$

Because $^{210}Pb_{us}$ concentration decays exponentially and assuming that sediment age increases with depth, a vertical profile of natural log(C) should yield a straight line of slope $b = -k/S$. We fitted a linear regression model to natural-log transformed ^{210}Pb concentration data to calculate b. The SAR over the depth of the fitted data is given by:

$$S = -(k)/b \qquad (4)$$

An advantage of the ^{210}Pb-dating method is that the SAR is based on the entire $^{210}Pb_{us}$ profile rather than a single layer, as is the case for ^{137}Cs. Furthermore, if the ^{137}Cs tracer is present at the bottom of the core then the estimated SAR represents a minimum value.

The ^{137}Cs profiles were also used to estimate time-averaged SAR based on the maximum depth of ^{137}Cs in the sediment column, corrected for surface mixing. The ^{137}Cs SAR is calculated as:

$$S = (M - L)/T - T_0 \quad (5)$$

where S is the ^{137}Cs SAR, M is the maximum depth of the ^{137}Cs profile, L is the depth of the surface mixed layer (SML) indicated by the ^{7}Be profile and/or x-ray images, *T* is the year cores were collected and T_0 is the year (1953) ^{137}Cs deposition was first detected in New Zealand.

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