Seagrass in Porirua Harbour

Preliminary assessment of restoration potential

Prepared for Greater Wellington Regional Council

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Executive summary

Porirua Harbour is the only estuary in the lower North Island with a substantial cover of seagrass (*Zostera muelleri*) beds. However, anecdotal evidence suggests that there has been a marked loss of seagrass beds in this harbour in recent decades. NIWA was contracted by Greater Wellington Regional Council (GWRC) to perform a preliminary feasibility assessment for seagrass restoration in the harbour. This assessment included: (1) an analysis of past and present seagrass abundance in the harbour using available aerial photographs and habitat maps, and (2) an analysis of the present suitability of environmental conditions within the harbour to support seagrass growth. We used these analyses to evaluate the likely causes of seagrass loss in the harbour and potential for restoration.

Aerial photographs and habitat maps were supplied in June 2011. These were georectified and past and present seagrass beds were delineated. On 14 July 2011, NIWA, GWRC and Porirua City Council (PCC) staff inspected six sites (2 past and 4 present). Seagrass cover was assessed and samples were collected for analysis of plant biomass and sediment particle size. Submersible loggers were deployed at each site for 6 weeks to measure light; this was repeated in January-February 2012. GWRC and PCC supplied NIWA with their harbour water and stormwater quality databases for the harbours. The data collected were compared to published thresholds and information in the international literature and other seagrass investigations in New Zealand.

Our analysis of past and present abundance shows that around 40% of the harbour's seagrass beds have been lost since the 1960-1980 period. A substantial area of seagrass (~32 ha) has been lost from the head of the Pauatahanui arm of the harbour since around 1980. Approximately 4 ha has also been lost from the head of the Onepoto arm since the 1960s and around 3 ha lost with the development of the Mana marina at the confluence of the two arms. Seagrass beds are still evident at most other former sites within the harbour.

The loss of seagrass from the head of both arms is associated with present-day elevated water column nitrate (NO_3^-) concentrations in these locations, at levels known to cause toxicity symptoms in *Zostera* and longer term exposure linked to plant decline. Comparison with historical water quality data suggests that maximum NO_3^- concentrations in the Pauatahanui arm have almost doubled since the mid-1970s.

Seagrass loss from the head of the Pauatahanui arm is also linked to slightly elevated sediment mud content (i.e., particles <63 µm) which could indicate detrimental effects associated with siltation; in particular smothering of plants and toxic changes to sediment chemistry. Light logger results indicated that light availability at former seagrass sites in the Pauatahanui arm is sufficient to support seagrass growth. Light is usually the primary factor regulating seagrass persistence and so we suggest that small plots of seagrass could be transplanted to test whether seagrass recolonisation of these areas is prevented by NO_3^- toxicity, siltation effects, or other factors, versus a lack of viable propagules from remaining beds in the outer harbour.

In the Onepoto arm, smothering and blocking of light by dense and persistent sea lettuce (*Ulva*) beds is a threat to remnant seagrass beds and may have contributed to the loss of seagrass from the head of this arm. Contamination of harbour sediments with heavy metals, polycyclic aromatic hydrocarbons (PAHs) and organochlorine pesticides is evident, particularly in the inner Onepoto arm. However, concentrations of these contaminants are

generally within the ranges found for viable seagrass beds elsewhere, except for dieldrin and dichlorodiphenyltrichloroethane (DDT) which were elevated in sediments at the Porirua Stream mouth. We recommend that concentrations of dieldrin and DDT are measured at former and present seagrass sites to further evaluate the contribution of these contaminants to seagrass loss. Additional factors that could be explored include sediment redox conditions, sediment nutrient levels and concentrations of other potential phytotoxins, such as the biocides diuron, Irgarol 1051 and atrazine. Detailed recommendations regarding future work are outlined at the end of the report.

1 Introduction

Seagrass (*Zostera muelleri*) meadows are an important natural attribute of many New Zealand estuaries. One of these estuaries is Porirua Harbour, a natural inlet on the North Island's south western coast, north of Wellington. The harbour has an inner estuary area of ~8 km^2 and has two distinct arms. The eastern arm, locally known as Pauatahanui Inlet, has the largest remaining area of estuarine saltmarsh in the lower North Island. Porirua City is located at the head of Onepoto arm. The harbour is the only one in the lower North Island with any substantial seagrass cover (Porirua City Council 2012). However, anecdotal reports suggest that the seagrass beds within the harbour have reduced considerably in abundance over recent decades.

In May 2011, NIWA was approached by Greater Wellington Regional Council (GWRC) and Porirua City Council (PCC) to undertake a preliminary feasibility assessment for seagrass restoration in Porirua Harbour.

NIWA was subsequently contracted to provide:

- An analysis of past and present seagrass abundance in the harbour.

  Suitable historical and recent aerial photographs and habitat maps were to be used for this analysis and to produce georectified, composite maps. This was to include the 1942, 1962 and 2002 aerial photographs provided by PCC and the habitat maps in Healy (1980) and Stevens and Robertson (2008).

- An analysis of present suitability of environmental conditions in the harbour to support seagrass growth.

  This analysis was to include relevant parameters in the 2011–2012 GWRC water quality monitoring database for this harbour. In addition, NIWA was to perform an on-site inspection in winter 2011 for the purposes of: a) visually inspecting remnant seagrass patches and former sites; and b) deploying submersible light loggers and collecting cores for analysis of plant condition and sediment particle size at a minimum of four sites (2 current, 2 historical). Light loggers were to be retrieved by GWRC staff and a new set deployed in summer 2011–12. The data collected was to be compared to published thresholds in the international literature and to information available for other seagrass sites in New Zealand.

2 Methods

Aerial photographs of Porirua Harbour were supplied to NIWA by PCC staff in June 2011. Suitable photographs, along with the Porirua Harbour habitat maps in Healy (1980) and Stevens and Robertson (2008), were georectified and composited into a single layered file using ArcGIS ArcMap 9.3.1. (ESRI Inc., Redlands, California). Historical and present seagrass beds were manually delineated in the aerial photograph layers by visual identification of dark, mottled patches in the shallow subtidal and intertidal zones, combined with other evidence of their presence or absence from particular locations (i.e., habitat map data, other photographs, report descriptions). Using the map file, six sites were selected for further examination during the on-site inspection. On 14 July 2012 NIWA visited selected sites (Table 2-1) at low tide with GWRC and PCC staff.

Table 2-1: Location details for sample sites in Porirua Harbour.

Site	Name	GPS coordinates (NZMG)	
		Easting	Northing
1	Kakaho Stream delta	2668744	6011441
2	Ration Point	2670355	6010234
3	Bradey's Bay	2668828	6009503
4	Ivey Bay	2667399	6009721
5	Paremata railway station	2666530	6009546
6	Elsdon	2664334	6007645

At each site two submersible pre-programmed light loggers (Hobo® Pendant, Onset Computer Corp., Bourne, Massachusetts) were deployed approximately 5 m apart and securely strapped to short wooden pegs hammered into the sediment. These loggers recorded light and temperature at hourly intervals from midnight 15 July 2011 to midnight 28 August 2011. At two of the sites with seagrass, a 0.25 m^2 quadrat was randomly placed on the seagrass bed and digital photographs taken for analysis of plant percentage cover. In the centre of each quadrat a sediment core (10 cm diameter, 10 cm length) was extracted for laboratory analysis of seagrass biomass and sediment particle size. At a third seagrass site, the depth of water over the seagrass beds did not allow reliable quadrat photographs to be taken but cores were collected. At sites without seagrass, cores were extracted from bare sediment at randomly selected locations in the vicinity of the loggers.

Light loggers were retrieved by GWRC staff on 29 August 2011. Two loggers were lost; one from site 3 and one from site 5. At this time photographs were taken of the remaining loggers and a visual assessment made of any epiphytic algal growth on the logger surfaces. Loggers were returned to NIWA for downloading and analysis of data. In December, another set of pre-programmed loggers was sent to GWRC staff for the summer deployment. These loggers were deployed on 9 January 2012 and collected data from midnight 10 January 2012 to midnight 21 February 2012. Photographs were taken of the loggers upon their retrieval on 22 February 2012. Three loggers were lost during this deployment; one from site 4 and both loggers from site 5.

Seagrass percentage cover in quadrat photographs was determined by overlaying a 10 x 10 square grid and counting the number of squares with >50% plant cover. For quadrats with sparse plant cover this technique can lead to underestimation so in these instances an overall visual estimate was performed instead. Seagrass above-ground (shoots, leaves) and below-ground (roots, rhizomes) biomass were extracted manually from each homogenised sediment core. The length and width of five representative leaf blades from each core were measured using calipers. Plant samples were dried to constant weight (at 70℃) to determine the dry weight of plant material per square metre. The homogenised sediment sample was analysed for particle size distribution by manual sieving and automated stream-scanning laser particle size analysis (CIS-100, Galai Production Inc., Israel).

Surface radiation data were obtained from the nearest climate stations (Paraparaumu Aero AWS and Paraparaumu EWS) corresponding to the periods of light logger deployment. Light data was converted from units of lux or joules to photosynthetically available radiation (PAR) according to Thimijans and Heins (1983). We calculated the minimum light requirement for seagrass as a percentage of surface radiation according to Duarte (1991).

GWRC provided NIWA with their water quality database for Porirua Harbour. This database comprises monthly sampling of six sites from January 2011 to February 2012 inclusive. Relevant parameters in this database include total suspended solids, turbidity, chlorophyll *a*, nutrients and seaweed cover. We calculated average values for these parameters over a one year period only (from 17 January 2011 to 5 December 2011) to avoid any seasonal bias. For values recorded as below detection limits we substituted values at the detection limit to enable these data to be used in the analysis. Porirua City Council also provided their stormwater monitoring database which consisted of nutrient and heavy metal data for a further six sites around the harbours perimeter/catchment from November 2011 to May 2012.

3 Results

3.1 Past and present abundance

3.1.1 Early photographs

An early photograph looking north over the outer Onepoto arm (date unknown, probably early 1900s) suggests that there were beds of intertidal seagrass on the tidal flats adjacent to the current Paremata railway station site, on the western side at Mana at the current marina site, and on the tidal flats on the western side of the Onepoto arm (Figure 3-1).

A photograph taken during the 1920s looking north over the head of the Onepoto arm shows what appears to be seagrass beds on the exposed tidal flats to the left of the Porirua Stream delta and along the western shoreline (Figure 3-2).

3.1.2 1942

In the 1942 aerial photographs, we identified approximately 24 ha of seagrass beds in Porirua Harbour, mostly in the Pauatahanui arm (Figure 3-3, Table 3-1). Extensive areas of seagrass were present on the tidal flats around Ration Point (near sites 2 & P2), with smaller beds also evident around Mana, from Ivey Bay to Moorehouse Point, and in Browns Bay. Some small beds were also identified in a small bay on the western shore of the harbour, close to the entrance channel (opposite site E1). No beds could be identified in the Onepoto arm; however the aerial photograph quality is not sufficient to be certain that seagrass was absent from this arm at this time. In fact, both earlier and later photographs (see above and below) suggest a seagrass presence in this arm so it is likely that these beds were present in the 1940's.

Table 3-1: Summary of seagrass area in 1942.

Location	Seagrass (ha)
Entrance	0.2
Mana and subtidal banks	2.0
Ivey Bay to Moorehouse Point	1.4
Brown's Bay	0.7
Ration Point	19.5

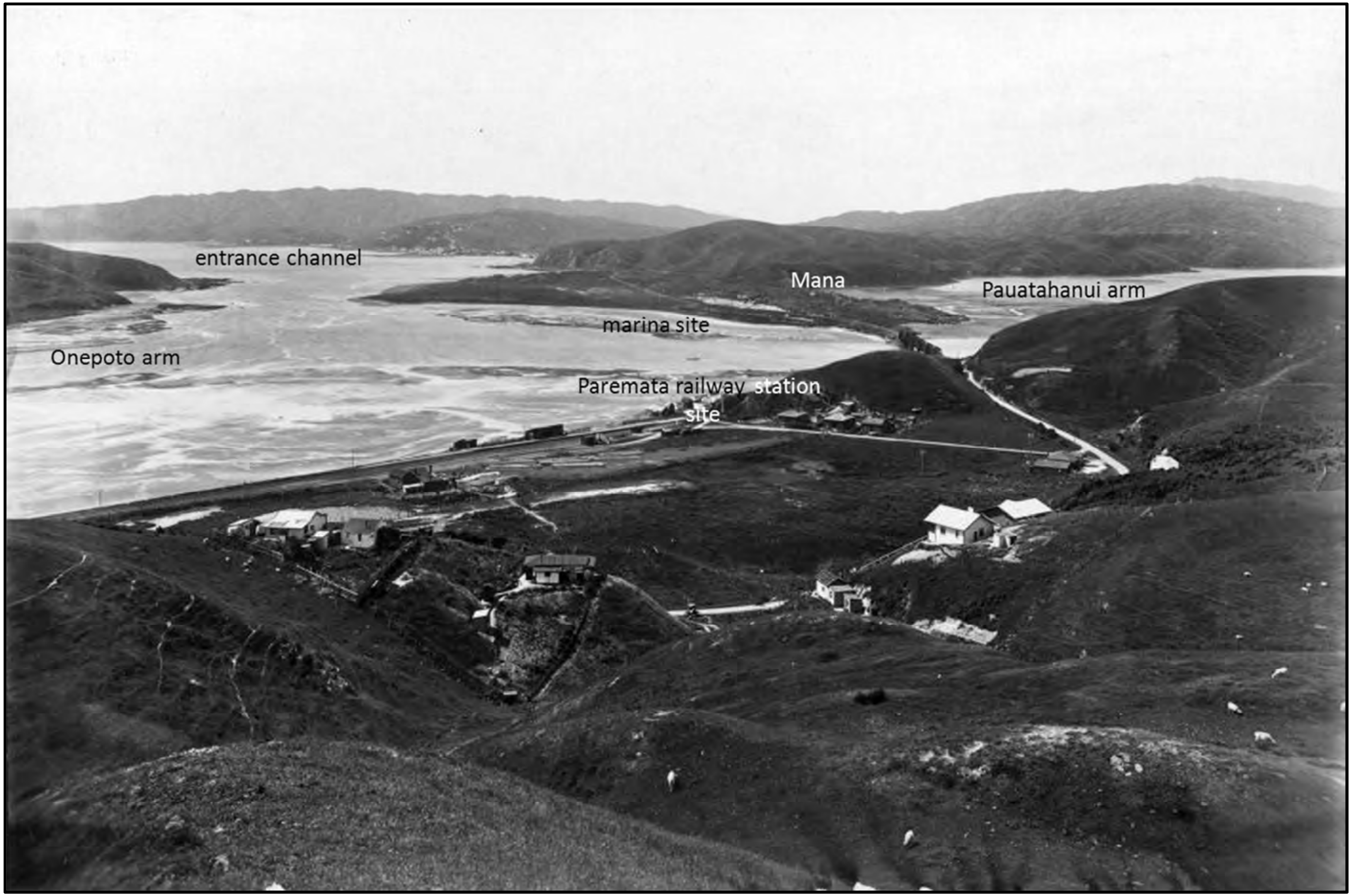

Figure 3-1: Early photograph of the outer Onepoto arm. Dark patches on the exposed tidal flats are intertidal seagrass beds.

Figure 3-2: 1920s photograph of the Onepoto arm. Dark patches on the exposed tidal flats are probably intertidal seagrass beds.

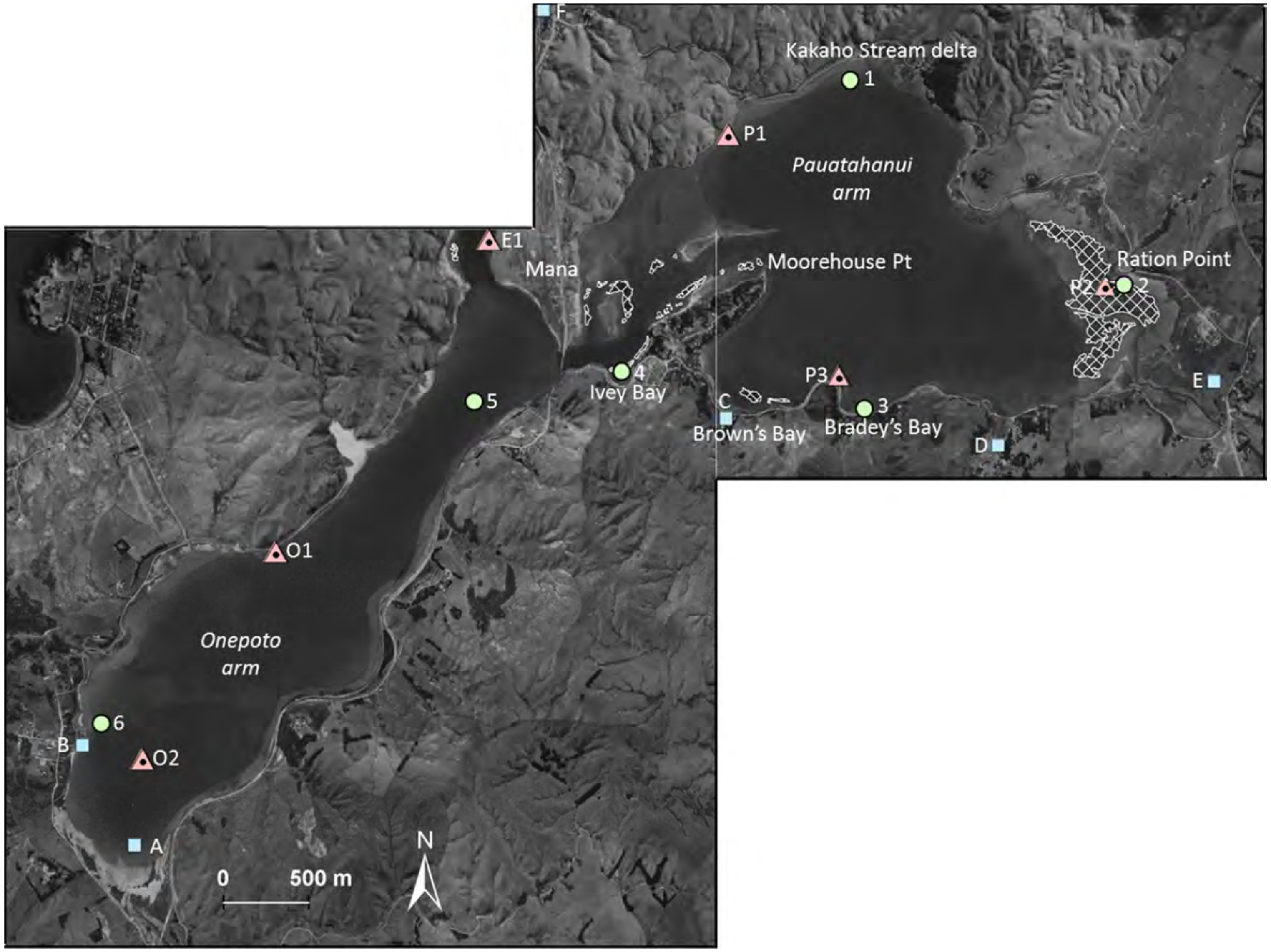

Figure 3-3: Seagrass extent in Pauatahanui arm in 1942. Poor photograph quality prevented identification in the Onepoto arm. White cross-hatched areas are seagrass beds. Circles (1-6) are our sampling sites. Triangles (E1, P1-3, and O1-2) are Greater Wellington Regional Council water quality monitoring sites. Squares (A-F) are Porirua City Council stormwater monitoring sites.

3.1.3 1962

We identified approximately 21 ha of seagrass in the 1962 aerial photograph (Figure 3-4, Table 3-2). This photograph covers the Onepoto arm but only part of the entrance channel area and the Pauatahanui arm. Extensive areas of seagrass were present on the tidal flats west of the Paremata railway station (around site 5). A large area of seagrass was also present on the western side of Mana (where the marina is located today) and at the head of the Onepoto arm (near Elsdon). Smaller beds were evident in the two bays on the western side of the entrance channel, on the banks east of Mana and from Ivey Bay (site 4) to Moorehouse Point. There may also have been some narrow beds on the western side of the Onepoto arm, north of Elsdon (as seen in the 1920s photograph); however the quality of the 1962 photograph is not sufficient to delineate these areas with certainty.

Figure 3-4: Seagrass extent in Onepoto arm, outer Pauatahanui arm and entrance channel in 1962. White cross-hatched areas are seagrass beds.

Table 3-2: Summary of seagrass area in 1962.

Location	Seagrass (ha)
Entrance	4.6
Mana and subtidal banks	0.4
Ivey Bay to Moorehouse Point	0.9
Paremata railway station	14.8
Elsdon	5.5

3.1.4 1980

Seagrass extent in the Pauatahanui arm was mapped by Healy (1980) which he recorded as low tidal areas dominated by *Zostera*. He estimated that there were around 38 hectares of seagrass at this time. The areas he identified are shown and summarised below (Figure 3-5, Table 3-3). The largest area was around Ration Point in the deltas of the Horokiwi and Pauatahanui Streams. However, substantial beds were also recorded around the Kakaho Stream delta and near Moorehouse Point. Other smaller beds were found at Camborne, Duck Creek, Bradey's Bay, Ivey Bay and the Mana area. Healy (1980) also noted that large areas of the tidal banks east of Mana supported "a luxuriant growth" of seagrass; however, these areas were not mapped.

Table 3-3: Summary of seagrass area in 1980.

Location	Seagrass (ha)
Mana	1.2
Ivey Bay to Moorehouse Point	2.7
Bradey's Bay	0.2
Duck Creek	0.2
Ration Point	26.0
Kakaho Stream delta	6.2
Camborne	0.2

3.1.5 Other historical photographs

The dates of two further historical photographs (Figure 3-6) are unknown but Paremata Road Bridge is evident in both, and this was opened in 1936. The first photograph shows a large area of intertidal seagrass beside the Paremata railway station site, on adjacent mid-channel banks in the Onepoto arm and at the current marina site. The second photograph, which looks east over Mana and the Pauatahanui arm, shows very dense seagrass beds at the marina site, dense seagrass patches on the tidal banks east of Mana and narrow beds along the Golden Gate Peninsula (Ivey Bay to Moorehouse Point) shoreline. Dark bands can be seen in the distance in Brown's Bay, Bradey's Bay and across the tidal flats at the head of the arm, which are also likely to be seagrass beds.

Figure 3-5: Seagrass extent in Pauatahanui arm in 1980 (from Healy 1980). Black cross-hatched areas are seagrass beds, shown on a 2010 aerial photograph.

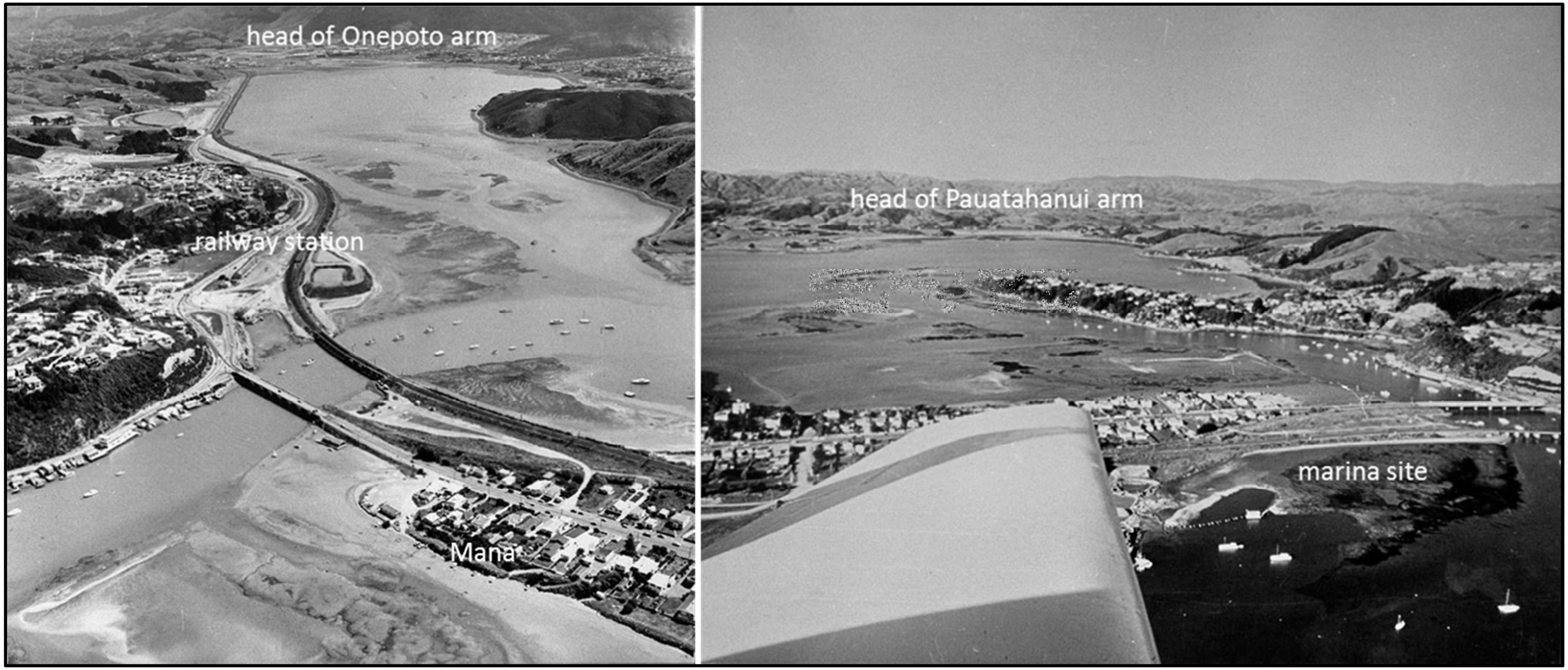

Figure 3-6: Two other historical photographs (dates unknown). Left photograph shows Mana, the Paremata railway station and the Onepoto arm. Right photograph shows Mana and the Pauatahanui arm. The dark patches on the tidal flats are intertidal seagrass beds.

3.1.6 2008

In the summer of 2007–2008, habitat mapping was undertaken in both arms of the harbour (Stevens and Robertson 2008), which included identification of seagrass beds and their characterisation into different percentage cover classes (Figure 3-7, Table 3-4). Notably, the extensive areas of seagrass that existed around Ration Point and the Kakaho Stream delta in 1980 were no longer present, nor were the smaller patches at Duck Creek and Camborne. However, seagrass beds of moderate to high density (i.e. 50–100% cover) persisted at many of the other former sites (i.e., the tidal flats adjacent to the Paremata railway station, from Ivey Bay to Moorehouse Point, Brown's and Bradey's Bays, and in the harbour entrance channel). The survey also showed an extensive area of seagrass on the two mid-harbour banks near Moorehouse Point. Some small, dense seagrass patches were also recorded along the shoreline around Elsdon in the Onepoto arm (north of site 6).

Table 3-4: Summary of seagrass area in 2008.

Location	Seagrass (ha)
Entrance	4.6
Mana	0.4
Mid-harbour banks	31.8
Ivey Bay to Moorehouse Point	4.1
Browns Bay	0.5
Bradeys Bay	1.3
Paremata railway station	10.6
Elsdon	1.5

Figure 3-7: Seagrass extent in Porirua Harbour in 2007–2008 (from Stevens and Robertson 2008). Beds are shown on a 2010 aerial photograph.

3.2 Present condition

3.2.1 Seagrass condition

Seagrass was found at four of the six sites we sampled (i.e., Bradey's Bay, Ivey Bay, Paremata railway station and Elsdon) (Table 3-5, Figure 3-8). However, there was insufficient plant material at Elsdon to sample for biomass. We found that the patches of seagrass at Ivey Bay (site 4) had the highest average cover, biomass and leaf size of the three sites assessed. While the area of seagrass adjacent to the Paremata railway station (site 5) was much more extensive than at other sites, plant cover and biomass was relatively low.

Table 3-5: Seagrass condition data for sample sites in winter 2011.

Site	Seagrass	Cover	Biomass (g/m^2)			Leaf size (mm)	
		%	Total	Above	Below	Length	Width
1	No	-	-	-	-	-	-
2	No	-	-	-	-	-	-
3	Yes	-	38 (±10)	7 (±3)	31 (±7)	46 (±14)	1.7 (±0.2)
4	Yes	44 (±23)	311 (±128)	60 (±26)	250 (±102)	66 (±3)	2.1 (±0.0)
5	Yes	8 (±2)	30 (±8)	6 (±2)	24 (±8)	45 (±3)	0.9 (±0.1)
6	Yes	-	-	-	-	-	-

Data are averages with standard error in parentheses (n=3).

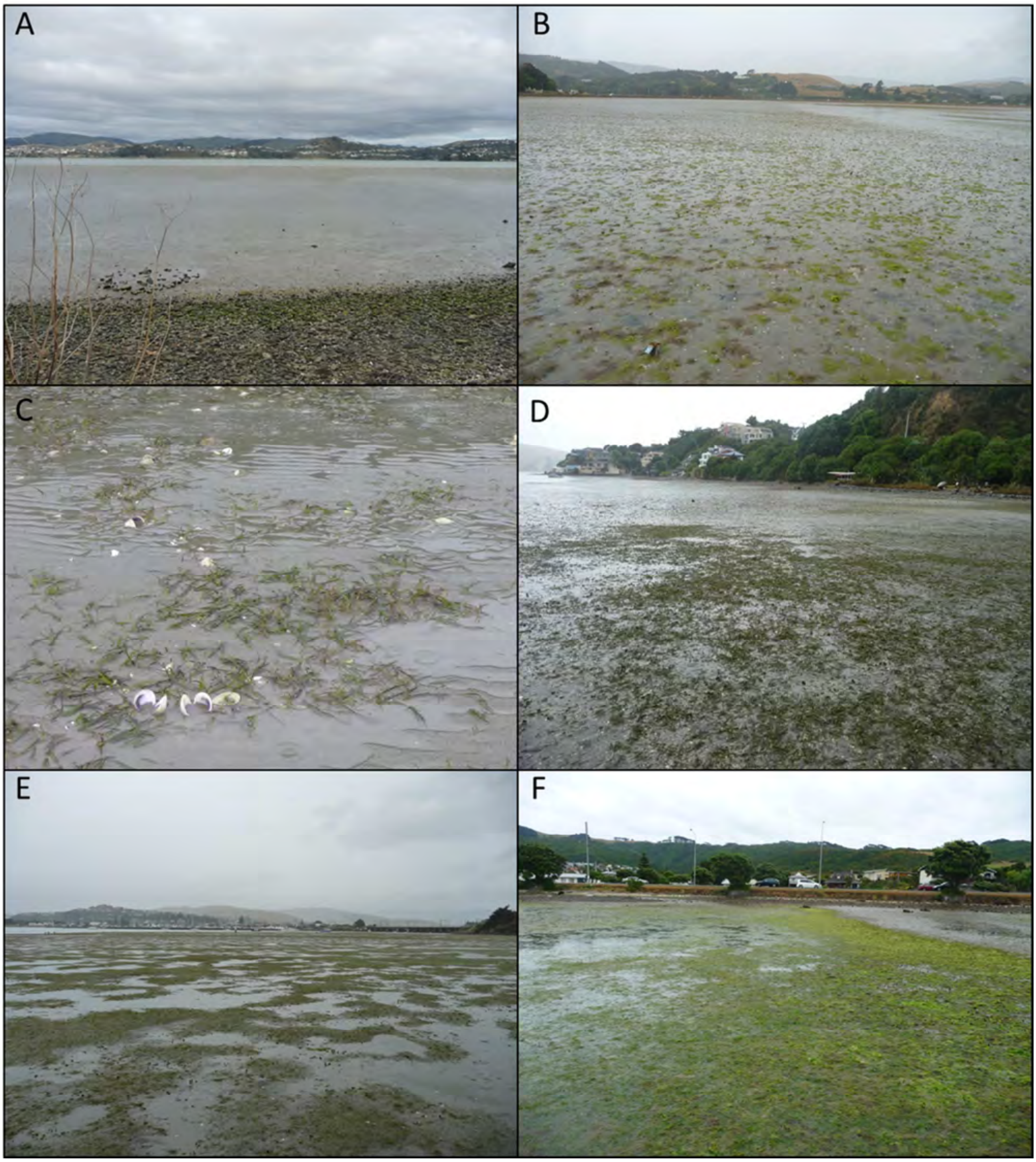

Figure 3-8: Sampling site photographs. A, Kakaho Stream Delta (site 1); B, Ration Point (site 2); C, Bradey's Bay seagrass patch (site 3); D, Ivey Bay (site 4); E, Paremata railway station (site 5); F, Elsdon (site 6) (Photos: Megan Oliver & Shyam Morar).

3.2.2 Light

Light is a critical factor influencing seagrass growth and persistence. We attempted to measure light at all six sample sites in winter and summer (Table 3-6). Data were collected from all sites in winter but the loss of both loggers from one site (site 5) in summer meant that data was only available for five sites at this time. There was minimal epiphytic algal growth on loggers at most sites during the two deployment periods except during winter for the single logger retrieved at Bradey's Bay and one of the loggers retrieved at Kakaho Stream delta.

Table 3-6: Summary light data for sampling sites. Nearby climate station summary and minimum light requirement data also shown.

Site	Seagrass	Winter		Summer	
		Logger no.	Light	Logger no.	Light
1-Kakaho Str. delta	No	448	104 (±13)	448	377 (±34)
		457	97 (±11)	003	365 (±33)
2-Ration Point	No	464	71 (±5)	457	267 (±29)
		004	81 (±6)	998	309 (±33)
3-Bradeys Bay	Yes	132	40 (±4)	442	241 (±28)
		459	*Lost*	001	213 (±23)
4-Ivey Bay	Yes	442	188 (±19)	461	502 (±38)
		002	168 (±15)	132	*Lost*
5-Paremata railway stn.	Yes	001	232 (±24)	004	*Lost*
		-	-	135	*Lost*
6-Elsdon	Yes	998	155 (±17)	130	379 (±44)
		003	138 (±12)	002	435 (±45)
Climate station	*n/a*	*n/a*	*422 (±25)*	*n/a*	*1185 (±73)*
Min. light			*46 (±3)*		*130 (±8)*

Light data are means of daily (24 h) average PAR (µmol m^{-2} s^{-1}) over 30 days (approx. one lunar month) from the date of deployment. Standard errors are given in parentheses (n=30). Only one logger was deployed at site S5 in winter as second logger was damaged on deployment. Average surface radiation data from the two nearest climate stations (Paraparaumu Aero AWS and Paraparaumu EWS) over the equivalent time periods are shown. Minimum light requirement is the calculated threshold for seagrass persistence as a percentage of surface radiation.

Light was consistently lowest at Bradey's Bay. In winter, light at this site was only just within the margin of error of the minimum light requirement for seagrass persistence. This may be due to the epiphytic algal growth found on the logger. However, such growths presumably also occurred on the leaves of the seagrass plants thus restricting light in a similar way. Some small seagrass patches were found at this site so light availability, particularly over longer time scales, is clearly sufficient to allow them to persist. Summer light levels at this site were well above the minimum light threshold which is consistent with this hypothesis. Interestingly, light was somewhat higher at the two sites at the head of this arm where seagrass is no longer present (Kakaho Stream delta and Ration Point). Light availability was also well above the minimum light threshold at both of these locations. The highest light levels we measured were at the Paremata railway station site in the outer Onepoto arm. However, light levels were also relatively high at the Elsdon site at the head of this arm.

3.2.3 Water quality

Water quality variables that affect light availability (i.e., total suspended solids and turbidity) showed a pattern that was slightly different to the light logger results (although note that the water quality monitoring sites do not correspond directly to the light logger sites – see Figure 3-7). Water turbidity and suspended solids concentrations were highest at the head of both arms (Elsdon and Ration Point areas, site O2 and P2) and lowest at the entrance to Bradey's Bay (site P3) and in the outer Onepoto arm (site O1) (Table 3-7). The results for Bradey's Bay (i.e., low light availability at the seagrass bed yet also low water turbidity and suspended solids relative to other sites) suggest that it is probably a steeper shore gradient and greater water depth covering the seagrass rather than poor water clarity that is responsible for the relatively low light levels at this site. Epiphytic algal growth is another possibility; however there was no evidence of this on the loggers at this site in summer.

Table 3-7: Summary of selected water quality variables from monthly water quality monitoring. Raw data provided by Greater Wellington Regional Council for sampling during 2011.

Site	TSS	Turb.	Salin.	Chl*a*	NO_3+ NO_2-N	NO_3-N	NH_4-N	TN	DRP	TP	Seaweed cover
	(g m^{-3})	(NTU)	(ppt)				(mg m^{-3})				(%)
E1	16 (5)	5.3 (1.8)	33.8 (0.4)	3.0 (0.0)	33 (14)	31 (13)	11 (1)	300 (0)	6 (1)	19 (3)	4 (3)
O1	16 (4)	8.0 (2.0)	32.0 (0.7)	3.4 (0.2)	52 (18)	49 (18)	16 (4)	200 (0)	7 (1)	31 (3)	0 (0)
O2	46 18)	20.4 (9.8)	27.6 (1.7)	4.9 (1.4)	148 (41)	143 (40)	31 (9)	510 (150)	9 (2)	59 (18)	0 (0)
P1	20 (6)	10.8 (4.1)	32.4 (0.6)	3.0 (0.0)	31 (13)	29 (12)	17 (3)	300 (0)	12 (2)	33 (6)	13 (13)
P2	33 (17)	20.7 (13.8)	29.2 (1.9)	4.1 (1.1)	100 (56)	97 (56)	19 (6)	500 (100)	8 (1)	53 (19)	18 (7)
P3	16 (5)	6.3 (1.1)	30.9 (1.2)	3.3 (0.3)	48 (22)	46 (21)	13 (2)	290 (10)	7 (1)	26 (2)	41 (11)

Data are averages with standard error in parentheses (n=12).

At the head of the Onepoto arm, light measured at Elsdon (site 6) was quite high whereas water turbidity and total suspended solids at the nearby water quality monitoring site (site O2) were also high relative to other sites. This suggests that there is some variation in water quality at the head of this arm. The O2 site is probably more strongly influenced by turbid inflows from the Porirua Stream. Average salinity levels at all sites were within the range suitable for seagrass habitation (i.e., >10 ppt and <45 ppt).

In July 1975 and March 1976, Smith and McColl (1978) recorded suspended sediment concentrations at sites around the Pauatahanui arm ranging from 6 to 58 g m^{-3} (average ~15 g m^{-3}). However during storm events concentrations of around 50 to 440 g m^{-3} were detected at some shoreline sites. Concentrations measured in 2011 are within the former range. Secchi disk depths in the Pauatahanui arm were measured by Forch (1983) in the mid-1970s with measurements ranging from 0.5 to 3.5 m. Secchi disk depths were not measured as a component of the GWRC water quality monitoring so no comparisons can be made but the measurements made by Forch (1983) are indicative of relatively low water clarity at that time. Forch (1983) also noted that "waters in the basin near the Kakaho Stream mouth were the most consistently turbid, with values usually less than 1 m".

In 2011 chlorophyll *a* and nutrient concentrations were highest at the head of the Onepoto arm (site O2). Concentrations were also relatively high at the head of the Pauatahanui arm (site P2). Forch (1983) also measured chlorophyll *a* concentrations in the Pauatahanui arm which ranged from 0.68 to 3.12 mg m^{-3}. However, she cautioned that these values should be viewed as only a general indication of activity due to some methodological issues. Chlorophyll a concentrations in the Pauatahanui arm in 2011 were generally higher and ranged from <3 to 16 mg m^{-3}.

Forch (1983) measured concentrations of bioavailable nutrients in the Pauatahanui arm of ~3-26 mg m^{-3} reactive-P, up to 400 mg m^{-3} NO_3+NO_2, and from ~150 to 754 mg m^{-3} TN in 1975–76. The concentrations measured in 2011 in the Pauatahanui arm span a comparable range for reactive-P (DRP <4–17 mg m^{-3}) but maximum NO_3+NO_2 and TN concentrations are 1.7 and 2.4 fold higher, respectively (NO_3+NO_2 <2-660 mg m^{-3}, TN <200–1800 mg m^{-3}). It is unclear if concentrations measured by Forch (1983) are in mg N m^{-3}/mg P m^{-3} as opposed to mg NO_3+NO_2 m^{-3}/mg PO_4 m^{-3}. We have assumed they are the former; but if not then the difference between sampling intervals is even greater.

Seaweed (macroalgae) cover is also monitored at water quality sites by GWRC (Table 3-7). Periodic high covers are evident at water quality monitoring sites in the Pauatahanui arm, particularly site P3 on the southern shoreline. A high cover of *Ulva* (sea lettuce) was also apparent at the inner Onepoto arm seagrass site (Elsdon, site 6) in January 2012 (Figure 3-8). Macroalgae cover has been mapped each summer since 2008 (Stevens and Robertson 2011). Persistent high covers (>50%) of macroalgae dominated by *Ulva* have been recorded in the inner Onepoto arm. In the Pauatahanui arm, macroalgal cover, dominated by *Gracilaria* or *Enteromorpha,* has periodically been high at the head of the arm near the Pauatahanui Stream mouth. Historically, there is little evidence for pervasive macroalgal problems in Pauatahanui arm, particularly for inner sites. Healy (1980) noted that a number of algae, including *Ulva*, *Enteromorpha*, *Gracilaria* and *Gelidium*, were associated with the seagrass beds in the Pauatahanui arm. However, *Ulva* apparently only formed large, dense beds in the area between the Paremata Bridge and the Golden Gate Peninsula during summer and was absent during winter.

From November 2011, Porirua City Council have monitored stormwater nutrient and heavy metal concentrations at a selection of sites around the harbour's catchment/perimeter. The monitoring results to May 2012 are summarised in Table 3-8 and Table 3-9. The nutrient data show that the stormwaters are typically enriched with nitrogen, with mean concentrations approximately 5 to 10-fold higher than in the harbour waters. These inflows presumably contribute to the nitrogen enrichment that is evident in the harbour waters. NH_4^+ (very high concentrations of which were measured at the Pauatahanui site) is readily transformed to oxidised nitrogen forms (i.e., NO_3^- and NO_2^-) under the aerated conditions typical of flowing waters and tidal systems. Phosphorus enrichment of the stormwaters is also evident. Very high concentrations of DRP have been measured at the Pauatahanui site. The heavy metal data show measurable concentrations of some compounds at most of the sampling sites. However in all cases, concentrations are well below effects thresholds that have been identified for *Zostera* species (Table 3-9).

Table 3-8: Summary of stormwater nutrient results. Raw data provided by Porirua City Council. Values are averages (±standard error).

Site	NO_3+NO_2-N	NH_4-N	TN	DRP	TP
			(mg m^{-3})		
A - Semple St	633 (39)	320 (120)	1530 (160)	71 (6)	132 (12)
B - Te Hiko St	349 (166)	320 (260)	680 (230)	31 (3)	62 (16)
Lower Kenepuru Str. [a]	648 (111)	11 (1)	1030 (180)	16 (0)	57 (13)
C - Browns Stream Mouth	330 (156)	80 (20)	760 (190)	13 (1)	97 (55)
D - Duck Creek	449 (153)	30 (10)	680 (180)	22 (2)	45 (14)
E - Pauatahanui	929 (514)	3190 (1140)	5150 (980)	1810 (509)	2046 (541)
F - Taupo Stream	69 (59)	50 (20)	780 (100)	21 (5)	71 (20)

[a] sampled from November 2011 to February 2012 only.

Table 3-9: Summary of stormwater heavy metal results. Raw data provided by Porirua City Council. Values are averages (±standard error) of total concentrations. Dash indicates parameter not measured/evaluated. Asterisks indicate values at detection limits

Site	Copper	Lead	Zinc	Cadmium	Chromium	Arsenic	Nickel
				(mg m^{-3})			
A - Semple St	4.3 (0.9)	2.0 (0.0)	85 (30)	1.0* (0.0)	3.0 (1.0)	2.0* (0.0)	1.0* (0.0)
B - Te Hiko St	2.0* (0.0)	1.1 (0.1)	10 (1)	1.0* (0.0)	1.4 (0.4)	2.0* (0.0)	1.1 (0.1)
Lower Kenepuru Str. [a]	2.3 (0.3)	1.0* (0.0)	9 (3)	1.0* (0.0)	1.0* (0.0)	2.0* (0.0)	1.0* (0.0)
C - Browns Stream	<0.5* [b]	<0.5* [b]	13 [b]	-	-	-	-
D - Duck Creek	0.6 [b]	<0.5* [b]	2 [b]	-	-	-	-
F - Taupo Stream	2.0* (0.0)	1.0* (0.0)	7 (1)	1.0* (0.0)	1.0* (0.0)	2.0* (0.0)	1.0* (0.0)
Effects [c] on *Z. capricorni* (10 h exposure, 4 day recovery)	1011	994	995	997	-	-	-
Effects [c] on *Z. marina* (19 d exposure)	320	10350	3250	560	2600	-	-

[a] sampled from November 2011 to February 2012 only.

[b] dissolved concentration measured on a single occasion.

[c] effects on *Z. capricorni* (syn. muelleri) chlorophyll pigments and on *Z. marina* growth rate. See Lewis and Devereux (2009).

3.2.4 Sediment particle size

The sediments sampled at all sites in 2011 (to 10 cm depth) were dominated by fine sands (63 µm to 250 µm (Table 3-10).

Kakaho Stream delta (site 1) and Ration Point (site 2) had the highest percentages of mud (8.3 and 3.4%, respectively) while the Elsdon site (site 6) had the lowest percentage of fine sands (68%) and the highest percentage of coarse sand (31%).

Table 3-10: Summary of sediment particle size results. Mud = clay + silt fractions. A graph showing a more detailed breakdown of the sediment particle size classes can be found in Appendix A.

Site	Mud (<63µm)	Fine sand (63-250µm)	Coarse sand (250µm-2mm)
1 – Kakaho Stream delta	8.3	90.5	1.3
2 – Ration Point	3.4	89.4	6.9
3 – Bradey's Bay	0.8	93.1	6.2
4 – Ivey Bay	2.9	93.9	3.1
5 – Paremata railway station	1.5	96.9	1.6
6 – Elsdon	0.9	67.4	31.4

4 Discussion

4.1 Changes in abundance

Aerial photograph analysis indicated that seagrass beds formerly present at the head of both the Pauatahanui and Onepoto arms of Porirua Harbour have been lost in recent decades. An extensive area of seagrass (~32 ha) was present at the head of the Pauatahanui arm in the delta areas of the Kakaho, Horokiwi and Pauatahanui Streams in the mid-1970s. These beds are no longer present. At the head of the Onepoto arm approximately 6 ha of seagrass was present in the 1960s. Now only isolated patches remain along the inner western shoreline of this arm (i.e., 1.5 ha in 2008). Approximately 3 ha of seagrass was lost from the western shore at Mana with the development of the marina. Seagrass biomass estimates made in the Pauatahanui arm in the mid-1970s suggests that the majority of the seagrass beds in this arm, including those at the head, were probably relatively dense. Minimum estimates of 80 g m^{-2} above-ground biomass and 180 g m^{-2} below-ground biomass (Healy 1980) are similar to those we measured in existing dense patches at Ivey Bay. However, total seagrass biomass in the range measured in Porirua Harbour (up to ~300 g m^{-2}) is at the lower end of the range found for intertidal beds elsewhere in New Zealand (up to ~800 g m^{-2}; Turner and Schwarz 2006, Matheson and Schwarz 2007, Matheson et al. 2009) and generally less than that recorded in subtidal beds (i.e., 400–1300 g m^{-2}, Eastern Bay of Islands) (Matheson et al. 2010).

While our results suggest that a considerable amount of seagrass has been lost from the head of both arms of the harbour, seagrass was present in comparable quantities at many sites where it has been recorded historically. In the Pauatahanui arm these sites include the shoreline from Ivey Bay to Moorehouse Point, the mid-harbour banks near Moorehouse Point, in Bradey's Bay and in Brown's Bay. In the Onepoto arm these sites include the tidal flats next to the Paremata railway station and the inner western shoreline. Relatively large seagrass beds are also still present in the two bays on the western side of the harbour entrance channel. In 2008, around 55 ha of seagrass beds remained in the harbour. Losses in the 1960-1980 period therefore equate to around 40% of the original seagrass extent in the harbour.

4.2 Causes of seagrass loss

Reduced underwater light availability as a result of estuarine siltation and eutrophication is often cited as the leading cause of seagrass loss in estuarine and coastal systems. Our assessment of the light environment at a selection of sites in Porirua Harbour representative of both existing and former seagrass locations suggests that lack of light may not be the primary cause of seagrass loss. In particular, the light environment at the two sites that formerly had extensive seagrass beds at the head of the Pauatahanui arm, was apparently more favourable than that in Bradey's Bay where some seagrass still persists. In addition, the light levels measured at the two former seagrass sites were above general minimum thresholds indicated in the seagrass literature, and above average summer time levels measured for subtidal seagrass beds in the Bay of Islands (52-111 µmol m^{-2} s^{-1}; Matheson et al. 2010). However, an alternative interpretation of these results is that there have been improvements in water quality since the loss of these seagrass beds that now render these areas suitable for seagrass habitation once more, yet they have been unable to re-establish due to a lack of viable propagules (seeds and/or floating vegetative fragments from other sites, remnant seed banks).

Comparing recent water quality data to that collected in the Pauatahanui arm in the mid-1970s does not suggest any significant changes in parameters directly related to water clarity, and thus light availability during this time. In particular, total suspended sediment concentrations are comparable. However, nitrogen concentrations (TN and NO_3+NO_2-N) appear to be higher now (by approximately 2-fold, based on maximum concentrations), possibly along with chlorophyll *a* concentrations. The two are often linked, with increased nitrogen levels stimulating phytoplankton growth, but there were methodological concerns with the 1970s chlorophyll *a* measurements so these results must be treated with some caution. Moreover, increased phytoplankton abundance would normally be expected to result in higher suspended sediment measurements (which is not apparent), unless there was also a concurrent decline in other suspended particles. Nitrogen concentrations at all sites in Porirua Harbour, but particularly at the former seagrass sites at the head of each arm (average ≥97 mg NO_3-N m^{-3}), are considerably higher than those measured at intertidal seagrass sites in Whangarei Harbour (3-5 mg NO_3-N m^{-3}) (Matheson et al. 2009). In addition, the elevated concentrations of NO_3-N measured at the head of each arm in Porirua Harbour are within the range of water column concentrations (6–12 µM, or ~80–170 mg NO_3-N m^{-3}) found to cause toxicity symptoms in the related species, *Zostera marina*, especially when combined with warmer water temperatures, with longer term exposure expected to lead to meadow decline (Burkholder et al. 1994). Moreover, dissolved inorganic nitrogen (DIN = NO_x-N + NH_4-N) concentrations exceed thresholds established in lower Chesapeake Bay, USA, to protect *Zostera marina* (i.e., maximum <140 mg DIN m^{-3}, Dennison et al. 1993; median seasonal upper limit <150 mg DIN m^{-3}, Batiuk et al. 1992). These results therefore suggest that nitrogen enrichment of the harbour waters has taken place in recent decades and this has contributed to the seagrass decline. Nitrogen enrichment may have also altered the nutrient status and biogeochemical processes of harbour sediments (which we did not assess), with other potentially detrimental side-effects for seagrass (e.g., increased sediment anoxia and release of oxygen-sensitive toxins such as sulphide).

In general terms, change to sediment properties appears to be a contributing factor to seagrass decline. Using sediments collected from existing and historical seagrass sites in Tauranga Harbour, we found that seagrass growth was significantly less on sediments from historical sites, suggesting that a change in sediment quality was associated with the loss of seagrass from these sites (Matheson and Schwarz 2007). In the eastern Bay of Islands, we found that seagrass decline was associated with an apparent increase in fine sand sized particles (125-250 µm) in the benthic sediments (Matheson et al. 2010). However, no such trend was evident in Porirua Harbour. Our sediment particle size results show that the two sites at the head of the Pauatahanui arm from which seagrass loss has occurred had higher percentages of mud relative to other sites (particularly the Kakaho Stream delta site). However, the percentage of mud at Ivey Bay, where dense seagrass patches persist, was only slightly less than that at Ration Point. The site we sampled at the head of the Onepoto arm had a relatively low mud content but it did not correspond directly with the area from which a number of hectares of seagrass has been lost (which is closer to the Porirua Stream delta). Loss of seagrass meadows in Tauranga Harbour has been linked to an increase in the mud content of surficial sediments (>13%, Park 1994), indicating detrimental effects associated with siltation. Very fine sediment particles are easily resuspended, leading to reduced water clarity and low underwater light levels, and plants leaves can become coated by silt deposits hindering gas exchange and photosynthesis. Siltation can also contribute to sediment nutrient enrichment and anoxia. Such effects may have contributed to the decline of seagrass from the inner sites within Porirua Harbour, particularly in the Pauatahanui arm at the Kakaho Stream delta site.

Persistent high cover macroalgae also has the potential to smother seagrass beds and block light availability. It is possible that this has contributed to seagrass loss in both arms, but more likely in the Onepoto arm. In recent times, macroalgal cover in the Pauatahanui arm has generally been low to moderate, although periodically high near the Pauatahanui Stream mouth. In the Onepoto arm, high densities of *Ulva* are often present in the inner arm in and around the former seagrass site. This also represents an on-going threat to the remnant patches surviving there.

Other toxicants in the water or sediment may also have played a role in seagrass loss, such as heavy metals, petrochemicals or biocides. Some of these contaminants have been measured at sites within Porirua Harbour in recent years. Concentrations of various heavy metals, polycyclic aromatic hydrocarbons (PAHs) and organochlorine pesticides, including DDT and dieldrin, have been measured at selected sites in both arms (Sorensen and Milne 2009) and heavy metals have also been measured recently in stormwater samples. The heavy metals most likely to be detrimental to seagrass growth are copper, lead, cadmium, mercury and zinc (Macinnis-Ng and Ralph 2004). The concentrations measured for most compounds are generally within the ranges that have been detected within seagrass rhizosphere sediments (Table 4-1) and stormwater heavy metal concentrations are well below effects thresholds. It is therefore unlikely that these compounds have contributed to seagrass loss, although we cannot rule out the possibility of synergistic effects or species-specific differences in tolerance levels. Compounds that did exceed those previously reported for seagrass sediments were dieldrin and DDT, which were found at elevated concentrations at some of the intertidal sampling sites close to the Porirua Stream mouth. It would be useful to measure the concentrations of these contaminants, and other biocides not previously measured (e.g., diuron, Irgarol 1051, atrazine), specifically at present and former seagrass sites in the harbour to further examine their potential contribution to seagrass loss. Irgarol 1051 and diuron have previously been measured on one occasion in waters at the Mana marina and in the Onepoto arm north of Te Onepoto Bay near a handful of swing moorings (Stewart 2006). Irgarol 1051 was not detected but diuron was measured at a concentration of 0.22 µg l^{-1} at the Mana marina site. Watercolumn exposure to 0.1 µg l^{-1} diuron over a five-day period has been shown to have detrimental effects on the physiological systems in *Zostera capricorni* (syn. *muelleri*) (Haynes et al. 2000). It would be useful to measure the concentrations of these contaminants within harbour sediments as an indicator of chronic exposure levels.

Table 4-1: Concentrations of heavy metals and organic contaminants in Porirua Harbour and seagrass rhizosphere sediments.

Contaminant	Porirua Harbour (from Sorensen and Milne 2009)	Seagrass rhizosphere (from Lewis and Devereux 2009)
Arsenic (µg/g)	1.2–10.7	-
Cadmium (µg/g)	<0.01–0.17	<0.03–270 (10.0)
Chromium (µg/g)	3.2–17	1.1–679
Copper (µg/g)	2.2–30	0.7–397 (9.4)
Lead (µg/g)	3.71–51.3	0.5–5,270 (1.7)
Mercury (ng/g)	10–150	<4–510
Nickel (µg/g)	2.2–10	0.3–1,890
Silver (µg/g)	<0.02–0.07	-
Zinc (µg/g)	14.7–410	3–16,700 (133)
Dieldrin (ng/g)	<0.98–1.3	<0.05–0.37
Total DDT (ng/g)	3.3–23.0	<0.05–10.3
Total PAH (ng/g)	110–5,945	150–6,000

Rhizosphere concentrations in parentheses are for *Zostera capricorni* (syn. *Z. muelleri*) sediments.

The presence of seagrass wasting disease (caused by the marine slime mould, *Labyrinthula zosteraceae*) was linked to the decline of seagrass beds in several locations around New Zealand in the late 1950s and early 1960s including Waitemata, Manukau and Purau near Christchurch (Armiger 1964). Current understandings suggest that this pathogen is often present on healthy plants, but overgrowths, and thus plant dieback, generally occur when plants become stressed by other factors, such as low light (see Turner and Schwarz 2006). It therefore seems unlikely that this was a primary driver responsible for the seagrass loss in Porirua Harbour.

4.3 Potential for restoration

Seagrass restoration to former sites is not a simple task. Suitable growing conditions need to be re-established which usually requires identifying and remediating the original causes of loss. There are many factors that can contribute to seagrass loss and we have made a preliminary assessment, as far as possible given the scope of this study, of those that are generally regarded as being most important. Light is usually regarded as the primary factor affecting seagrass persistence, as this incorporates effects of the two most pervasive human influences on estuarine environments (siltation and eutrophication), but our results suggest that light levels are currently sufficient at former seagrass sites at the head of the Pauatahanui arm. It is unclear whether these results mean that other factors are primarily responsible for seagrass loss from these sites (our results suggest that watercolumn NO_3^- toxicity is a strong possibility). Alternatively, seagrass may have been lost from these areas during a prior period of sustained low light levels sometime after the mid-1970s and has not been able to re-establish due to a lack of viable propagules. In the Pauatahanui arm, potential sources of propagules are the remaining seagrass beds in the outer arm, from which vegetative fragments, or even seeds, could be released, circulated by harbour currents and deposited at the former sites. Since little is known about the magnitude or frequency of propagule release from *Zostera muelleri* beds (Turner and Schwarz 2006), we cannot comment on the likelihood of this occurring. However, a relatively simple and direct way to test the above hypothesis, would be to transplant some small plots of seagrass into this area. Should they not survive, then this provides good evidence that factors other than light have probably contributed to the seagrass loss. Further work would be required to identify and remediate those causes before any restoration could be undertaken or natural regeneration expected. In the case of remediating NO_3^- contamination this would more than likely entail reducing catchment inputs of this contaminant via best management practices (e.g., riparian set-aside and planting, fertiliser and effluent management).

In the Onepoto arm, we did not quantify light and other parameters at the exact site where seagrass beds were formerly present and comparisons of the data from the adjacent site with GWRC monitoring data suggest that there may be considerable variation in water clarity in this part of the harbour. The restoration potential of this site warrants further investigation, taking into account our observation that the elevated heavy metal concentrations at the head of this arm, and in stormwaters entering this area, are probably not at levels detrimental to seagrass growth. However, elevated organochlorine pesticide levels at the nearby Porirua Stream mouth are a cause for concern. A persistent high cover of *Ulva* in this location may have been a contributing factor to seagrass loss in the past and also presents an on-going stress on remnant patches in this area.

5 Conclusion and recommendations

This preliminary investigation of seagrass restoration potential in Porirua Harbour has shown that:

- Around 32 ha of seagrass beds have been lost from the head of the Pauatahanui arm since 1980. At least 4 ha have also been lost from the head of the Onepoto arm since the 1960s and a further 3 ha at the Mana marina site. However, seagrass persists at the majority of other former sites in the harbour.

- The loss of seagrass from the head of both arms is associated with elevated NO_3^- concentrations in these areas, with 2011 average levels known to cause toxicity symptoms in seagrasses and long term exposure linked to seagrass decline. A reduction in average NO_3^- concentrations in these areas to <80 mg m^{-3} may be required before seagrass recolonisation can occur.

- Light availability at former sites in the Pauatahanui arm is currently adequate for seagrass growth. Transplanting some small plots of seagrass to one or both sites would be a useful means to test the hypothesis that seagrass recolonisation of these sites is hindered by a lack of viable propagules rather than NO_3^- toxicity or other factors.

- Seagrass loss in the Pauatahanui arm is associated with elevated sediment mud content, suggesting that siltation effects (not related to light availability) may have also contributed to plant decline in this arm. This includes direct smothering of plants and changes to sediment properties affecting growth (e.g., increased nutrient enrichment, anoxia and compound toxicity). Further investigation of sediment redox and nutrient concentrations at the present and former seagrass sites studied here is suggested to evaluate this possibility.

- Contamination by heavy metals and organic contaminants is apparent in the harbour sediments but the concentrations measured are generally within the ranges reported for viable seagrass beds elsewhere. The exceptions are dieldrin and DDT which, along with other biocides, warrant further investigation at past and present seagrass sites.

- Smothering by dense and persistent macroalgal beds may have contributed to the loss of seagrass beds in the harbour, particularly in the Onepoto arm.

- Since our assessment site at the head of the Onepoto arm did not correspond directly to a former seagrass site, and there is likely to be a considerable localised impact from the Porirua Stream discharge, some further investigation of this area is recommended. In particular, it would be useful to evaluate the parameters measured and recommended in this study specifically at the former seagrass site.

Our specific recommendations for future work in order of priority are as follows:

- A small amount of seagrass should be transplanted to the former site at Ration Point at the head of Pauatahanui arm (Site 2) to test the hypothesis that recolonisation is prevented by a lack of viable propagules from remnant beds. We suggest that 6 x 0.25 m^2 sod plots of seagrass are carefully extracted from the margins of the existing seagrass bed at Ivey Bay and transplanted within 24 hours to the Ration Point site. The plot areas at both sites should be marked and these areas photographed initially and then at least every three months for at least one year to monitor recovery of the donor site and survival of plants at the transplant site. We suggest that light should be continuously monitored at the transplant and donor sites during the trial. This is consistent with the approach taken during successful transplanting of seagrass to a former site in Whangarei harbour (Matheson et al. 2009). At this time we do not recommend that seagrass be transplanted to any other former sites in Porirua harbour. We consider that there is a strong possibility that the transplanting may not be successful given the high levels of nitrate pollution in upper reaches of the harbour and the demonstrated sensitivity of a related *Zostera* species to this pollutant. However, we consider that a small trial of this nature is a direct and cost-effective way to test this theory.

- The concentrations of a number of important biocides (dieldrin, DDT, atrazine, diuron and Irgarol 1051) should be evaluated at the past and present seagrass sites investigated in this study (i.e., Sites 1 to 6) but also at an additional site at the head of the Onepoto arm, within the extent of the former seagrass beds (we suggest E2664559 N6007233). We recommend that the concentrations of these compounds plus particle size and organic matter content are measured in replicate sediment samples (minimum three, sectioned into 0-2 cm and 2-10 cm depth fractions) collected on at least one occasion from each site. In addition, diuron, Irgarol 1051 and atrazine have frequently been measured in the watercolumn (rather than sediments) so, if resources allow, we also recommend that the concentrations of these compounds are measured in water samples collected every month from each site for at least one year, preferably including some sample dates immediately following significant rainfall events.
- Sediment redox and nutrient concentrations should also be evaluated at all of the sites mentioned above. We recommend that *in situ* redox profiles (1 cm intervals to 20 cm depth) are measured at a minimum of three locations at each site, once per season, for at least one year. Sediment core samples (as above) should also be collected at the same time from the same locations to measure porewater and bound sediment nutrient concentrations. Porewaters should be analysed for TN, TP, NH_4^+, NO_3^- and DRP and dried sediments for TN and TP (see Lohrer et al. 2010 and Matheson & Schwarz 2007 for appropriate methods).
- Light should be quantified at the additional 'head of Onepoto arm' site described above using the approach detailed in this report. It would also be useful if light measurements were repeated at all other sites at the same time.
- If resources allow we suggest that it would also be useful to measure concentrations of copper, lead, cadmium, mercury and zinc in the sediment samples collected for biocide analysis to confirm that heavy metals concentrations are ubiquitously low across all sites.

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Appendix A Sediment particle size results

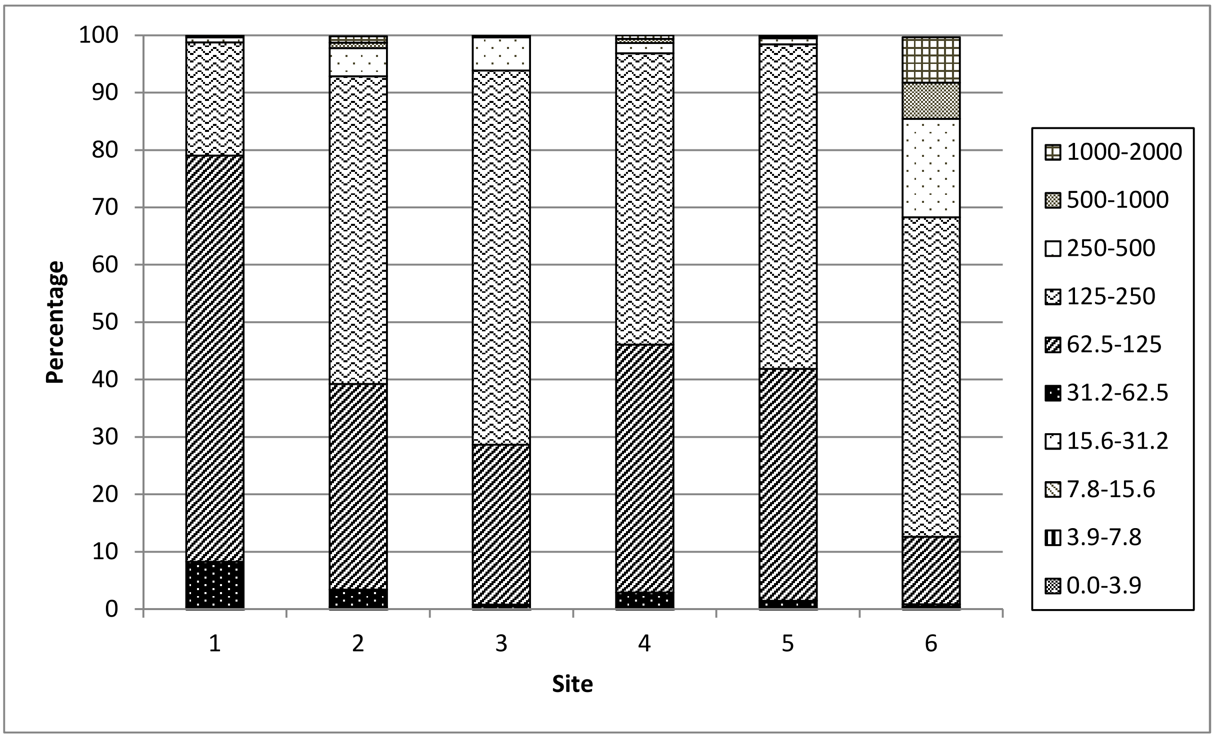

Figure A-1: Overall sediment particle size distribution for sample sites in July 2011.