Monthly to Decadal Sediment Accumulation Rates in a Semi-Enclosed Embayment

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ABSTRACT


Recent sediment accumulation in Wellington Harbour was recorded by core and sediment trap data. Three cores were analysed by 137Cs, one producing an annual to decadal record of sediment accumulation, the first recorded examples from marine sediments in New Zealand. Sediment traps were deployed adjacent to core sites for a period of 15 months. Sediment accumulation rates of up to 60 mm yr⁻¹ were recorded with a marked and sustained, increase occurring in the early 1950's as a result of anthropogenic activity (dumping of dredged material and aggregate extraction). There are distinctly seasonal patterns of low summer and high winter sediment accumulation rates, although there are individual peaks related to flood events. During flood events, wind direction, speed and duration have a significant influence on sediment deposition. Gross and net sedimentation rates were of a similar order of magnitude. Changes in organic content with depth are used to show that contemporary sediment accumulation rates at some locations have reduced the ability of benthic fauna to rework sediment.

ADDITIONAL INDEX WORDS: 137Cs, cores, sediment traps, sedimentation rates, anthropogenic influence, Wellington Harbour, wind, flood events, organic content.

INTRODUCTION

Sedimentation in semi-enclosed embayments has either been studied using sediment traps (e.g. MONACO et al., 1990; LUND-HANSEN et al., 1993; 1994; HEISKANEN, 1995) or cores (e.g. DUNBAR et al., 1997). The former technique has concentrated generally on the processes that affect contemporary sediment flux, such as vertical mixing, turbulence and stratification (e.g. KOJIMA and OHTA, 1989; VAN et al., 1989; SHANKS and EDMONDSON; 1990; WEST et al., 1990; RIEBESSELL, 1992; LUND-HANSEN et al., 1994; HEISKANEN, 1995). On the other hand, cores have been used to determine sedimentation rates based on radiometric, palynological and geochemical dating techniques (DUNBAR et al., 1997).

A comparison of sediment accumulation rates between sediment traps and cores is problematic. Results from sediment traps yield Gross Sedimentation Rates (GSR) which measure the total vertical flux of Suspended Particulate Matter (SPM) during a known, short time period; whereas a core chronology produces an average net sedimentation rate (NSR) over a given time period (LUND-HANSEN, 1991; LUND-HANSEN et al., 1993). Intuitively, the former method should produce higher sediment accumulation rates than the latter. However, providing that care is taken the two methodologies may allow comparisons to be made between past and present sediment accumulation rates. In particular, reducing the time period over which NSR are averaged from core data can make such comparisons more meaningful. In the absence of annual laminations, either 210Pb (e.g. LUND-HANSEN, 1991; LUND-HANSEN et al., 1993) or 137Cs (e.g. GEARING et al., 1991) dating techniques best serve this purpose.

This paper presents the results of a study of variations in sediment accumulation rates in Wellington Harbour using sediment traps and vibracorer.

PHYSICAL SETTING

Wellington Harbour is located at the southern end of the North Island, New Zealand (Lat. 41°16'S/Long. 174°51'E); (Figure 1). The harbour is a roughly circular, semi-enclosed embayment, about 85 km² in area with one entrance leading south to Cook Strait (DUNBAR, 1994). Mean water depth is approximately 14 m, with a maximum of 32 m to the SW and SE of Somes Is. (HEATH, 1977; HARDING, 1996). Shallow slopes of approximately 2° are generally typical for the cen-
concentrations are measured. The method was used on dried sediment samples from 10 km, first detected in 1954 (LONGMORE, 1982). A peak of activity of 1963-1964 can be related to a maximum in above-ground nuclear testing in 1962, that

Subsequent to $^{137}$Cs analysis, a short core (65 cm long) was taken from the location of C1, C2 and C3 by SCUBA diver in order to determine short term changes in organic content near the harbour floor (organic content was measured at cm intervals to 65 cm, and then at every 5 cm or more). Surface sediment samples were taken by SCUBA diver from the sites of C1, C2 and C3 (Figure 1).

Grainsize analysis followed procedures described in BARRETT and BROOKER (1989). Organic material was removed with $\text{H}_2\text{O}_2$ treatment for 7 days (organic content is reported for the full core length, not only the section analysed for $^{137}$Cs). Salts and acids were removed with distilled water and then centrifuging. After the supernatant liquid was poured off, sediment samples were washed with sodium hexa-metaphosphate and wet sieved at 60 µm to separate the sample into coarse and fine fractions. Coarse fractions were dry sieved at half phi intervals using a frisch shaker. Fine fractions were dried for 24 hours at 100°C and a 1.5 to 2 gram subsample used in SediGraph analysis. Data were entered into a PC software package (SIZE) to produce grainsize distribution indices. Bulk density was determined by sampling a known volume of sediment (10 cm$^3$) and recording the wet weight. Samples were then dried for 24 hours at 100°C, re-weighed and dry bulk density calculated.

Core recovery of the upper sections of C1, C2 and C3 was generally poor, but the uppermost part of each core was subsampled for $^{137}$Cs (Figure 2). Seven samples were taken at irregular intervals (0.20–0.80 m) from the uppermost 1.70 m of C1 (an actual downcore depth of 2.10–3.80 m). In C2, the upper 25 cm (representing a downcore position of 40–65 cm) were subsampled at 5 cm intervals (6 samples in total). For C3 the top 63 cm was subsampled, 30 core slices were taken at about 1 cm intervals over the first 33 cm, and 5 slices at 5 cm intervals from 40–63 cm.

The $^{137}$Cs method was used on dried sediment samples from known depths. Samples were counted on a gamma ray spectrometer having a solid state Ge (Li) detector, following the method of LEWIS (1974). $^{137}$Cs concentrations are measured in picocuries per gram (pCi g$^{-1}$) of freeze-dried sediment. Counting errors were generally about 10%.

$^{137}$Cs (half-life of 30.2 years) is an artificial radio-isotope, which is produced during nuclear fission. Therefore, its presence in the environment is mainly the result of fallout from atomic-bomb testing (WALLING and BRADLEY, 1988). Although the first atmospheric nuclear tests began in 1945, significant levels of $^{137}$Cs were first detected in 1954 (LONGMORE, 1982). A peak of activity of 1963–1964 can be related to a maximum in above-ground nuclear testing in 1962, that
Sediment Accumulation Rates

was followed by the Test Ban Treaty of 1963 (Carter and Moghissi, 1977; Ritchie and McHenry, 1990). Global radioactive fallout rates have since declined steadily, with minor peaks in 1971 and 1974 caused by atmospheric nuclear testing by non-treaty countries. Peaks caused by nuclear accidents have not been recorded in the Southern Hemisphere (Ritchie and McHenry, 1990). Total radioactive fallout is higher in the Northern than in the Southern Hemisphere, due to the greater number and larger tonnage of atmospheric nuclear tests carried out in the Northern Hemisphere (Matthews, 1989).

\(^{137}\text{Cs}\) is preferentially held onto clay and organic particles (e.g. Tamura and Jacob, 1960; McHenry et al., 1973), and is strongly adsorbed to cation exchange sites (Aston and Durosuma, 1973). It is therefore relatively immobile in sediments and can be used as a tracer for estimating erosion and sedimentation rates (Wise 1980; Longmore, 1982; Ritchie and McHenry, 1990). Variations in \(^{137}\text{Cs}\)-concentration versus depth in sediment profiles (of constant lithology) can be compared to the fallout record with time, and used to determine sediment accumulation rates (e.g. DeLaune et al., 1978; Sharma et al., 1987; Patrick and DeLaune, 1990; Ehlers et al., 1993; and others). However, bioturbation and mixing of sediments can introduce errors into dating, and there is evidence for \(^{137}\text{Cs}\) migration in the sediment column (e.g. Robbins et al., 1979). Post-depositional \(^{137}\text{Cs}\) mobility, diffusion and exchange have been reported in acidic and saline waters (Oldfield et al., 1979; Sholkovitz et al., 1983; Schell et al., 1986; Schell, 1987; Varekamp, 1991). However, in well-preserved, unmixed salt marsh and marine sediments, elevated levels of \(^{137}\text{Cs}\) are found to occur in the correct age horizons (e.g. DeLaune et al., 1978; Sharma et al., 1987; Patrick and DeLaune, 1990; Gearing et al., 1991; Ehlers et al., 1993; Clague et al., 1994).

In New Zealand, the deposition of \(^{137}\text{Cs}\) has been measured regularly at two sites, Lower Hutt (1959–1984) and Ohakea (1965 onwards). It is against these records that sedimentation rates are calculated using the criteria laid down by Matthews (1989; and references therein). Studies in New Zealand include recent work on \(^{137}\text{Cs}\) and sedimentation rates in lacustrine environments (Page et al., 1994), and unpublished data on \(^{210}\text{Pb}\) and \(^{137}\text{Cs}\) concentrations measured in six New Zealand lakes (N. Whitehead, pers. comm., 1995). Estimated \(^{137}\text{Cs}\) depositions at Wellington have been calculated by Matthews (1989) and are shown in Figure 3.

Sediment Traps

Five Rice University-type sediment traps (MacPherson, 1985; 1987) were deployed in the harbour to measure contemporary sediment accumulation rates; three traps were placed near core sampling positions (Figure 1). All traps were deployed below the effective wave base. Each trap consisted of two 1 m high, baffled funnels, with 460 mm inner diameter at the top, and 46 mm inner diameter at the base. These dimensions give an aspect ratio of 2.2 (based on the upper internal diameter) and a funnel area of 0.167 m². Fibreglass-impregnated cardboard, honeycomb hexel baffles (12 mm diameter hexagonal holes, 30 mm deep) were secured on the top of each funnel to reduce the effects of sediment resuspension and to break-up eddies that form at the mouth of traps (Hargrave and Burns, 1979; Gardner, 1980). Funnel
walls were angled at 7° off the vertical and gel-coated to inhibit particles settling on the sides during deployment (MacPherson, 1985; 1987). 500 ml Nalgene sample bottles were attached to the bottom of each funnel. Each trap was connected by a 2 m long “mast” to a concrete block on the seafloor to raise the traps above the observed bottom resuspension layer of 1 m (Goff, 1996). A rope fixed to surface and subsurface buoys was anchored adjacent to each trap to aid relocation. Bottles were changed and sealed, and traps were inspected by SCUBA diver approximately every month (periods actually ranged from 13–288 days) over a sampling period of 15 months. A poison was added to the traps at each inspection, and baffles were regularly cleaned and replaced. The poison used was a borax-buffered formalin solution (30 g of sodium tetraborate was added to 1 l of 40% formaldehyde, and the stock solution was diluted to about 4–5%). Encrustation of baffles was noted after the first sampling period, but in all cases this was not considered to be a major problem (in ST5, baffle encrustation was less than 10% after 288 days). All traps were deployed for the entire 15 month study.

Samples were stored at −3°C prior to analysis, dried for 24 hours at 100°C and weighed. Inorganic content was determined by combusting in a furnace for 8 hours at 500°C and reweighing the sample. Trap samples were analysed using the same grain size and bulk density methods used for core sections. The mud fraction represented about 98% of all grain size samples by weight (n.b. the mud fraction in Sediment Trap 5 (ST5) was about 88% by weight). Annual sediment accumulation rates are expressed as g m⁻² yr⁻¹ using the equation:

\[
\text{Annual Rate (g m}^{-2}\text{yr}^{-1}) = \frac{\text{weight of inorganic material (g)}}{\text{funnel area (m}^2\text{)}} \times \frac{\text{days per year (365)}}{\text{no. days deployed (n)}}
\]

Sediment accumulation rates calculated from the cores are inclusive of a natural percentage of organic matter within the sediment (Lund-Hansen, 1991). The organic content of the top sample from each core varied from 3.0 to 7.0%. For sediment traps, overtrapping and swimmers were a particular concern during long time intervals between sampling. In order to allow for an excess of organic material in the samples, the percentage by weight of near-surface organic material for the nearest adjacent core was added to the weights obtained for inorganics from all sediment traps (e.g., C3–4°F added to ST3). This produces a GSR with an organic content similar to the NSR.

To allow comparison between sediment trap and core data, sediment accumulation rate conversions between mm yr⁻¹ and g m⁻² yr⁻¹ were made using a bulk density figure of 1240 g m⁻³ which is the mean bulk density of the cores sampled (1.24 ± 0.1) with little downcore variability in bulk density. Sediment accumulation rates obtained from the cores use variations in °C-s-concentration versus depth in sediment profiles (i.e., at the time of core retrieval), and so a wet bulk density figure was used as opposed to the dry bulk density method described by Lund-Hansen (1991).

### RESULTS

#### Sediment Accumulation Rates

Sediment accumulation rates based upon, a) °C-s analyses of cores and, b) sediment trap samples are shown in Tables 1 and 2, and Figure 4. In the cores, sediment accumulation rates vary considerable both downcore and across the harbour. C3 has the most detailed chronological record and, not surprisingly, shows the largest fluctuations in sediment accumulation rate from a high of 74400 g m⁻² yr⁻¹ to a low of

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Table 1. Sediment accumulation rates (NSR) (mm yr⁻¹ / g m⁻² yr⁻¹) for cores 1, 2 and 3 (mm yr⁻¹ to g m⁻² yr⁻¹ conversion as per text). Sediment accumulation rate based upon the first appearance of Pinus pollen in the core (Dunbar, 1984).

<table>
<thead>
<tr>
<th>Year</th>
<th>CORE 1</th>
<th>CORE 2</th>
<th>CORE 3</th>
</tr>
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<tbody>
<tr>
<td>1890</td>
<td>20.00</td>
<td>24.800</td>
<td>9.900</td>
</tr>
<tr>
<td>1907</td>
<td>8.00</td>
<td>9.900</td>
<td>15.00</td>
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<tr>
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<td>25.00</td>
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<tr>
<td>1954</td>
<td>60.00</td>
<td>74.400</td>
<td>4.00</td>
</tr>
<tr>
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<td>50.00</td>
<td>62.000</td>
<td>4.00</td>
</tr>
<tr>
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<td>43.400</td>
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<td>25.00</td>
<td>31.000</td>
<td>4.00</td>
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<tr>
<td>1994</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
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Table 2. Sediment accumulation rates (GSR) - (mm yr⁻¹ g m⁻²yr⁻¹) for sediment traps 1-5 (mm yr⁻¹ to g m⁻²yr⁻¹ conversion as per text). Traps were deployed throughout the period - sediment accumulation rates are therefore based upon the time since they were previously sampled.

<table>
<thead>
<tr>
<th>Year</th>
<th>Sample Day</th>
<th>ST1 (14 m depth)</th>
<th>ST2 (15 m depth)</th>
<th>ST3 (23 m depth)</th>
<th>ST4 (15 m depth)</th>
<th>ST5 (16 m depth)</th>
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<tr>
<td></td>
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<td>mm yr⁻¹</td>
<td>g m⁻²yr⁻¹</td>
<td>mm yr⁻¹</td>
<td>g m⁻²yr⁻¹</td>
<td>mm yr⁻¹</td>
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<tr>
<td>1993</td>
<td>November 11</td>
<td></td>
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<tr>
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<td>12.2</td>
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<td>August 12</td>
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<tr>
<td></td>
<td>August 15</td>
<td>1.4</td>
<td>1,700</td>
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<td>129.2</td>
<td>160,200</td>
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<td>19100</td>
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<td>50,700</td>
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</tr>
<tr>
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<td>MEAN</td>
<td>55.5</td>
<td>68,800</td>
<td>31.4</td>
<td>38,900</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Sediment Accumulation Rates

4900 g m⁻²yr⁻¹. Poor core recovery truncated the¹³²Cs record from C1 and C2, but fluctuations in sediment accumulation rate are of a similar order of magnitude to C3. Historically, rates are higher today than they were prior to 1953. There is considerable between-core variability in contemporary and historical sediment accumulation rates. To the north, C1 has had a consistently higher accumulation rate (excluding C3: 1954-56), up to 13 times greater than the other sites. C3 has the lowest contemporary sediment accumulation rate.

In general, sediment accumulation rates obtained from the sediment traps appear to be highest in austral winter (April to August) and lowest in early austral summer (November and December) (Table 1).

Attempts were made to sample every trap on each sampling day, but relocation was hampered by temporary equipment loss, resulting in sampling periods without any sediment trap record. The sediment accumulation rate entered after an interval of “no recording” covers the complete period since a sample was previously taken (e.g. ST5: December 14, 17900 g m⁻²yr⁻¹ represents the sediment accumulation rate from August 28-December 14). Thus, the information from ST3 is limited and is only used to compare annual sediment accumulation rates.

There are some distinct anomalies in the sediment trap data. Contrary to the general winter (high)-summer (low) trend, ST5 had peak sediment accumulation rates (111200 g m⁻²yr⁻¹) in January/February 1995. Conversely, the lowest rate at ST1 occurred in the winter months between June 2 and August 15 (1700 g m⁻²yr⁻¹). This low rate was followed by the highest recorded sediment accumulation rate of the study on August 28 (160200 g m⁻²yr⁻¹).

In C1, organic content gradually decreases downcore from a high of 5.6% near the surface to 3.1% at 2.05 m (Figure 5). There is a marked decrease from 3.1 to 0.9% from 2.05-2.35 m, followed by a gradual decline to a low of 0.5% at the base of the core. Organic content in C2 decreases from 7.0 to 2.0% in the top 7 cm of the core. Percentages remains relatively constant downcore to 1.3% at the base. At the surface, the organic content of C3 is 4.0%. Downcore, percentages gradually increase to a maximum of 5.7% at 27 cm, then steadily decrease to 4.7% at 56 cm. Organic content decreases markedly to 1.2% at 60 cm and remains stable to the base of the core.

Wind Direction

Wind direction and Hutt River discharge were recorded during the study period (Figure 6); rainfall data have been excluded because of the strong positive correlation with Hutt River discharge. To assess the influence of wind direction on sediment accumulation rate, three flood events (1: June 12-14, 2: August 16, 3: November 8-10; 1994) that occurred during different wind conditions were identified (Goff, 1995). Extensive sediment plumes are associated with Hutt River flood events, and it is assumed that sediment accumulation during such events would represent a significant proportion of the monthly total. The timing of these freshwater flood
Figure 4. Summary of $^{137}$Cs activity with depth for cores taken from Wellington Harbour: (a) Core 1; (b) Core 2 and; (c) Core 3 (pre-1950's chronological data taken from DUNBAR, 1994).
events and prevailing winds are compared with sediment accumulations rates calculated from sediment traps (Figure 5).

During event 1 (June 12-14), flood flows varied from 109000-245000 l s⁻¹ and winds were dominated by a strong southerly (up to 13.5 m s⁻¹), changing to a light northerly on the 14th (Figure 6). Sediment accumulation rates recorded in traps in the northern part of the harbour (ST1, ST2) were below the annual mean, whereas those in the south (ST3-5) were above. Sampling intervals varied for all traps, but no southerly (up to 13.5 m s⁻¹) blew at all times. Flood flows varied from moderate southerly (11 m s⁻¹) to light northerly (6 m s⁻¹), and finally to light southerly (5 m s⁻¹). Sediment accumulation rates were well above the annual mean at all sediment trap locations.

During event 3 (November 8-10) a strong northerly wind (up to 15.5 m s⁻¹) blew at all times. Flood flows varied from 124000-548000 l s⁻¹. Sediment accumulation rates were well below mean annual levels at all traps. Sampling intervals varied and another flood took place soon after event 3 in the same sample period. However, the event was smaller than the November 8-10 flood, no southerly winds occurred during the intervening period, and a strong northerly wind blew throughout the event. It is assumed that sediment accumulation patterns were similar to those recorded in event 3.

**DISCUSSION**

**Sediment Accumulation Rates**

$	ext{^{137}Cs}$ analysis of core samples has shown that there are variations in sediment accumulation rates. Temporally, this is shown by a general increase in sediment accumulation rates in the early 1950's. Significant decadal and annual changes in sediment accumulation recorded in C3 suggest that this change is not merely a function of the onset of $	ext{^{137}Cs}$ accumulation in harbour sediments. $	ext{^{137}Cs}$ records from C1 and C2 are equivocal. Spatially, core data provide evidence for the northern half of the harbour only.

The $	ext{^{137}Cs}$ chronologies from the cores are considered to be largely unaffected by bioturbation. This is partly because there are low numbers and poor species diversity of benthic fauna which mainly consists of 3-6 species of polychaetes and 1-3 molluscs (Booth, 1972; Wear and Haddon, 1988; Wear et al., 1990). Bioturbation is also considered to be minimal because of variations in the organic content discussed below.

Highly variable sediment accumulation rates in the harbour centre (C3) are unusual (Figure 4). The site is well below effective wave base, has a grainsize distribution consisting of 98% mud, and a 4.5 Ka record prior to 1855 that indicates that accumulation rates were normally around 0.3 mm yr⁻¹ (Dunbar, 1994). Harbour-wide sediment accumulation rates increased from the mid-1800's as a result of European land clearance and reached a maximum of 5.5 mm yr⁻¹ at C3, although rates had started to decrease by the turn of the century (Dunbar, 1994). Harbour-wide rates increased further as a result of a 50% increase in the level of aggregate extraction from the Hutt River mouth from 1954 (Easther, 1991). Like deforestation, sediment input from dredging is via the Hutt River, and so it most likely caused a general harbour-wide increase in sediment accumulation rates over a period of decades. This additional localised anthropogenic input, therefore, seems to be the most likely cause of the extreme variability in sediment accumulation rates at C3.

Between 1930 and 1970, the area in the vicinity of C3 was designated as a disposal site for sediments dredged from the wharves of Wellington City (Wellington Harbour Board, 1938; 1942; 1960). Disposal commenced in 1953, attained a maximum in 1964 and ceased in 1966 (Wellington Harbour Board, 1967). Dumping records correlate remarkably well with changes in sediment accumulation rate, but it is likely that dredged sediment would have a different $	ext{^{137}Cs}$ signature to the surrounding sediment. It is possible that dumped material either mixed with in-situ sediments to produce the low levels of $	ext{^{137}Cs}$ activity recorded, or that displacement of in-situ sediments by dumped material created localised debris flows which may be responsible for changes in sediment accumulation rates recorded in C3 over this period. There is no direct evidence of debris flow activity in Wellington Harbour, although such events have been postulated as a result of earthquake disturbance (R. Grapes, personal communication, 1996).

Sediment accumulation rates are highest in the Petone foreshore area (C1) where southerly winds trap sediment in the enclosed northern section of the harbour. Historically, rates are consistently higher than other cores sites in the
harbour. However, the maintenance of a consistently high sediment accumulation rate in excess of 50 mm yr$^{-1}$ over the past 40 years is somewhat surprising. It is suggested that this has been caused by a combination of wave-grading processes along the north shore of Wellington Harbour, and increased levels of aggregate extraction in the Hutt River mouth (EASTHER, 1991). Grainsizes of between $-1$ and 4 phi are extracted with the coarse and fine residues returned to the eastern end of Petone foreshore. A study of wave-grading processes and grainsize distributions offshore from Petone suggests that a relatively high proportion of this fine residue ($<4$ phi) is being deposited below 5.0 m water depth in the vicinity of C1 (DUNBAR et al., 1997). Removal of the armoured river bed by dredging may also be resuspending fine sediments which are transported into the harbour.

Low levels of $^{137}$Cs activity in harbour sediments, particularly in C1, may not only be a function of low concentrations in the Southern Hemisphere (and differences in grainsize). Extensive dredging and river management over the past 40 years has accelerated channel bed erosion in the Hutt River (EASTHER, 1991). This may have introduced “inert” inorganic material (i.e., pre-1953 sediments—before the onset of $^{137}$Cs deposition) into the harbour which would have diluted $^{137}$Cs concentrations.

Prior to 1953, sediment accumulation rates in C2 and C3 were similar and post-1953 rates are also comparable (e.g., C3: 40 year average to 1993 is approx. 15 mm yr$^{-1}$ or 18600 g m$^{-2}$ yr$^{-1}$). However, each site has a different sedimentary environment (C2 being adjacent to the Hutt River, C3 in the harbour centre) which should be borne in mind when considering similarities in accumulation rate.

Data from sediment traps used during the study period show a distinct seasonality in sediment accumulation. In 1994, the combined rates of winter and spring comprise a significant part of the annual sediment accumulation. Similar seasonal patterns have also been recorded in other studies (e.g., MONACO et al., 1990; WASSMANN, 1991). However, examples of high sediment accumulation rates in summer (January/February 1995: ST4) and low rates in winter (June/July 1995: ST1 + ST2), indicate that there are intraseasonal variables to consider as well.

Wind direction and speed appear to be the most significant intraseasonal variable (e.g., BARTLETT, 1977; LUND-HANSEN, 1991; CARTER and LEWIS, 1995). During event 1 (June 12–
14), a strong southerly wind trapped sediment in the northern section of the harbour. The strength of the wind was sufficient to confine material to depths where wave grading processes were active and sediment was kept in suspension. A reversal of wind direction was sufficient to drive most of the sediment south towards the harbour entrance where deposition started to take place in the vicinity of Ward Is. (Figure 6). Event 2 (August 16) was dominated by changes in wind direction. Northerly wind speeds appear to have been insufficient to transfer sediment into Cook Strait, but rather allowed sediment to mix throughout the harbour 'bowl' and settle out prior to the onset of a stronger northerly on August 17. Event 3 marks the largest flood event of 1994, conversely it also records one of the lowest sediment accumulation periods harbour-wide for that year. Strong northerly winds were able to cause sufficient turbulence in the shallow waters of the eastern harbour (5 15 m) to maintain sediment suspension and to transport sediment directly into Cook Strait.

The general correlation between sediment accumulation and wind direction and speed applies in this study. Strong winds in particular dominating the spatial patterns of sediment accumulation (LUND-HANSEN, 1991). However, a simple "northerly wind-sediment out, southerly wind-sediment in" scenario (Brodie, 1958) is complicated by wind duration. Short-term changes in wind direction and speed have a significant impact on the patterns of sediment accumulation in the harbour. This is particularly important for northerlies, where duration is probably more important than speed.

Mean tide level data in Wellington (1903-1977) show that relative sea-level has risen at an average rate of 2.4 mm yr \(^{-1}\), a combination of a eustatic sea-level rise of 1.6 mm yr \(^{-1}\) and 0.8 mm yr \(^{-1}\) of tectonic subsidence (Gibb, 1979). Both sediment trap and core data indicate that recent sediment accumulation in Wellington Harbour rates are far higher than sea level rise. However, core (NSR) and sediment trap (GSR) data show marked differences.

Characteristically, GSR (sediment traps) data are normally higher than those for NSR (cores); (e.g. Gardner, 1980; Fass and Carson, 1988; Lund-Hansen et al., 1993), although similarities have been reported (Lund-Hansen, 1991). Differences normally occur as a result of resuspension of sediment by waves and currents (LUND-HANSEN et al., 1993; and references therein). A comparison between GSR and NSR requires that sediment traps be deployed for a minimum of 12 months to cover a reasonable period of wind climate. Comparison between C1-C3 and ST1-3 are made assuming that there has been a uniform sediment accumulation rate at C1 and C2. Unfortunately, a comparison between C1 and ST1 may not be realistic because of differences in grainsize distribution (C1: 60.0% mud, ST1: 98% mud), sediment supply (see above) and depth. However, locations are similar and are indicative of the regime operating in the northwest section of the harbour. Surprisingly, both NSR and GSR are similar. Comparison between C2 (15 mm yr \(^{-1}\)) and ST2 (31.4 mm yr \(^{-1}\)) must also consider some grainsize differences. However, rates for ST2 are still considerably higher. Similarly, ST3 has an annual rate about 1.5 times higher than C3. Data are limited, but GSR exceeds NSR at all locations. More sample stations and further research are needed to assess harbour-wide variations.

Variation in organic content with sediment depth are markedly different in each core (Figure 5). In C1 and C3 there are distinct increases in organic content at about 2.10 m and 0.59 m respectively. Chronologically, these increases occur in the early to mid 1950's (Figure 4) and are considered to represent an increase in sediment supply and an over-abundance of organic matter beyond the capacity of benthic fauna to rework. If this is the case, then a near-surface decrease in organic content in C3 from 5.7% at 27 cm to 4.0% at the surface, is probably the result of a decline in sediment accumulation rate (Figure 5). Conversely, the continued increase of organic content in C1 from 210 cm to the surface is an indication of a gradual increase in sediment accumulation, which is possibly related to aggregate extraction in the Hutt River mouth (as discussed above, sediment accumulation rates are believed to have increased as result of a higher levels of aggregate extraction from the Hutt River mouth since 1954 (Easther, 1991). The organic content profile for C2 is indicative of "normal" benthic faunal activity, with near-surface levels slightly higher than the underlying reworked material.

It is inferred from these data that large and sustained increases in sediment accumulation rates are sufficient to prohibit benthic faunal activity. There appears to be a threshold of "swamping" which is likely to be a function of annual rate and duration. This suggests that sediment accumulation rates in C2 have been steady at about 15 mm yr \(^{-1}\) for several decades; in C1 they have remained high since the early 1950's and are most likely increasing; in C3 rates increased and have started to decline in the past thirty years. Sediment accumulation rate and organic content data for C3 concurred and other corroborative evidence has been reported for C1.

CONCLUSIONS

Sediment trap and core data indicate that sediment accumulation rates in parts of Wellington Harbour vary considerably through space and time as a result of natural and anthropogenic factors. Levels of \(^{137}\)Cs activity were low, probably as a result of dilution by 'inert organic matter' entering via the Hutt River. Core data show that over the past few decades the dumping of dredged material and aggregate extraction from the Hutt River mouth have significantly affected sediment accumulation in some areas. Sediment trap data reveal a seasonal pattern of sediment accumulation (e.g., high in winter, low in summer), with distinct peaks related to flood events regardless of season. In flood events, the wind direction, speed and duration significantly influence sediment deposition.

Comparison between GSR and NSR was inconclusive, although rates were of a similar order of magnitude. Sediment accumulation rates as high as 60 mm yr \(^{-1}\) were recorded, with a marked and sustained increase taking place in the early 1950's. Changes in organic content with depth indicate that contemporary sediment accumulation rates at some locations have reduced the ability of benthic macrofauna to rework sediment.
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LITERATURE CITED


Sediment Accumulation Rates


WELLINGTON HARBOUR BOARD, 1942. Plan showing proposed dumping areas for dredgings. Drawing No. S403.


