THE PORIRUA HARBOUR AND ITS CATCHMENT: A LITERATURE SUMMARY AND REVIEW
Report for
Porirua City Council & Wellington City Council

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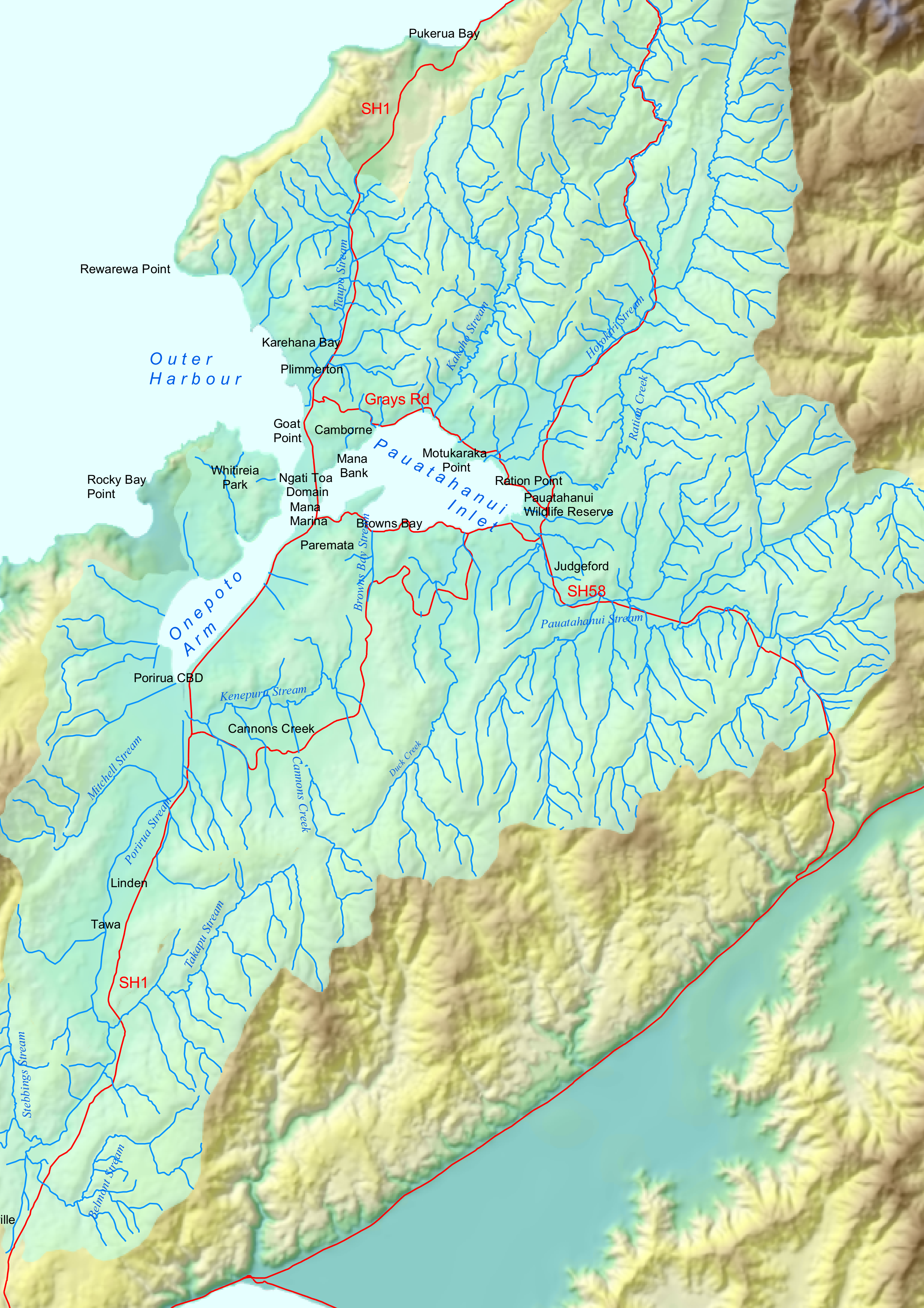
Upper: Overlooking Porirua Harbour and Paremata ca. 1920. Photographer: Sydney Charles Smith. PA Collection-3082-5, Alexander Turnbull Library

Lower: Paremata Vista, 2009. Photographer: Keith Calder.



Pukerua Bay
SH1
Rewarewa Point
Taupo Stream
Karehana Bay
Outer Harbour
Plimmerton
Kakaho Stream
Horokiri Stream
Grays Rd
Ration Creek
Goat Point
Camborne
Pauatahanui Inlet
Motukaraka Point
Mana Bank
Rocky Bay Point
Whitireia Park
Ngati Toa Domain
Ration Point
Pauatahanui Wildlife Reserve
Mana Marina
Browns Bay
Paremata
Browns Bay Stream
Judgeford
Onepoto Arm
SH58
Pauatahanui Stream
Porirua CBD
Kenepuru Stream
Cannons Creek
Mitchell Stream
Cannons Creek
Duck Creek
Porirua Stream
Linden
Tawa
Takapu Stream
SH1
Stebbings Stream
Belmont Stream

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Lower: Paremata Vista, 2009. Photographer: Keith Calder, Porirua City Council.

Executive Summary

Porirua City Council, with support from Wellington City Council, requested Blaschke and Rutherford to compile a summary and review of literature about the environment of Porirua Harbour and its catchment. This review enables an assessment of existing information about the area and highlights information gaps and future research needs for catchment management. The geographical scope of the review is the entire Porirua Harbour (Pauatahanui Inlet, the Onepoto Arm and the Outer Harbour), and the catchment surrounding these Harbour arms, a total area of just under 200 km^2.

The body of research about Porirua Harbour and catchment has grown considerably in the last decade. Research on the Onepoto Arm and its catchment has been much less than that on Pauatahanui Inlet and catchment but has increased significantly in the last five years. Knowledge and understanding of the Outer Harbour is still very limited.

From a whole harbour and catchment perspective, there is reasonable knowledge of the physical environment and environmental history, and of terrestrial, freshwater and estuarine habitats and macroscopic biota. There have been a number of studies of water and sediment quality but our understanding of the causes of some significant water quality problems is still very limited. Harbour sedimentation rates have been studied in detail, but a full understanding of the catchment-harbour and harbour-ocean sediment transfer system is hampered by poor knowledge of the variability of sub-catchment sediment production and transfer processes, and of harbour hydrodynamic and exchange processes. A particular issue for integrated catchment management is the effects of the roads and other hard surfaces that encircle Porirua Harbour, to a degree that is unique in New Zealand. This issue needs to be better understood.

Recommended research priorities for Porirua Harbour and catchment

Research priorities have been identified and are listed below. Immediate management actions should not be delayed pending further research outcomes. There is already enough information available to at least begin the development of a catchment management strategy or plan to counteract some of the adverse trends that are becoming apparent. Research on similar issues (especially land use impacts on stream water quality and harbour condition) in other harbour catchments in New Zealand can also be applied to Porirua Harbour and catchment.

1. Gather and maintain a consolidated reference collection of all published and known unpublished reports on Porirua Harbour and catchment, to be housed at Porirua City Council and made available to interested parties.
2. Improve understanding of the transfer of pollutants and sediments within Porirua Harbour, by undertaking an integrated Porirua Harbour hydrodynamics study, focussing on Onepoto Arm, and the exchange processes between Pauatahanui Inlet, the Onepoto Arm and the Outer Harbour.
3. Obtain background information on water quality at sites across the entire Porirua Harbour in order to understand natural variation within the system. Parameters measured should include: turbidity, salinity, pollutant and nutrient concentrations,

dissolved oxygen, temperature and pH. Sample sites should be located to enable assessment of the relative influence of fluvial inputs, tidal flushing and harbour morphology.

4. Continue to monitor changes in Porirua Harbour bathymetry over time, and relate changes to estuarine hydro-dynamic processes.
5. Characterise the catchment in terms of geomorphology and stream morphology, and document recent changes e.g. channel straightening. In particular, investigate the effects of Porirua Stream (and tributaries) flood control and other engineering works on stream and harbour processes.
6. Identify which sub-catchments urgently need erosion control, and prioritise enhancement works, based on representative sub-catchment sediment budgets and field measurements, and continued assessment of sediment inputs into Porirua Harbour using already installed sediment plates.
7. Complete biological inventory and ranking of significant terrestrial sites in Wellington City, and where necessary update inventory and rankings of Porirua City ecosites, in order to obtain complete information on priorities for terrestrial site protection and management in the Porirua Harbour catchment.
8. Continue habitat mapping consistently over the entire Porirua Harbour, and extend to sub-tidal areas, along with broad-scale description of the benthic communities.
9. Derive a definitive list of indicator species for Porirua Harbour and catchment, including key estuarine fish species.
10. Extend the monitoring of cockle populations in Pauatahanui Inlet to include the monitoring of key indicator species in all parts of the Harbour.
11. Continue long-term monitoring of sediment chemistry and benthic ecology at sample sites in Onepoto Arm and Pauatahanui Inlet. Sediment samples that are above ANZECC (2000) guidelines should be analysed for their bioavailable fraction to determine if high concentrations could affect biota.
12. Investigate the hypothesis that some Porirua Stream tributaries are at or near their ecological "tipping point", based initially on a close analysis of any trend data available and the presence/absence of indicator species.
13. Investigate sources of gravels in the Porirua Stream and Harbour, especially those that are removed by dredging. Investigate the effects of all current dredging activities in the Porirua Harbour.
14. Document changes in human uses of the Porirua Harbour over the last 150 years, in particular focussing on the extent and use of cockle and oyster beds.
15. Investigate adaptation and mitigation strategies for the environmental consequences of the high degree of road/transport encirclement of the Porirua Harbour.
16. Investigate the potential and preferred methodology for enhancing inanga habitat in the lowest reaches of Kenepuru Stream.
17. Obtain and analyse further information on fish habitat and fish populations in the Porirua Harbour, especially the Outer Harbour. Research the effects of Porirua Harbour fishing and catchment land use on Harbour and adjacent coastal area fisheries and ecosystems.

Introduction

Porirua City Council (PCC), with support from Wellington City Council, requested Blaschke and Rutherford to compile a literature summary and review for the Porirua Harbour and catchments, to enable an assessment of existing information on the Harbour and any future research and information needs.

The purposes of the review were specified as:

- To understand the physical history and changes that have occurred in the Porirua Harbour and catchment since human habitation.
- To ensure that current decision-making about areas and/or matters that could affect Porirua Harbour is better informed by existing knowledge.
- To collate existing knowledge to assist agencies and the community to better plan and implement appropriate management for the Harbour and its catchment.
- To identify areas where information is lacking about the Harbour so that research can be undertaken to address these deficiencies.
- To enable more detailed and realistic goal-setting for the management (including restoration) of Porirua Harbour.

The geographical scope of this review is shown in Figs 1 and 2. Porirua Harbour (the Harbour) has two main arms, the Pauatahanui Inlet, and the Onepoto Arm (PICT 2001; Milne et al. 2004). Other components of the Harbour include the Outer Harbour, and a third small arm, the Taupo Swamp, which was formerly seawater arm, draining into the Outer Harbour. These four Harbour components all have catchments draining into them, as shown in Fig. 1.

This review is NOT intended to draw definitive conclusions about the Harbour's various ecological, hydrological, or physical characteristics. Rather it is a summary of the existing literature and known information on the matters listed in the various headings in the following chapters, and discussion of issues and research needs arising from this summary. The review was undertaken using traditional literature searching techniques for both written and electronic resources. The main holdings searched for the bibliography were collections at Porirua City Council, Greater Wellington Regional Council and Victoria University of Wellington’s libraries. Most material used for the review is either formally published, or in the form of unpublished reports for local authorities available through those authorities. Other unpublished information has been kept to a minimum.

This review follows an earlier review prepared by Boffa Miskell Ltd (BML) (2000) that summarised and reviewed a considerable amount of written material relating to the Pauatahanui Inlet and catchment up to the year 2000. The current review primarily involves updating the Pauatahanui Inlet material to incorporate a significant amount of new material which has become available since 2000, and geographically extending the scope of the earlier review to include the whole of Porirua Harbour and its catchments, i.e. the Onepoto Arm, the catchment areas flowing into the Onepoto Arm, and other smaller catchments and streams flowing into the Outer Harbour. For this latter task we have also had the benefit of a recent report on ecological restoration in the Porirua Stream catchment (Blaschke et al 2009). One of the authors (PB) has been involved in all three reports.

This review concentrates on the recent material relating to Pauatahanui Inlet, as well as all the material relating to other parts of the Harbour, but we have also included earlier work relating to Pauatahanui Inlet which we felt was of lasting value. In particular, Pauatahanui Inlet was the subject of a far-sighted, intensive three-year study (Pauatahanui Environmental Programme or PEP) carried out by the former Department of Scientific and Industrial Research between 1975 and 1977. The results of that study were summarised in the book *Pauatahanui Inlet - an environmental study* (Healy 1980), as well as published in individual scientific reports. In many cases the results of PEP studies are still the most comprehensive or only information on a given topic.

Appendix 2 is an annotated bibliography of all the literature we have read (including the entries for the earlier review of Pauatahanui Inlet). The chapters that follow in the main report (Chapters 2 -9) summarise and discuss this literature under various headings. We then briefly review relevant catchment studies from other parts of New Zealand. In the final chapter we synthesise and summarise all material reviewed in terms of what we know and do not know about the Porirua Harbour and its catchments, and our suggested priorities for further research. Our comments in Chapters 2-9 are generally restricted to how adequately the literature found covers the subjects. Our substantive comments and conclusions are mainly in the final chapter. All unreferenced comments are our own conclusions, except in the final chapter which is unreferenced. Only New Zealand literature is referred to. A glossary of technical terms and scientific names is at the end of this report.

Acknowledgements

We thank Keith Calder and Matt Trlin, Porirua City Council, who commissioned this study and maintained keen interest throughout. Thanks also to Amber Bill, Wellington City Council, who supported and contributed towards funding the project. Keith Calder has reviewed successive drafts in detail and provided a large amount of information. Peer reviewers Dr Ken Grange (NIWA), Prof. John Wells (Guardians of Pauatahanui Inlet), and Juliet Milne (Greater Wellington Regional Council) provided many helpful comments and leads to further references. We thank Nick Page and library staff at Greater Wellington for GIS advice and willing access to library facilities. We also thank Gary Stephenson (Coastal Marine Ecology Consultants), Peter Handford (PA Handford and Associates) and Graeme Hastilow (Te Runanga o Toa Rangatira) for helpful comments on specific sections and recommendations, and Blake Abernathy (Ministry of Fisheries) for fisheries information.

Physical dimensions, components, characteristics and significance of Porirua Harbour and its catchment

Porirua Harbour and catchment is shown in Figure 1. Its total area is just under 200 km^2, comprising a land area of about 185 km^2 and a harbour area of about 14 km^2. The area of the Pauatahanui Inlet catchment is 109 km^2 (Milne et al. 2004); it has six major sub-catchments: Browns Bay, Duck Creek, Pauatahanui, Ration Point, Horokiri and Kakaho[1] and six small catchments which drain only to the shoreline (Page et al. 2004). The main stream draining into the Onepoto Arm is Porirua Stream which has a catchment of about 53 km^2. The sub-catchments of the Porirua Harbour are listed in Table 1.

The maximum elevation of the catchment is 530 metres above sea level at the head of the Horokiri sub-catchment and 470 metres above sea level at Colonial Knob on the western side of the Porirua sub-catchment. The catchment is characterised by much-dissected plateaux at around 150 m altitude. These occur between Porirua East and Pauatahanui; between Judgeford and the Horokiri Valley; and from Mana to around 800 m north of the Pauatahanui Inlet coast (Grant-Taylor et al. 1970).

Taupo Stream drains a catchment of 820 ha, much of which is occupied by the Taupo Swamp. Taupo Swamp rises to 20 m above sea level at its north end. Presently its southern end is drained and developed for farming, industrial use and playing fields, but prior to development the base of the swamp lay at 2m above sea level behind Plimmerton beach. The remaining swamp land is protected by Queen Elizabeth II Trust, and it is one of the few remaining large wetlands in the Wellington Region (Cochran 2000).

The Harbour can be described as an estuary[2], as it has free exchange with marine water, which is appreciably diluted by freshwater inputs (Dalrymple et al. 1992). The Harbour is thus influenced by fluvial and ocean processes, receiving water and sediment from both. The area of Pauatahanui Inlet is 4.7 km^2 and that of Onepoto Arm 2.4 km^2 (Gibb and Cox 2009). The area of the Outer Harbour (up to a line between Te Rewarewa and Rocky Bay Points is about 6.4 km^2.

The Harbour has no large river inflow, but the two largest streams (Pauatahanui and Porirua Streams) enter at the heads of the arms (see Figure 1). The Pauatahanui Inlet catchment area is about 25 times bigger than Pauatahanui Inlet itself (BML 2000; PICT 2001). The shoreline length of Pauatahanui Inlet is 13.2 km (Bellingham 1998) whilst that of Onepoto Arm is 9.0 km (Gibb and Cox 2009).

[1] Horokiri and Kakaho Streams have sometimes been referred to as Horokiwi and Kahao Streams respectively.
[2] Notwithstanding the nature of the two main arms of the Harbour as estuaries the term ‘Harbour’ has been used throughout this report in relation to the whole Porirua Harbour, while ‘estuary’ is retained for reference to estuaries in general.

Table 1. Sub-catchments of Porirua Harbour[3]

Sub catchment	Area (ha)	Percent of catchment
Outer Harbour		
Karehana	**330**	**1.8**
Taupo Stream	**880**	**4.8**
Sub-catchment total	***1210***	***6.6***
Pauatahanui Inlet		
Kakaho Stream & Mana	**1470**	**8.0**
Horokiri Stream	**4100**	**22.2**
Pauatahanui Stream	**4160**	**22.5**
Duck Creek	**1000**	**5.4**
Browns Bay	**120**	**0.6**
Pauatahanui sub-catchment total	***10850***	**58.7**
Onepoto Arm		
Porirua Stream		
Kenepuru Stream	**1500**	**8.1**
Linden /Tawa	**690**	**3.7**
Takapu Stream	**850**	**4.6**
Belmont Stream	**720**	**3.9**
Stebbings Stream	**700**	**3.8**
Mitchell Stream	**800**	**4.3**
Porirua sub-catchment total	***5260***	***28.5***
Aotea & Papakowhai	**380**	**2.1**
Elsdon	**420**	**2.3**
Whitireia	**350**	**1.9**
Onepoto sub-catchment total	***6410***	***34.7***
Catchment total	**18470**	

Figure 1. Map of Porirua Harbour and catchments, showing location of places referred to in text (separate file)

The salt and freshwater marshes of the Harbour have been heavily modified by humans since the time of European settlement, with filling in of salt marsh occurring in both arms. Filling in of marsh has been almost complete in Onepoto Arm, and substantial in Pauatahanui Inlet. Several areas of marsh in the Pauatahanui Inlet are now protected as reserves including Pauatahanui Wildlife Management Reserve (43ha), a wildlife refuge

[3] Data primarily drawn from authors' analysis of Landcover Database and cadastral data 2009 and 2010. Some information for verification drawn from Irwin (1976), Boffa Miskell (2000) and Blaschke et al. (2009). Analysis does not include very small sub-catchments in the vicinity of Rocky Bay and Rewarewa Points.

covering the east of the inlet (169 ha), Duck Creek Scenic Reserve (1 ha) and Horokiri Wildlife Management Reserve (5 ha).

The westward-facing entrance of the Porirua Harbour contains rocky platforms, gravel banks and sandy beaches, whilst the embayments of both arms are filled with sandflats (Robertson and Stevens 2006, 2008), many of which are exposed at low tide. Pauatahanui Inlet has 1.1 km^2 of tidal flats (just under 25% of the Inlet area) whilst Onepoto Arm has 0.5 km^2 of tidal flats (20% of the Arm's area) (PICT 2001; Milne et al. 2004). Rock platforms are present throughout much of the Harbour, and from Karehana Bay east; all are deeply weathered (Grant-Taylor et al. 1970).

The average annual rainfall around the Porirua Harbour is 1200mm, with the wettest periods occurring in the winter months (May to October). The mean annual temperature is 12.9°C, and the prevailing winds are northerlies or northwesterlies (Stirling 1983).

The Harbour has long been recognised as scientifically significant, characterised by unique biological features, and with many other values for residents and visitors. Habitats in the Harbour have recently been mapped (Stevens and Robertson 2006, 2008). The Harbour is one of only two significant natural harbours in the North Island south of a line between Kawhia and Whakatane (the other being Wellington Harbour). Therefore, degradation of the Harbour would mean a significant habitat loss to many estuarine species (Bell et al. 1969). The Harbour is also unique in that unlike most New Zealand estuaries (which empty completely at low tide) Porirua Harbour is mainly subtidal, with 65% of its area underwater at low tide (Stevens and Robertson 2008). Pauatahanui Inlet has been rated as a site of National Significance in the SSWI (Sites of Special Wildlife Interest) database (DOC 1995). It has various forms of statutory recognition in territorial and regional planning documents such as the Porirua City District Plan, the Regional Freshwater and Coastal Plans and the Department of Conservation's Conservation Management Strategy.

Statutory bodies with responsibilities for the inlet include Porirua City Council, Wellington City Council, Greater Wellington Regional Council, Department of Conservation, New Zealand Transport Agency and Ministry of Fisheries.

There are approximately 85 000 residents of the Porirua Harbour catchments, comprising most of the Porirua City's 51,000 residents, and approximately 23-25,000 residents of Wellington City within the Porirua catchment. The recognised tangata whenua of the area is Ngati Toa, while the Te Atiawa iwi have historical connections with the southern parts of the Porirua catchment, especially the Takapu sub-catchment (BML 2005).

Tectonic and geological/geomorphic history, including current movement rates

Geology

The bedrock within the catchment is part of the Rakaia Terrane, a grey sandstone-mudstone sequence with thick poorly bedded sandstone called greywacke and argillite. Beds of this bedrock strike north-northeast, dip steeply and face west. This rock also has minor components of conglomerate, basalt and chert. The rock was formed in the late Triassic –Early Jurassic (255-170 million years ago) as a submarine fan and has since undergone multiple fold events (Webby 1958; Suneson 1993; Begg and Johnston 2000).

The remaining geology is composed of unconsolidated beach, alluvial, fluvial, loess and fan deposits of Quaternary age (1.8 million years to the present). These deposits are generally confined to the Harbour fringes, alongside rivers, and with some loess deposits mantling local hills. Some aggredational and degradational terraces are present throughout the Harbour, and a portion of land has been reclaimed by fill at the southwest end of the Onepoto Arm (Webby 1958; Begg and Johnston 2000).

Interpretation of the history of the Quaternary terraces has been contentious. The terraces were long interpreted as marine deposits of interglacial periods (Leamy 1958), but the prevailing more recent thought is that they have a variety of origins including fluvial and marine, and represent both interglacial and glacial time periods (Webby 1958; Williams 1975; Begg and Mazengarb 1996). Immediately southwest of Porirua Central Business District (CBD) is an extensive suite of terraces of highly weathered gravels (Williams 1975), now showing a characteristic rounded topography. Terraces on the western edge of the lower Porirua Stream valley are interglacial, and gravel terraces further south in the Porirua Stream valley are last glacial. The southern shore of Pauatahanui Inlet, showing loess-capped marine sequences above sea level, probably date from the last interglacial (100-125,000 years before present (BP)) (Begg and Mazengarb 1996). Pauatahanui village lies over approx. 75 m of Quaternary sediment (Begg and Mazengarb 1996).

The rocky escarpment on the north of Whitireia Park was identified as a notable geological feature in the 'geological features of the Wellington Region', and was assessed as worthy of protection and conservation (DLS 1978), but this assessment was not carried through into specific conservation management objectives for the Wellington Conservancy in the Wellington Conservation Management Strategy (DOC 1995).

There are few mineral resources of any value for mining. A short-lived gold rush occurred in the 1860's (Heath and Balham 1994), but the miners unfortunately mistook a chert outcrop as a quartz vein (Begg and Mazengarb 1996). Aggregate was quarried from Rewarewa Point on the northern outer Harbour area until the late 1990s.

Faults

Three major fault lines intersect the catchment, running in a northeast to southwest direction, the Ohariu, Pukerua and Moonshine Faults. The Pukerua Fault runs from

Pukerua Bay to Hongoeka Bay and has caused substantial relative uplift of the Wairaka ridge (Grant-Taylor et al. 1970). The Moonshine Fault intersects the tributaries of Pauatahanui Stream in the southeast of the catchment, and shows repeated movement during the last 500,000 years (Grant-Taylor et al. 1970). The Ohariu Fault, which runs along Kakaho Stream, intersects the harbour and exits at the southwest end through Porirua City (Begg and Johnston 2000). Ration Point Fault, a smaller fault lying on the west side of Horokiri Stream, is thought to move once every 5,000 years on average (Grant-Taylor et al. 1970).

Ohariu Fault splits into a 500 m wide fault zone that passes through the centre of Porirua City, including the CBD, and aligns with each side of Onepoto Arm. At the harbour end the triangular area around the fault is approx. 600 m wide, and extends around 4.5 km to the south. The zone formed in the late Pliocene or early Quaternary, with later movements mainly occurring at the zone margins. The fault appears to move every 840 years on average, favouring the fault branch on the west. The latest movement, a right lateral displacement of 5 m, occurred around 200 years BP (Williams 1975). The faulted structure of the catchment is in part responsible for the creation of Onepoto Arm, which formed by fluvial erosion of the Ohariu Fault crush zone and later flooding by higher sea levels (Begg and Mazengarb 1996).

Movements on the Ohariu Fault are difficult to predict because individual recurrence intervals, movement amounts and last rupture events can only be interpreted north and south of Porirua Harbour. The Pauatahanui Inlet shoreline was not displaced during the Holocene by the Ohariu Fault, suggesting no movement on the northern end since sea level reached its current level ~7000 years ago (Swales et al. 2005a). South of the Harbour, the slip rate is estimated at 1-2 mm/yr, the single event lateral displacement of 4-5 m with a recurrence interval between 2000-5000 yrs and the last event having occurred 150 to 1130 BP. North of the Harbour, the slip rate is estimated at 0.6-1.9 mm/yr, and the single event lateral displacement of 2.9 m with a recurrence interval between 1530-4830 yrs last event having occurred 1070-2130 BP. Accordingly, it has been estimated that the last fault rupture occurred between 1070-1130 years BP, with a horizontal displacement of 3.7 m at an estimated 7.1-7.3 magnitude (Heron et al. 1998; Begg and Johnston 2000).

Relative tectonic uplift of the area is estimated at around 0.3mm/yr from radiocarbon dating (Gibb 1986, in: Swales et al. 2005a). Unpublished ages suggest that this may be a maximum value (Swales et al. 2005a).

The nature and cause of uplifted sections of the coast have been extensively debated. Originally the Pauatahanui Inlet was believed to have been raised by around 3 feet by the 1855 earthquake (Adkin 1921). The presence of raised rocky platforms above high tide level between Plimmerton and Karehana Bay and along Whitireia peninsular seems to support a recent relative sea level movement. Descriptions of Whitireia Park mention uplifted beach ridges behind bays between Te Nehe and Kaitawa (Walton 2002). Eiby (1990) describes a wave-cut feature at the southern end of the railway bridge. However, there is no evidence of shallowing or platforms of Pauatahanui Inlet coinciding with the

1855 earthquake (Leamy 1958, Eiby 1990). Eiby (1990) attributed the uplifted platforms of the outer harbour to movement of the Ohariu Fault. Gibb and Cox (2009) reviewed available information and concluded that areas west of the Ohariu Fault are undergoing coseismic tectonic uplift at between 0.2 – 05 mm/yr, whereas areas east of the Ohariu Fault are either tectonically stable or subject to very low tectonic uplift.

It can be concluded that a full explanation of the cause of the preserved raised coastal features such as uplifted beach ridges and wave cut platforms throughout the Harbour is not yet available. The nature and extent of these movements have not been fully described nor correlated with known fault movements, and may possibly be a relict of eustatic sea level change. This issue is relevant to current management considerations, because if there has been no uplift, then there has been higher sea level in the past, which if studied would give an indication of the effects of future higher sea level (e.g. old shorelines etc). On the other hand, if there has been greater uplift than previously thought, this means that calculated past sediment accumulation rates (SAR) may be inaccurate.

Due to the large number of faults the area has a significant earthquake hazard. Areas most susceptible to shaking in the Porirua catchment are swamp land, unconsolidated alluvium that is water saturated and coastal reclamations (Hancox et al. 2005), located at Pauatahanui Stream, west of Ration point, and behind Plimmerton beach (Grant-Taylor et al. 1970).

Geomorphic evolution

The current geomorphology of the Harbour is a function of changing sea levels, the eroding and flooding of valleys and subsequent valley infill, and the formation of sandy barriers and shorelines, all of which are complicated by relative uplift by active faults as discussed in the previous section. The complex pattern of fluvial and marine terraces is evidence of these factors.

At the maximum of the last glaciation (around 22,000 years BP) both arms of the Harbour were dry river valleys. Pauatahanui Inlet was a gravel outwash plain, most likely formed from fluvial deposits. The current location of Porirua CBD was a swamp which progressively dried out until it supported forest around 9500 years ago. Around 8360 years BP Pauatahanui Inlet was a shallow freshwater swamp. As the global sea level rose, around 7970 years BP, marine waters rapidly filled the former Porirua and Pauatahanui Stream valleys, forming drowned river estuaries. Since then both arms have been infilled, with Pauatahanui Inlet accumulating a depth of around 7-10 m of sediment (Begg and Mazengarb 1996).

Taupo Stream underwent a similar evolution, but with complications from coseismic uplift (Cochran 2000). The rising sea level swamped the valley, creating a predominantly open lagoon at the head of an inlet (5900-2580 BP). From 2580-2380 BP the swamp was characterised as a fresh brackish pond with no connection to the sea. The change from open lagoon to fresh brackish pond is interpreted as the result of co-seismic uplift, due to its suddenness. It also coincides with a fault movement described by Heron et al. (1998). It is inferred that the Ohariu Fault created a relative uplift of 0.7-1.7m between 2800-

2380 BP, isolating the swamp from marine influences, which gradually went from a brackish to freshwater swamp.

Mana Spit evolution

Post-glacial sea level rise has been an important force in the creation of Mana Spit. When sea level rose to its present level (~6000 years ago) the sea cut a cliff in the bedrock. This now stranded sea cliff is located 50m due east of Mana esplanade. A gravel spit grew about 450 m, from north to south, which constricted the entrance to Pauatahanui Inlet. Once a gravel spit formed, off-shore sediment was moved shoreward against the spit by wave and current action. As the coastal sand was progressively removed from the sea's influence dunes were able to form on top of the gravel spit (Gibb 1993).

Over the last 4,000 years the coastline has advanced a maximum of 330 m (Stevens 1974 in: Gibb 1993), pinching out to zero near Goat Point to form the present wedged shaped coastal plain (Gibb 1993).

Drainage systems

Drainage systems in the catchment are almost entirely fault controlled. Most drainage systems show marked parallelism 5 degrees east of north, due to faults that were active in the Pleistocene but are now inactive. The best indication of this is the east side of the Plimmerton-Pukerua corridor. The exceptions strike northeast, and are influenced by active faults. These include the west side of the Plimmerton-Pukerua Bay corridor (Pukerua Fault), the lower part of Horokiri Valley (Ration Point Fault), Moonshine Valley (Moonshine Fault), Kakaho Valley and the Porirua arm of Porirua Harbour (Ohariu Fault) (Grant-Taylor et al. 1970). Tributaries of Porirua Stream have been laterally offset by the Ohariu Faulting, initially running southwest but turning 180 degrees to continue northeast and join the Porirua Stream (Williams 1975).

Environmental setting

The overall environmental setting of the catchment was described in BML (2000) in terms of a series of ecodomains, described as areas of similar environmental factors. Factors used in this assessment were primarily topography, climate, underlying geology and soil parent material. These factors were the primary determinants of natural vegetation cover. Four ecodomains were recognised: the "severe salt belt" on the coast, a mild, humid "nikau belt" inland from the salt belt, "cool tops" on the highest hill tops, and "inland hills and basins" on the remainder. Within each ecodomain, phases recognised microclimatic and topographic differences. Although this classification applied only to the part of the catchment within Porirua City, other work on Wellington City and the Wellington region (BML and WRC 1999; BML 2002) shows that these same ecodomains are broadly reflected in the rest of the Porirua Harbour catchment.

It can be seen that there are fundamental differences between the two main arms of the Harbour in terms of their orientation, geomorphic setting, fault history, soils, and the source of fluvial inputs into the estuaries. The two main arms, in turn, are very different from the Outer Harbour.

Summary of literature on Porirua Harbour catchment

Catchment land use, vegetation and soils

At the time of first European settlement in the early 1840s, early settlers described the Porirua catchment as "noble forest trees with plenteous underwood" (Elsdon Best in TCB 1965), and as 'densely wooded' (Blake 2002). At least two thirds of the Pauatahanui catchment was covered in native vegetation, whereas in 2001 only 6% retains native forest cover (PICT 2001). Healy (1980) recorded further descriptions of "well timbered" land, especially in the lowlands, but stony and more open on upper slopes. Healy also noted some clearance by Maori for cultivation, of flat land around the Pauatahanui Inlet and low east-facing slopes.

The second half of the nineteenth century and first half of the twentieth century saw an uninterrupted process of clearance of native bush and replacement by introduced pastures for grazing (BML 2000). A map from 1910 (in BML 2000) shows that in the Porirua Basin and Whitireia Peninsula this process was almost complete even by then. Initially, deforestation was preceded or accompanied by milling of native timber, but Quennell (1938) provided photographic evidence that almost all the landscape was stripped bare by 1938. Streambank and creep erosion was also seen in early photos.

Current vegetation and land use, derived from the NZ Land Cover Database[4], is shown in Figure 2. In various reports quoted in this review, a number of estimates of current or recent land use and vegetation cover have been given, with little recognition of the dynamic changes occurring as former pasture or cleared exotic forest on steep slopes regenerates to native and introduced scrub communities and eventually into forest. For example, an estimate of the gross cover of the Pauatahanui catchment as 54% pasture, 23% native forest, and 19% exotic forest (Milne et al. 2004), includes all regenerating scrub as native forest. Even the figures originating from the Landcover Database only provide a snapshot in time (2006), which can be subject to misclassification or arbitrary classification of a continuum from reverting grassland to scrub and treeland.

Small remnant areas of "old-growth" native forest are scattered within the catchment (mainly on the edges), as described and mapped by Park (1999), BML (2000) and Blaschke et al. (2009). Most are now protected as public reserves or as open space covenanted areas registered with the Queen Elizabeth II National Trust.

Changes in land use for Pauatahanui catchment over the last 60 years have been mapped using aerial photography (Page et al. 2004). The earliest photographs are from 1941-42 and show that 83% of the catchment was grassland. Since this period, grassland has decreased and woody vegetation (of mixed native and exotic species) has increased from 16% to 42%. A rapid increase in exotic forest occurred between the 1970s and 1990s.

[4] The NZ Landcover Database is a digital map of the land surface of the country, identified from satellite images, taken in 1996-97 and 2001-02

Figure 2: Map of broad scale vegetation cover in the Porirua Harbour catchment, 2006 (from Landcover database)

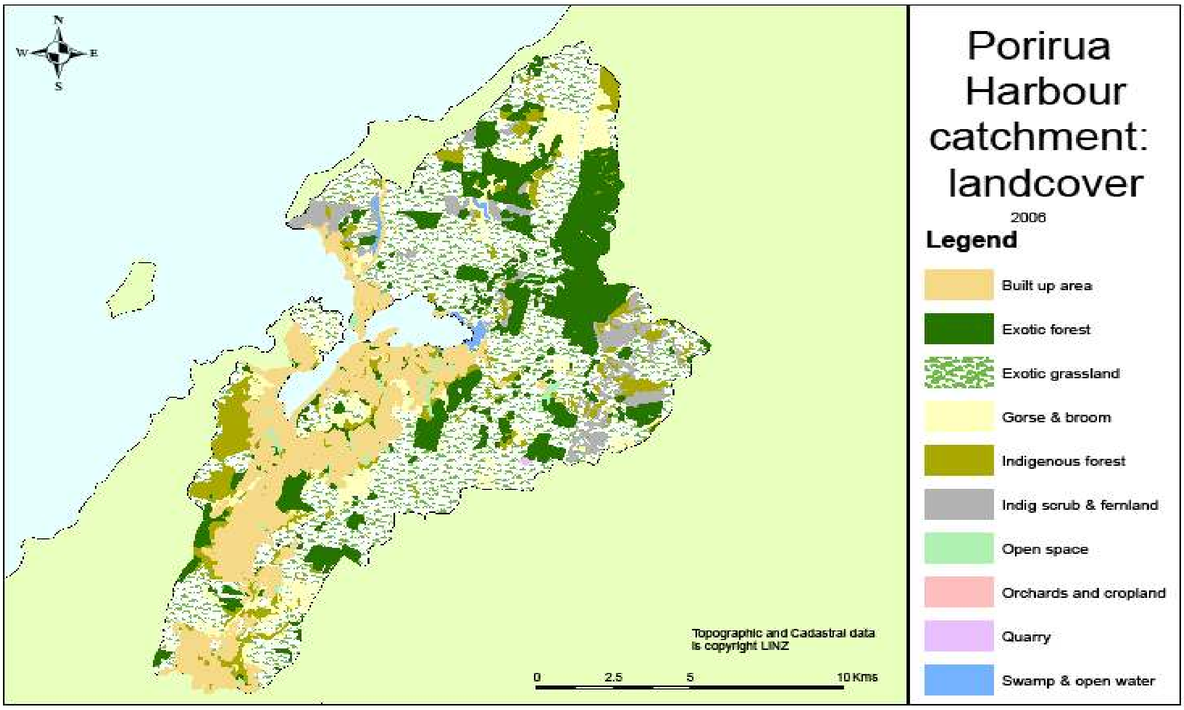

Table 2: Broad scale vegetation cover/land use in the Porirua Harbour catchment, 2006 (from Landcover database)

Landcover type	Area (ha)	Mean size of polygon (ha)	Percent of catchment
Built up area	2590	63	13.8
Exotic forest	2700	11	14.4
Exotic grassland	8580	119	45.8
Gorse and broom	1570	13	8.4
Indigenous forest	1870	7	10.0
Indigenous scrub & fernland	930	15	5.0
Open space[5]	340	4	1.8
Orchards and cropland	20	4	0.1
Quarry	10	9	<0.1
Swamp and open water	120	11	0.6

[5] Open space areas are principally non-grazed council reserves but also include privately-owned golf courses and urban grassland areas.

Vegetation of the Pauatahanui catchment was mapped in late 1970s as part of the PEP (Healy 1980). Land in the Horokiri Stream catchment in 1990 was described as supporting grazing stock on its upper and middle sections and market gardens in lower reaches. At the same time Porirua catchment was described as industrial and residential land, and the Takapu and Pauatahanui sub-catchments were mostly rural (Cameron and Sando 1990). Dairying was common in earlier decades (Allen 1951).

The recent growth of urban (mainly residential) development in Pauatahanui catchment has been described by Page et al. (2004). Initially, urban areas were only at the mouth of the Inlet at Mana and Golden Gate. Starting in the 1960s rapid development at Whitby occurred, with development spreading to Browns Bay and Duck Creek catchments, and reaching the hills near Pauatahanui Village in 2004. On the northern side of the inlet, residential development is limited to Camborne and the Motukaraka Peninsula, but throughout the remaining rural parts of the catchment there are many ‘life style’ blocks. Urban areas comprise 50% of the Browns Bay catchment, 16.2% of Duck Creek catchment and 41.1% of the smaller shoreline catchments. Residential development is continuing in eastern Whitby and elsewhere.

Catchment land use for the Pauatahanui catchment over historical time was also recorded in the pollen record taken from sediment cores in 2004 (Swales et al. 2005a). Prior to European farming (pre-1850 AD) native podocarp and hardwood pollen associations dominated, with an absence of introduced weeds, grasses and pine pollen. In the early farming period (1850-1950 AD) high levels of bracken pollen were present, following catchment deforestation. Bracken pollen gradually disappeared as pasture improvement and cultivation continued. By the late farming period (1950-1985) bracken pollen fell significantly and pine pollen increased after the late 1970s[6]. From 1985 on, massive quantities of pine pollen are present, as well as an increase in charcoal from wood fires as urbanisation increases.

Soils

There is no systematic soil mapping available for the whole catchment, soils information being generalised in the New Zealand Land Resource Inventory (Page 1995) and in Bruce (2000). Weathering of basement rocks produces sandy clays (Grant-Taylor et al. 1970), whilst loess deposits tend to produce silty soils. Overall, soils are mainly sandy or silty loams in the lowlands; and in the uplands are normally silty loam on rolling topography and poorer soils on steep topography (Grant-Taylor et al. 1970). Judgeford soils, the main soil on the easier slopes, are developed in deep loess and are among the most versatile soils in the Wellington region. Korokoro Hill soils occur on steep slopes but have a relatively low erosion potential. Other soils in the catchment include Makara Steepland, Waiwhetu and Belmont series (Bruce 2000). Plaggen[7] soils (soils altered by Maori for agriculture), from about 440 years ago, are present around Pauatahanui Inlet (McFadgen 1980).

[6] Pine trees take around 10 years from germination until they produce pollen.
[7] Sometimes known as anthropogenic soils

Stream geomorphology and hydrology

The geomorphology of streams in the Porirua Harbour catchment is largely undescribed, except where drainage has been altered by major fault movement, or in terms of assessing flood risk. As mentioned above, tributaries of Porirua Stream and Horokiri Stream have been laterally offset by the Ohariu Fault (Williams 1975). The geomorphology of Porirua Stream, and some sections of Duck Creek and Pauatahanui Stream has been assessed in relation to hydrological assessment of flood risks (TCB 1965; Anon 1987, 1989, no date; Synergy 1987; WRC 1989, 1998a; CWRH 1991; Beca 1993a, 1993b, 2003; GWRC 2004b; Eyles 2006; Connell Wagner no date). These studies give information on flooding contours and stream bed cross sections. Allen (1951) provides some information about morphology of the Horokiri Valley. We know of no other detailed studies of sub-catchments giving information on channel gradients, migration patterns or major geomorphological controls.

A description of Porirua Stream in 1840 collected by the scholar Elsdon Best describes the stream as: “no more than six yards wide or knee deep at any point” (TCB 1965). Porirua Stream and some of its lower tributaries have been heavily modified and channelised through flood protection works (TCB 1965; Beca 1993a, b), largely in order to channel water from the upper catchment and reduce flooding risk in the CBD and surrounding areas in Porirua City. Of all flood protection options considered, flood detention structures in the Belmont and Stebbings sub-catchments were deemed to have the least environmental impact (Synergy 1987). Significant flood detention structures were also constructed at Cannons Creek in the Kenepuru sub-catchment, and at Whitby in the Duck Creek sub-catchment, during development of eastern Porirua to Whitby as a major suburban area in the 1960s and 1970s. The overall approach to flood control in the Porirua catchment has been described as an engineering one, as a response to the limited options because of the existing land use and tenure along the valley floor and stream edges (McConchie 2000).

As described in some of the references above, lower Porirua Stream now experiences a considerable amount of gravel accumulation. This aggradation could potentially cause flooding, as it threatens to block stormwater outlets (WRC 2001), some of which reaches the Onepoto Arm. It is probable that gravel is accumulating as a response to the flood protection works. It is also possible that gravel is accumulating in response to increased upstream erosion and runoff. However, further information on the gravel source, the flow rate and the ability of the stream to adjust its morphology is needed.

Information for stream hydrology (Table 3) provides information on flow and flood rates for the main tributaries. This information is considerably dated, and no recent flow data is available for Kenepuru, Kakaho, and Duck Creeks. Greater Wellington operates continuous flow monitoring stations on the Porirua, Taupo and Horokiri Streams, with data available since 1965, 1976 and 2002 respectively (GWRC 2004a, b, c). Data from flow stations is summarised in annual hydrology reports (Watts and Gordon 2008). Similar information is available from a NIWA gauge on Pauatahanui Stream (NIWA 2009).

Table 3: Freshwater inflows (m^3/s), from river gauging (Heath 1976)[8]

Stream	Low flow	Mean flow	Annual flood	Maximum flood
Porirua	0.10	0.70	28.0	140
Kenepuru	0.04	0.10	7.1	40
Kahao[9] (Kakaho)	0.02	0.18	3.5	30
Horokiri[10] (Horokiwi)	0.08	0.45	18.0	110
Pauatahanui	0.09	0.50	17.0	95
Duck	0.02	0.09	4.2	35
TOTAL	**0.35**	**2.02**	**77.8**	**450**

A pilot study of landslip hazard in Porirua City indicated potential problem areas in the catchment if future urban development felt within a high landslip hazard class (Kingsbury 1990). Potential erosion hazards can be identified and planned for through a hazard identification and mapping approach.

Further discussion on erosion in the catchment is made in the section on "catchment erosion and input to streams" in a later chapter.

Freshwater quality

Baseline water quality studies consulted for this review include Cameron 1988, 1991, 1993, 1994; Cameron and Sando 1990; Cameron and Wall 1992; Berry 1995, 1996a, 1997b, 1998b; Stansfield 1999, 2000; Warr 2001; Milne and Perrie 2005; Perrie 2007, 2008. In the Porirua catchment, comprehensive water quality monitoring data are available for Porirua, Pauatahanui and Horokiri Streams. The number of sites measured on these streams has dropped from around 8 sites per stream in 1987 – 88 (Cameron 1988), to 6 sites in 1991-92 (Cameron and Wall 1992), 4 sites in 1994-95 (Berry 1995) and only 2 in Porirua and 1 each in Horokiri and Pauatahanui Stream (Berry 1998b). However, the number of parameters measured has risen, with nutrients being added in 1992-93 and extended in 1994-95 to include ammonia and inorganic nitrogen (Berry 1995).

These water quality studies, although providing an excellent resource for water quality trends, rarely discuss or investigate probable causes of water quality issues. Nor do they propose ways to ameliorate the issues identified as this is beyond their scope. They simply present the data and occasionally speculate on possible sources of measured contaminants from general knowledge of catchment properties.

8 It is not clear from the publication how long a period these data cover.
9 Now generally known and mapped in the Topographic Map Series as Kakaho Stream but often previously referred to as Kahao Stream
10 Now generally known and mapped in the Topographic Map Series as Horokiri Stream but often previously referred to as Horokiwi Stream

From the water quality data in the above reports we draw the following trends and conclusions regarding individual contaminants:

Faecal contamination: Faecal contamination, where monitored, appears to come from a number of sources including: agriculture (especially piggeries and stock crossings), and septic tanks in Pauatahanui Stream; urban stormwater in Porirua Stream and agriculture in Takapu Stream. Faecal coliforms are still above ANZECC[11] water quality guidelines. While results at some sites have improved over time, the reasons for improvements or drops in faecal counts are not usually known (Berry 1996a). Even fixing the sewer/stormwater cross connections in Porirua in 1996 (Berry 1996a) had no effect on faecal coliforms; in fact they rose in the following monitoring period (Berry 1997b). Turbidity can occasionally be an issue, but values are generally low, whilst Porirua Stream occasionally records pH in the 'basic' range.

Since nutrients have been measured (1992 onwards), Porirua and Horokiri Streams have frequently recorded nutrient concentrations that could result in the presence of nuisance algae, and not surprisingly have significant periphyton cover (Cameron 1993). The Macroinvertebrate Community Index (MCI) is a measure commonly used to reflect the degree to which a freshwater community is impacted by pollution, as shown in the composition of its macroinvertebrate species[12]. MCI scores for the Porirua Stream indicate some persistent pollution problems. Although high species density is present, species that are sensitive to pollution are persistently absent. Physical water quality parameters measured do not account for this, indicating that other pollutants (metals or organics) are present in Porirua Stream. Trends in water quality between 1997and 2003 are summarised by Milne and Perrie (2005). The Pauatahanui Stream MCI improved over the period 1997 – 2003, and in 2003 reached a 'high' water quality score (Milne and Perrie 2005).

Various anomalies between MCI values and other water quality indicators for Porirua Stream were investigated by sampling water and sediments for metal and organic pollutants. The stream and stormwater outfalls were also measured after rainfall events (Cameron 2001). Sediments exceeded the ANZECC 'low' value for zinc at all sites, and for lead at one site. Similar sediment concentrations of zinc and lead, both well-known freshwater contaminants, were observed in 2005 and 2006 (Milne and Watts 2008).

The pesticide DDT was also present at all sites above the ANZECC 'low'value: in 2005-6 DDT in Porirua Stream was always above the ANZECC 'low' and in one case above the 'high' value (Milne and Watts 2008). These results indicate a moderate probability of a toxic effect on biota (Cameron 2001). DDT concentration was highest at Takapu, which drains a rural catchment (Cameron 2001). The use of DDT was banned in 1970,

[11] The Australian & New Zealand Environment and Conservation Council (ANZECC) have issued guidelines for fresh and marine water quality, containing Interim Sediment Quality Guidelines (ISQG) (ANZECC 2000). These guidelines are commonly used in the interpretation of water quality testing results.

[12] MCI scores of >119 indicates an excellent quality class, 100-119 is good, 80-99 is fair and <80 is poor.

(previously it was used to control the grass grub in pastures). It is possible that there has been subsequent illegal application (Cameron 2001). Water quality was poor, with wet weather events resulting in high concentrations of zinc, copper, lead and chromium delivered to the water column (Cameron 2001). Similarly, stormwater quality of Porirua Stream monitored in 2005-6 showed elevated concentrations of copper, zinc, and chromium delivered in higher flow events (Milne and Watts 2008). Sites sampled in 2001 in the estuarine reach had a lower concentration of metals, probably due to the effect of flushing (Cameron 2001). The MCI at Porirua was 90, and at Takapu, 106, both indicating possible pollution. The concentration of DDT did not appear to be affecting biota, as the highest concentration was found at Takapu, where the MCI is highest. This is likely due to the ability of DDT to strongly bind to the sediment, and thus become less bioavailable.

In Porirua Stream, poor water quality, and especially the pollution pulse delivered by rainfall events, appeared to have caused a reduction in life-supporting capacity of the stream. Such pollution explains the loss of the sensitive macroinvertebrate taxa *Ephemeroptera*, *Plecoptera* and *Trichoptera*[13] (Cameron 2001).

The quality of sediments in urban streams was assessed in 2005 and again in 2006. The results of the investigation indicated that urban stormwater discharges are negatively impacting on the health of local stream and rivers. In the Porirua Harbour catchment, six streams were monitored, Duck Creek, Pauatahanui, Browns, Porirua, Mitchell and Kenepuru Streams. Sediments in all these streams exceeded the ANZECC guidelines 'low' value for DDT and in 2006 one site on Porirua Stream and one in Duck Creek exceeded the 'high' value. Polycyclic aromatic hydrocarbon (PAH) pollutants were present in all streams, but only exceeded 'high' trigger guidelines at Kenepuru Stream. Of metal contaminants, zinc and lead showed elevated concentrations, with zinc above the 'low' trigger value at Browns, Mitchell and Porirua Streams, and above the 'high' at another site on Porirua Stream. Lead concentrations were above the ANZECC 'low' value at two sites in Porirua stream.

Lindane at Porirua Stream exceeded the 'high' ANZECC guideline trigger (Milne and Croucher 2005, Milne and Watts 2008), and therefore requires specific analysis. Lindane is an organochloride, previously used as an insecticide on a range of crops. As a toxicant in the water column, it has high to moderate toxicity, negatively impacting on freshwater and marina biota. However, there is no information regarding the toxicity of lindane in sediments. The effects-based sediment guidelines recommended for Australia and New Zealand are primarily based on a single, large biological-effects dataset of North American sediment data. In the case of lindane, no sediment toxicity values are available, so the guideline given is only an interim value (ANZECC 2000). Hence the toxicity effect of the high value of lindane in Porirua Stream is uncertain. Comparison of porewater from this site with the freshwater guideline values would better determine if there is a toxic effect on biota.

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[13] These types of pollution sensitive macroinvertebrates such as mayflies, caddisflies and stoneflies are referred to as "EPT" taxa.

Ecological assessments were undertaken for Stebbings Stream and Belmont Stream to identify stream values, evaluate stream health, and identify water quality issues and sites and habitats to be protected (BML 2004a, 2004b). Stebbings Stream is a highly modified stream, impacted by farming. It has few sites of remnant vegetation and relatively little undisturbed stream habitat. Water quality was good, and concentration of metals in sediments is below ANZECC (2000) guidelines whilst PAHs were below detection limits. The stream had good MCI values and the stream habitat was good in some respects. However, the stream suffered from degraded riparian habitat, was under pressure from organic pollution in some places, showed some early issues with sedimentation, had a lack of in-stream cover and woody debris, and lacked shade and hydraulic homogeneity (BML 2004b). The BML study concluded that the stream condition was on a cusp, stating that without management and restoration the stream would suffer a downward decline (BML 2004b). Belmont Stream had very good physical habitat upstream and good quality lower sites, although there was a lack of riparian vegetation and channel shading in some places (BML 2004a).

Stream biota including macroinvertebrates and freshwater fish

Annual monitoring of macroinvertebrate communities has been undertaken in streams in the Porirua, Pauatahanui and Horokiri catchments, coinciding with annual water quality surveys. Most reports from these surveys do not list individual species, but rather the results of the Macroinvertebrate Community Index (MCI) assessment. MCI values for Horokiri Stream are consistently good, whilst those for Pauatahanui and Porirua Streams reflect pollution levels since monitoring began in 1987 (Cameron 1993; Stansfield 1999, 2000; Warr 2001; Perrie 2007), with key macroinvertebrate species that are more sensitive to pollution missing. In 2008 the MCI scores had improved to fair for Porirua and Pauatahanui Streams, and remained good for Horokiri (Perrie 2008).

The main stem of the Porirua Stream at Tawa was assessed as having good aquatic fish values, due to the natural character and stream morphology, riparian vegetation and large macroinvertebrate numbers (KM 2003).

Macroinvertebrates and fish species have been surveyed in Stebbings Stream (BML 2004b). The MCI scores for the stream were good. Some components of the habitat were of high quality, but significant amounts of habitat were under pressure from organic pollution. Freshwater fish found at the site included common bully, short and long finned eels, banded kokopu, freshwater shrimp, koura, giant kokopu and trout (BML 2004b). The giant kokopu found during the survey were all large adults, suggesting that they are a remnant population without recruitment. In other Porirua Stream reaches and tributaries, only juveniles are present, suggesting stream conditions are not suitable to maintain adult populations (Blaschke et al 2009). Some issues for fish passage were also noted both by BML (2004b) and Blaschke et al (2009). The presence of barriers to fish passage at several other parts of the main stem and tributaries of the Porirua Stream was noted by Blaschke et al (2009).

Macroinvertebrates were also assessed for Belmont Stream. Consistently high MCI values indicated very good habitat quality. Long and short finned eels and banded kokopu are present in Belmont Stream (BML 2004a).

A baseline survey of the Cannons Creek Lakes Reserve (BML 2009) also identified high freshwater ecological values. The stream had good aquatic invertebrate health; a high percentage of indigenous vegetation cover, was habitat for threatened indigenous fish species including giant kokopu and long-finned eel; and provided inanga spawning habitat. Sites from upper Cannons Creek had high macroinvertebrate biodiversity and MCI scores, indicating that ecological health and water quality was excellent across the upper Cannons Creek catchment.

Suitable inanga spawning habitat in the lower reaches of streams around the Harbour has been assessed by Taylor and Kelly (2001). Porirua Stream is an unsuitable spawning habitat, as the sides are lined with concrete walls and there is little or no emergent vegetation at normal or elevated water levels. Shoals of inanga were present in the stream. Kenepuru Stream had good spawning habitat, with inanga schools present, but there was a significant potential for further enhancement of inanga habitat in lowest reaches. Duck Creek has some very suitable spawning habitat in the lower part of the stream. Pauatahanui Stream had significant suitable habitat, which partly lies within the Wildlife Management Reserve and can be managed and enhanced. Horokiri Stream has suitable sites downstream of bridge, upstream stock grazing has destroyed potential habitat. Taupo Stream has some good habitat, but large trees mean that the light demanding species that inanga lay their eggs in cannot grow. Kakaho Stream has no current habitat as it has graded banks with no vegetation. This stream was ranked as possessing the best potential for habitat restoration, not only because of its then degraded nature, but the physical nature of the site is good, fresh tidally influenced site with graded banks (Taylor and Kelly 2001). Since 2001 there has been considerable habitat restoration work in the estuary of the Kakaho Stream.

Terrestrial biodiversity

Ecological surveys of all types of terrestrial sites in Porirua City and of primary forest remnants in Wellington City have been completed (BML 2001; Park 1999). In Porirua City, the survey of ecological sites provided reconnaissance inventory information for each site, a ranking of ecological significance, and a summary of threats and management issues (BML 2001). The Wellington City information is confined to a listing of prominent species for each delineated primary forest site. This information is currently being updated and extended to all types of sites (Mike Oates, Wellington City Council, pers. comm.). A number of detailed vegetation species lists for individual areas within the Porirua Harbour catchment are listed in Sawyer (2001)[14]. Key Native Ecosystem surveys

[14] Species lists compiled since 2001 are available on the New Zealand Plant Conservation Network website: http://www.nzpcn.org.nz/newsletter_publications/index.asp

have been conducted at a number of the more significant sites in the catchment, including Elsdon Bush (WRC 1998b), and at Whitireia Park (GWRC 2003). We are not aware of any studies of terrestrial invertebrates anywhere in the catchment.

As an example of notable remaining vegetation, Elsdon Bush, Porirua Scenic Reserve, together with surrounding Porirua City Council land and Pikarere Farm Forest, form a continuous forest area of 290 ha including ecosystem types not represented elsewhere in the ecological district (WRC 1998b; BML 2001). Bird species observed include grey warblers, fantails, blackbirds, kingfishers, waxeyes, shining cuckoo, harrier hawks, paradise ducks, tui, morepork, and kereru. The threatened gecko species *Hoplodatylus gramulatus*, as well as other plant and animal species uncommon in the Wellington area have been recorded in this reserve (WRC 1998b). In another example, Bagnall (1979) documented the rapid rate of loss of forest area and shift from kohekohe-tawa co-dominance to kohekohe dominance at Redwood Bush in Tawa. These undesirable changes resulted from fragmentation and edge effects associated with residential development, and damage associated with uncontrolled recreational use.

As discussed earlier, the original vegetation would have been tall and dense podocarp-broadleaved forest over most of the catchment, except only on the edges of the estuaries and on the most exposed coastal areas on the Outer Harbour. The forest vegetation types in the catchment included swamp forest on the floodplain of the major sub-catchments, broadleaf podocarp forest with a tawa-kohekohe canopy on the hills, and kowhai-dominated coastal forest fringing the inland estuaries. Kahikatea, rimu and matai, tawa, rewarewa, kohekohe and hinau are the main canopy trees (BML 2001; Blaschke et al. 2009). Most of the remnants of this forest are smaller than 2 ha with the notable exceptions of Porirua Scenic Reserve, Colonial Knob Scenic Reserve, Redwood Bush in the Porirua catchment and a few larger patches in the headwaters of the Pauatahanui and Horokiri Streams. However, there are a number of larger areas (more than 20 ha) of regenerating native bush, mahoe being most common canopy species, in some cases associated with small remnants of old forest.

Current vegetation in the Porirua Stream catchment is summarised in WCC (2008) and Blaschke et al 2009). There is also a list of flora and fauna found in Porirua Stream and tributaries in the late 1980s (Roper-Lindsay 1990). The catchment marks the southern limit of some plants, notably the shrub *Rhabdothamnus solandri*. The threatened pygmy button daisy (*Leptinella nana*) is found in Whitireia Park, and is found in only two other locations in New Zealand (DOC 2001).

The terrestrial vegetation buffer around the edges of both main arms of the Porirua Harbour is poor. Most of the edge is characterised by residential, grassland or artificial structures (Milne 2008; EMS and Blaschke 2008). The 47-hectare salt marsh habitat reserved as Pauatahanui Wildlife Reserve forms a significant exception to this pattern.

Many plant and animal pests are established in the catchment. The main species present in Porirua City sites are listed in BML (2001). Pest species within Key Native Ecosystem sites are regularly monitored by Greater Wellington biosecurity staff. Possums were introduced to the area in 1926. Feral goats, rats, mice and magpies are found at Elsdon

Bush (WRC 1998b). Eradication of possums was attempted (and largely achieved) from Whitieria Park in 2003 (GWRC 2003). Hares and rabbits are common at Whitieria Park (GWRC 2003).

Birds

Birds in the catchment and Harbour have been documented by the Ornithological Society of New Zealand and others for some time, with a focus on the wide variety of wading and shore birds at Pauatahanui Wildlife Reserve. More than 30 bird species were observed to be living at Pauatahanui Inlet at various times of the year during the PEP (Healy 1980), with a number of species noted since that time. Recent more detailed survey by the Ornithological Society (2002-2004) noted an increase in species diversity at Pauatahanui Inlet. The second edition of the *Bird Atlas of New Zealand* (Robertson et al 2007) provides a current summary of this information. The number of species has increased from 37 in the 1970s to 53 at present. Many of the birds are migratory and visit the inlet on an occasional or seasonal basis.

The most commonly seen native shore birds and waders are pied stilt, black swan, variable oystercatcher, gulls, NZ shoveler, grey teal, paradise shelduck, white-faced heron, pukeko, and shags. Spoonbills are a notable relatively new arrival at the Pauatahanui Inlet, now apparently resident, although not yet breeding there. Common birds in a wider variety of habitats in the catchment include tui, grey warbler, spur-winged plover, welcome swallow, Australasian harrier, banded dotterel, eastern bar-tailed godwit, Caspian tern, NZ kingfisher, silvereye and North Island fantail (White 2005).

With the introduction of predator control to the unfenced forest reserves of greater Wellington over the last ten years there has been an increase both in numbers and diversity of native birds seen and heard (Miskelly et al. 2005), and this regional trend is reflected in many parts of the catchment.

Summary of literature on Porirua Harbour

Water quality

Water quality of Porirua Harbour can be assessed in terms of physical parameters (temperature, turbidity), chemical parameters (pH, salinity, % dissolved oxygen), chemical concentrations (nitrogen or phosphorus concentrations, chlorophyll-a concentrations[15]), or through biological assessment (faecal coliform or enterococci count, percentage cover of nuisance algae). Physical and chemical parameters can give an indication as to the nature of the system, and ongoing monitoring would highlight major changes.

Because Porirua Harbour is a tidally flushed estuarine system, which can occasionally receive large freshwater inputs, the variations in salinity and temperature are expected to be considerable. pH fluctuates naturally according to salinity, with sea water having a pH of 7-8.5 and freshwater from 6.5-8 (ANZECC 2000). Concentrations of nutrients[16] and chlorophyll-a highlights possible eutrophication issues, whilst biological measurement of faecal contamination assesses health risks.

Ongoing monitoring of water quality in the Harbour is conducted primarily in terms of health risks. For Pauatahanui Inlet, other water quality parameters (such as salinity, temperature, and nutrient concentrations) were assessed as part of the PEP study in the late 1970s. Since then, these parameters have not been measured, and no such water quality data has been collected for Onepoto Arm.

Water quality of Onepoto Arm is currently monitored for enterococci weekly in the swimming season and monthly in the off season in order to assess health risks associated with water recreation (Sillars 1991; Berry 1998a). Data on enterococcal shellfish contamination is not systematically collected. However, the microbial counts from local water quality sampling are used to assess health risks of shellfish consumption (Milne 2005). The primary purpose of this sampling is to assess water quality in respect to public health for recreation and swimming.

Porirua Harbour typically has poor compliance with microbial levels for recreational contact. During the period 2001 to 2006, 12 of the 14 sampled sites exceeded guidelines 10% of the time. Some of those exceedance events were one or two orders of magnitude above the guidelines (Milne 2005a). Breaches have most frequently occurred at the site on Plimmerton beach near Taupo Stream mouth (Berry 1996b, 1997a; Robertson 2000; Stephenson 2001; Milne 2005a; Milne and Wyatt 2006). Water quality at a site near the entrance of Porirua Stream and a sampling site near Te Hiko Street (Takapuwahia) has also been poor or very poor (Berry 1997, 1999; Stephenson 2001; (Milne and Wyatt

[15] Chlorophyll-a concentration is an important biological indicator of the amount of photosynthesizing algae present at a site.
[16] The nutrients of greatest interest are generally those forms of phosphorus and nitrogen referred to on page [17] [freshwater quality]

2006). The site at Paremata Bridge has generally been satisfactory for swimming and seafood collection. The source of high bacterial counts near Porirua Rowing Club is currently being investigated (Warr 2009). The 2005-2006 monitoring period is the only occasion where ANZECC guideline values for enterococci concentrations were not at some time or location breached for contact recreation (Berry 1997a, 1998a, 1999; Robertson 2000; Stephenson 2001; Stephenson and Sevicke-Jones 2002; Stephenson 2004; Milne 2005a, 2005b, 2006b, 2007; Milne and Warr 2007; Ryan and Warr 2008).

Assessment of water quality compliance to health standards over the period 2001- 2006 indicates that of all breach events in the Porirua area, 77% were associated with some rainfall prior to sampling (Milne and Wyatt 2006). In these cases the most likely source of bacteria counts is stormwater delivering urban catchment run-off. Not all of the high contamination events are associated with rainfall, so the source of the contamination remains uncertain (Stephenson and Sevicke-Jones 2002; Milne 2005b, 2007). Rainfall has less influence on breach events at sites sampled at Plimmerton Beach and Browns Bay. For these locations it is thought that Taupo Stream and Browns Stream, respectively, are responsible for breach events in dry conditions (Milne and Wyatt 2006). Taupo Stream has been identified as a significant source of faecal contamination, with higher counts at Plimmerton Beach correlating with the proximity of Taupo Stream (McBride et al. 1995), confirming that the water quality at this location is dominated by local inflows.

It is likely that the high levels of faecal-derived bacteria in Porirua Harbour are sourced from the catchment, as the Porirua, Pauatahanui and Horokiri Streams have consistently high faecal coliform counts (see previous chapter). A review of the stormwater quality in the Wellington Region suggested that sewage contamination and diffuse sourced runoff from rural land are probably major factors influencing microbial levels in coastal waters (Williamson et al. 2001), although this suggestion was not conclusively tested. Additional microbiological sampling in Porirua Harbour and stormwater drains in 2008 showed no obvious source of faecal contamination (Ryan and Warr 2008). What is known is that rainfall has a significant influence on breach events, but this varies according to each site sampled (Milne and Wyatt 2006). The only other possible contamination source is from outside the catchment, i.e. carried by the sea from sources outside the Harbour. It is known that traces of discharges from the Porirua City wastewater treatment plant south of Titahi Bay are occasionally detected close to the Harbour entrance (K Calder, PCC, pers. comm., June 2009), but these traces are too small and irregular to be responsible for to be a significant source of contamination with the tow main arms. As yet, a conclusive understanding of the various possible sources of microbial contamination in the catchment is not available.

An eutrophic water body is characterised by high nutrient inputs, dense algal concentrations[17], high chlorophyll-a concentrations, dissolved oxygen concentrations in the surface waters which fluctuate according to light exposure, low dissolved oxygen in the lower water column, and anaerobic sediments. In 2008 Porirua Harbour was

[17] often called algal blooms

described as moderately eutrophic as reasonably extensive growth of macroalgae including some nuisance algal growth (e.g. sea lettuce[18]) was present (Milne 2008; Stevens and Robertson 2008). However as there is no ongoing monitoring of nutrient inputs, dissolved oxygen fluctuations, concentrations of algae or chlorophyll-a, nor is there information on the role of tides in flushing the system, it can only be said that this indicator is suggesting an eutrophic environment. Continued monitoring of the above parameters should indicate whether the nuisance algal cover is simply a natural occurrence, or evidence of increased nutrient input causing human-induced eutrophication with negative biological impacts.

Salinity, temperature and turbidity were measured in Pauatahanui Inlet over 1975-76 as part of the PEP study (Förch 1983). Over summer, the Inlet was cooler and less saline than the adjacent coastal water. It was also prone to rapid changes in salinity and occasional stratification in the entrance channel at times when there was a substantial amount of freshwater runoff into the Inlet. The concentrations of suspended sediments were high, whilst nutrient levels were comparable with other estuaries (Förch 1983).

The other water quality parameters listed at the beginning of the section are not measured on a regular basis within Porirua Harbour. Water quality in estuarine systems is difficult to assess due to the change caused by the tidal flux, and the dilution of pollutants below detection levels. It is for this reason that sediment contamination is more often assessed. However, without further baseline information on the water quality of the Harbour, it is impossible to adequately monitor or assess change.

Little can be definitively said regarding spatial variations of water quality, due to the small number of sites where water quality parameters are regularly measured. Visually, Onepoto Arm appears more polluted as it also has a significant amount of rubbish polluting the upper area of the Harbour closest to Porirua CBD (Stevens and Robertson 2008). Generally, it seems that Onepoto Arm has lower water quality than Pauatahanui Inlet, indicated by higher concentrations of macroalgal cover, and more frequent and higher breaches of recreational guidelines for enterococci. This is likely a function of storm water inputs to Onepoto Arm, as these poor water quality indicators generally occur at the southern end of the inlet. The role that tidal processes and hydrodynamics have in flushing or pooling pollutants within the Arm is unknown, although it has been long known that flushing processes are pronounced in the Pauatahanui Inlet (Healy 1980), and likely to be more pronounced there than in Onepoto Arm..

Sediment characteristics (quality and quantity)

Sediments of Pauatahanui Inlet have been described in terms of their characteristic mineralogy and chemistry. Sediments in the catchment are generally composed of quartz, feldspar, mica and chlorite, with a quartz/feldspar ratio of 3.6 and abundant heavy minerals (Stoffers et al. 1983). Chemically, silicon oxides dominate at 60%, followed by

[18] Sea lettuce (*Ulva* species) is naturally occurring (many species are edible) but under some conditions as described above form extensive sheets in inter-tidal areas which can interfere with other uses.

aluminium oxides (14%). Iron, sodium, potassium, calcium oxides and organic carbon make up the remaining chemical contribution. These chemical ratios are typical of North Island harbours and estuaries (Stoffers et al. 1983). There have been no mineralogical analyses undertaken in Onepoto Arm; however, composition is unlikely to vary significantly from Pauatahanui Inlet.

The grain size distribution of intertidal and subtidal surficial sediments in Pauatahanui Inlet was mapped as part of the PEP. Surficial sediments are very coarse gravel and shell at the main channel outlet, progressing to sandy tidal banks and muddy intertidal areas at the centre, whilst the basin margins and beaches are composed of coarser pebbles and shells (McDougall 1976; Healy 1980). This distribution is a function of the intensity of wind, wave or tidal forces; higher energy sites retain only coarse grain sizes, while fine material is concentrated at lower energy sites. Hence the sandy shore to the south of Pauatahanui is a result of wind-wave exposure, which winnow out fines (Swales et al. 2005a). Cores from Pauatahanui Inlet indicate that sediments are characteristically sandy-mud, with the percentage of mud decreasing with depth (Swales et al. 2005a).

Subtidal sediments of Onepoto Arm have not been described; however grain size of surficial sediments of the intertidal zone has been mapped across both Onepoto Arm and Pauatahanui Inlet (Stevens and Robertson 2008). The GIS information indicates that most of the intertidal area is composed of poorly sorted firm muddy sands (Table 4). In general sediments in Pauatahanui Inlet are coarser than those from Onepoto Arm (Stephenson and Mills 2006).

Table 4. Surficial intertidal sediment types and areas for Pauatahanui Inlet and Onepoto Arm (Milne 2008; Stevens and Robertson 2008)

Sediment type	Area in Pauatahanui (ha)	Area in Onepoto (ha)
Firm muddy sands	122.0	33.0
Firm sands	28.0	4.4
Soft muds	1.9	1.5

For Onepoto Arm, data on sediment size has been collected from a few sites as part of pollution investigations (Stephenson and Mills 2006; Sorenson and Milne 2009), but there has been no targeted study on the characteristic trends of particle size or of sediment mineral and chemical composition. Further information on the characteristics of subtidal sediments throughout the Onepoto Arm would shed light on the flows experienced there compared with Pauatahanui Inlet, and would also give an indication of flushing capacity.

Recent work analysing the relative proportions of stable carbon isotopes in Porirua Harbour sediments and in estuarine biota may be a useful tool to identify the sources of sediment (as well as pollutants). Recent work, for example, concludes that farming areas and recently urbanised areas are much more likely to deliver sediment to the Pauatahanui Inlet than the older urbanised areas (Kurata and Rogers 2005; Rogers 2009).

Sediment contamination and Harbour contaminants

Estuarine sediments often act as a 'sink' or storage area for pollutants that have been sourced from the catchment. Although in many cases removal from the water column to the sediment renders the pollutant harmless, polluted sediment can negatively affect bottom-dwelling fauna and possibly be released back into the environment with changes in physical or chemical parameters such as dissolved oxygen.

In Porirua Harbour, surficial sediments from both arms have been analysed on several occasions for a range of metal pollutants (Stoffers et al. 1983; Milne et al. 2004; Williamson et al. 2004; Swales et al. 2005a; Stephenson and Mills 2006; Milne 2008; Robertson and Stevens 2008; Sorenson and Milne 2009). Direct comparison of these results is not possible due to the different methods used to chemically process and analyse the samples. Results show a number of pollutant levels which are somewhat elevated but generally below the ANZECC 'low' guideline pollution concentrations. The exception is zinc which has occasionally breached the ANZECC 'low' guideline value (Milne et al. 2004; Williamson et al. 2004; Sorenson and Milne 2009), and in one core sample zinc has exceeded the 'high' value (Sorenson and Milne 2009). In addition, some studies have highlighted minor infringements of nickel, lead, copper and zinc above Auckland Regional Council's Environmental Response Criteria (ERC) (ARC 2004) (Glasby et al. 1990; Milne et al. 2004; Williamson et al. 2004; Stephenson and Mills 2006; Sorenson and Milne 2009).

The authors of these studies caution that these levels are not necessarily causing an adverse environmental impact. Firstly, the ERC (2004) amber and red guidelines are at a lower concentration than the ANZECC guideline values and are an alert or early warning that pollution is occurring. Breaching of the ARC ERC (2004) indicates an opportunity for management to respond and intervene (Sorenson and Milne 2009) rather than an adverse impact on the environment. Secondly, zinc concentrations that have breached ANZECC guidelines were analysed for 'total' metals (which analyses all metals and not just the bioavailable metals). Bioavailable concentrations (i.e. only those of loosely bound metals) give a better indication of the probability of negative impacts to the environment. Analysis of bioavailable metals indicate that most metal concentrations are below ANZECC guideline levels (Mine et al. 2004; Stephenson and Mills 2006); however zinc and lead concentrations have been recorded above guideline 'low' concentrations (Williamson et al. 2004).

Finally, there has been no analysis and correction for the natural mineral contribution of the sediment by comparison with a background. Some information on background concentrations of metals and PAHs is available from Greater Wellington soil resource investigations, and these are well below the concentrations associated with particulates in urban stormwater taken from pipes in the catchment (G. Stephenson, Coastal Marine Ecology Consultants, pers. comm., January 2010). However, for corroboration, a 'background' sample, taken at depth, would be useful for definitive comparisons of natural and anthropogenic contributions of metal concentrations, and give a better indication of the extent of pollution. Although the concentrations of metals found in

Harbour sediments are not at toxic concentrations, evidence suggest that copper, lead and especially zinc are present at or near threshold levels where impacts on benthic aquatic life may begin to occur (Williamson et al. 2004).

The concentration of contaminants is generally regarded as higher in the Onepoto Arm than in Pauatahanui Inlet (Milne et al. 2004; Milne 2008). However, information on the grain size of sediments is rarely presented to correct metals concentrations, and hence comparisons between samples are difficult. Metals accumulate in muds and clays, and therefore sandy sediments will yield significantly lower results. Analysing metals is the mud fraction is the most precise method for detecting spatial trends. There is a possibility that high or low concentrations are simply a function of grain size, as sediments are generally coarser in Pauatahanui Inlet than the Onepoto Arm (Stephenson and Mills 2006). In the three studies that have corrected for grain size, concentrations of zinc, lead and copper were higher in Onepoto Arm than in Pauatahanui Inlet (Glasby et al. 1990; Williamson et al. 2004; Stephenson and Mills 2006). This is especially so in the vicinity of Porirua City, pointing to both the Porirua Stream and the city stormwater as major sources of these contaminants.

In 2004, four long-term baseline sediment monitoring sites were established, two in the Onepoto Arm and two in Pauatahanui Inlet (Williamson et al. 2004; Stephenson and Mills 2006). The results of these studies have been discussed in these reports in terms of pollution exceedence events; however, in the long term they will also shed light on temporal changes and be used to detect trends in sediment pollution.

Potentially toxic organic compounds, such as tributyltin (a chemical formerly used as an anti-fouling agent) and DDT, are found in the sediments of both Pauatahanui Inlet and Onepoto Arm in concentrations above the ANZECC ‘low’ guidelines, and may have an affect on biota (Milne et al. 2004; Williamson et al. 2004; Sorenson and Milne 2009). Other toxic organic compounds such as PAHs have been monitored, with concentrations in the sediment being well below ANZECC guideline levels (Williamson et al. 2004; Stephenson and Mills 2006; Milne 2008), with the exception of sites located adjacent to Porirua Stream and Onepoto Stream which exceed the ‘low’ guideline value (Sorenson and Milne 2009). There have been no local toxicological studies to ascertain if the concentrations of pollutants found in the sediment are toxic to local biota, or if the local fauna is adversely impacted by these concentrations.

Recent work analysing the relative proportions of stable carbon and nitrogen isotopes in Porirua Harbour sediments and in estuarine biota (Kurata and Rogers 2005; Rogers 2009), as mentioned above, may be a useful tool to identify the sources of pollutants. This work concludes for example, that Onepoto Arm sediments contain more terrestrially-derived nitrogen than those of Pauatahanui Inlet. Sites with the most positive stable nitrogen isotope values in *Ulva* samples are located around the industrial area and stormwater drains servicing long established urban habitats. These values are consistent with human or animal waste-derived nitrogen. The method used samples from macroalgae and cockles, so may be able to make specific conclusions about the effects of nutrients and contaminants on organisms.

Harbour hydrodynamics

Flow constrictions, including bridges and reclamations.

Large areas of the Porirua Harbour have been filled in, on several parts of the Harbour. More extensive filling has occurred in the Onepoto Arm, for example, north of the Porirua CBD where 770,000 m^3 of soil was moved in reclamation works in the 1970s (Scrimgeour 1995). Earlier, large reclamations occurred for road and railway construction on both sides of the Onepoto Arm. In Pauatahanui Inlet, at least half of the natural salt marsh area has been drained, primarily for pastoral conversion, but also for roading and a now-abandoned go-cart track and cricket pitch. About 10ha of this drained area has been returned to a more natural state as the Pauatahanui Wildlife Management Reserve (BML 2000). Behind the Mana Marina, 2ha of land was filled in for shore facilities of the boating club (Stirling 1983).

There is little known about the impact on hydrology of these various reclamations, although during planning for a Mana Bypass option on the Western Corridor SH1 route, a hydraulic model of Pauatahanui Inlet was constructed to assess the effects of various motorway embankments across the Inlet. Extensive reclamation at the head of the Onepoto Arm has been accompanied by restricting and channelising the downstream end of the Porirua Stream, which is likely to have had hydrological consequences there. In Pauatahanui Wildlife Management Reserve, filling of marsh land as well as the construction of Grays Rd, which bisects the area, caused localised drying out, and a subsequent change in marsh species to a greater abundance of grasses and rushes, thereby reducing wader feeding areas (Owen 1984). A large portion of the salt marsh and rushland in the Wildlife Management Reserve is artificially watered using sluice gates to capture tidal waters for the purposes of providing bird feeding habitat (BML 2000).

Increased residential development and transport provision, over time, have seen several bridges built across the Pauatahanui Inlet entrance between Paremata and Mana. The first railway bridge was built in 1885, a road bridge in 1936 and 1938 (PCC 2005), and a new railway bridge followed in the 1950’s (Heath and Balham 1994). The 1950s railway bridge, with flanking causeways, increased constraints on tidal flow. The bridge reduced the likelihood of ebb flow varying in direction and tended to confine the current to a well defined channel (Stirling 1983). It has been hypothesised that the narrower channel may have also caused changes to the flushing of the Pauatahanui Inlet and possibly increased its rate of infill (Beca 1997).

A second road bridge was added in 2005, which was required to be constructed without permanently changing water flows or volumes (WRC 1989a). Possible impacts of the second Paremata SH1 bridge were outlined in the Assessment of Effects on the Environment (Beca 1997). The small decrease in volume across the inlet caused by the pylons was estimated to have a minimal effect. The maximum spring tidal velocity was predicted to increase from 0.5 to 0.55 m/s. Hence, the former sand circulation pattern should change. However, the increased tidal velocity may have slowed the rate of accretion at the inlet, and cause localised scouring at the base of the pylons. Scouring was estimated reach to not more than 2 m, due to the influence of the reversing flow direction of the tides and the resistant clay beneath the sand. It was expected that there would be no permanent impact on plankton or fish species (Beca 1997; WRC 1989a). There has not been an assessment of the accuracy of these predictions and no assessment of the state of the Harbour after the bridge was constructed.

Development of the Mana Marina (see below) effectively removed 6 ha of tidal flats and dunes from the hydrologic system by enclosing them behind a seawall of rock and fill for safe anchorage. The curve of the sea wall was constructed to parallel the existing channel edge to minimize impact of flow hydrodynamics (Stirling 1983). There is little information on the post-construction marina effects on flow or hydrology.

Harbour flushing

The extent to which waters in an estuarine harbour are ‘flushed’, either with freshwater from the catchment, or tidal exchange with the ocean, has an important bearing on the impact of many pollutants (including sediment) on the environment. A long residence time for nutrients in an estuary can trigger an algal bloom, whilst strong flushing can significantly dilute nutrients, thus removing their concentrated effect. Similar effects can occur with other pollutants.

The exact role of tides in flushing high concentrations of nutrients is unclear. However, the densest covering of algal blooms in 2007/8 (Stevens and Robertson 2008) occurred at the upper end of Onepoto Arm, where tidal influence is less, suggesting that tidal dilution may be a significant control over potential algal blooms, as was previously suggested for the Pauatahanui Inlet (Healy 1980; BML 2000). There is evidence that sites around Paremata bridge receive significant flushing, as often this site has the lowest counts of enterococci bacteria (Berry 1996b, 1997a; Robertson 2000; Stephenson 2001). Water and sediment quality improves in the lowest reaches of Porirua Stream (when compared to upstream sites) and is probably due to the effect of flushing (Cameron 2001).

In terms of fresh water delivery to the Harbour, the volume of water from each tributary is reasonably well known, but there is little understanding of how much, and for how long, fluvial discharges (and any associated pollutants) are retained in the Harbour. A heat budget has also been estimated for Pauatahanui Inlet. The tidal flow velocities in the Harbour throat are easily capable of transporting sediment into and out of the Harbour (Wynne 1981; in Gibb and Cox 2009). Temperature at the entrance exhibits strong tidal fluctuations resulting from exchange with cooler waters (Heath 1977). The factors that influence such flushing (such as storm intensity, tidal level) are not known, nor the ultimate destination of any sediments that remain. There is no information on how much of the sediment delivered to Onepoto Arm from its tributaries is lost to the open coast.

Unlike most New Zealand estuaries, which tend to empty almost completely at low tide, Porirua Harbour is mainly subtidal (65% remains underwater at low tide), especially the Onepoto Arm (Stevens and Robertson 2008), where a large fraction of the original intertidal zone has been reclaimed. Residence time (a measure of the rate of exchange between an estuary and the adjacent coast) is three days for Pauatahanui Inlet. The exchange is mainly caused by tides although enhanced by wind waves and to some extent seiches (oscillation). Three days is a relatively short time, indicating a strong flushing action (Healy 1980). Whether that same flushing action occurs in the Onepoto Arm is unclear. This area may experience less flushing, as a greater volume of water is retained at low tide. An understanding of the flushing capacity of the Onepoto Arm would be useful in determining the effects of pollutant loads at the entrance of Porirua Stream. It is possible that limited flushing occurs as algal blooms occurred in 2008 at this location although continued monitoring is needed to confirm whether this is an ongoing phenomenon (Stevens and Robertson 2008).

Dredging and impacts

Prior to the construction of Mana Marina, the tidal flats in front of the Mana Cruising Club were regularly dredged for boat access. An estimated 170,000 m^3 of sand was removed from this area (Stirling 1983). In 1950 this area was 60% tidal flats, but by 1983 the proportion of tidal flats had decreased to 25%. The bed level of the area had dropped by 2 or 3 m, equating to a net removal of 100,000 -150,000 m^3. Therefore, during the period of dredging 20-70,000 m^3 of sediment accumulated in the mudflat area, most likely sourced from the sand dunes of Ngatitoa Domain, which lost approximately that amount of sediment.

Dredging in front of the marina (prior to its construction) has also had an adverse impact on fauna. Species present elsewhere in the Harbour were often either absent or in reduced numbers at the Mana sites. This was most likely due to past dredging activities (Stirling 1983).

Mana Marina has kept records of the amount of dredging in recent years, but there is no further information regarding the impacts of dredging.

Biota

A large amount of information has been collected on the marine and intertidal biota in both Arms of the Harbour. Benthic fauna includes plankton, free swimming fauna (copepods), many worms (such as polychaetes, nematodes) shellfish (snails and cockles) and crustaceans (crabs), and many fish species. In this section we also summarise information on macroalgae, attached plants and invertebrates of subtidal and intertidal habitats and the associated seagrass, salt marsh and wetlands. Birds inhabiting the salt marshes and coastal fringes were summarised in section on terrestrial biodiversity.

The Pauatahanui Inlet is recognised as an important conservation area in the Wellington region in both the Wellington Regional Policy Statement (WRC 1995) and the Wellington Conservation Management Strategy (DOC 1995). The former lists the Inlet as a Site of National or Regional Significance for Indigenous Vegetation and a Significant Habitat for Indigenous Fauna.

Habitats and vegetation

Stevens and Robertson (2008) have mapped intertidal habitats throughout the Harbour. The GIS maps produced from their work show intertidal sediment types, macroalgal beds, seagrass beds, saltmarsh vegetation and a 200m band of the terrestrial margin. Stevens and Robertson's methodology can be used to identify areas important for protection and, when repeated, also to monitor habitat change. This methodology has also been combined with the authors' fine-scale habitat monitoring (Robertson and Stevens 2008) to apply a 'rating' to estuary health. There have been no studies of sub-tidal habitats in the Harbour since the broad survey of subtidal species groups reported in Healy 1980 (Fig, 59).

Saltmarsh is absent from the Onepoto Arm except for a tiny amount at Te Onepoto Bay), but occupies extensive areas at the head of Pauatahanui Inlet. Here, wide beds of rushland are dominated by sea rush and jointed wire rush, progressing landward to salt marsh ribbon wood and onto highly modified introduced grassland (Stevens and Robertson 2008). In 1969 the Pauatahanui Inlet margin was described as being composed of sea primrose in seepage areas, glasswort in delta flats and valley mouths and above this *Juncus* spp. At the eastern end of the Inlet, marginal species are browntop and jointed wire rush (Bell et al. 1969).

Stevens and Robertson (2008) also mapped the distribution of eelgrass and the terrestrial margin into a GIS database. 41.2ha of eelgrass are present in Pauatahanui Inlet and 17.3ha in Onepoto Arm. The eelgrass[19] beds are extensive, healthy, stable and free from fine sediment. The apparent decline in eelgrass has been discussed by several authors in varying studies (Bell et al. 1969,. 1988; Bell and Hicks 1991; Milne 2008; Blaschke and Anstey 2002). In terms of the terrestrial margin, most of the Harbour is bounded by artificial structures, hence the terrestrial buffer is often separated physically from the Harbour (by roads, railways etc). The terrestrial land cover around the Harbour margin is dominated by residential and commercial/industrial developments or artificial structures (Table 5). Grassland is a significant part of the terrestrial margin, while native forest or scrub is minor apart from on the Whitireia Peninsula (Stevens and Robertson 2008).

Mana Bank was identified as a key aquatic habitat of high ecological value during the environmental impact assessment of Porirua roading options (WRC 1989a). The sediment type and form, well sorted, open rippled uncompacted sand, is not found on a similar scale elsewhere in the harbour. The area contained a variety of unusual crustacean species, some of which were extremely abundant. The abundant numbers of copepods and others lower on the food chain were shown to support a high number of other species including flounder, kahawai, spotted dog fish and sole. Young flatfish preferentially feed at Mana Bank as they prefer sandy substrates; they do not feed elsewhere in the harbour even though the same food source is readily available. The area was identified as an important habitat for the paddle crab, as the soft sands provide shelter during the moulting season (WRC 1989b).

[19] Sometimes known by the common name of sea grass (Stevens and Robertson 2008) but this name is often confused with sea rush Juncus kraussii

Table 5: Composition of the terrestrial margin land cover (from Stevens and Robertson 2008)

Terrestrial margin type	Areas in Onepoto Arm (ha)	(%)	Areas in Inlet (ha)	Pauatahanui (%)
Residential	41	19	118	39
Grassland	56	26	108	36
Artificial structures	50	23	43	14
Scrub and forest	71	33	33	11

Plankton species

Microscopic plants (phytoplankton) and animals (zooplankton) were described as part of the PEP. Phytoplankton is dominated by diatoms which are most abundant in autumn. There is a relationship between diatom morphology and water temperature. The dominance of discoid species may be due to the high surface/volume ratio and efficiency of nutrient absorption. Zooplankton is dominated by copepod species and the larvae of cockles, worms, crabs and barnacles. They are most abundant in summer when higher temperatures allow them to reproduce frequently. Coastal species are also more abundant in summer, probably because Pauatahanui Inlet water is more saline then. The eastern end of the Inlet is generally more productive for zooplankton (Healy 1980).

More detail on ecology of copepods in the Inlet is given by Förch (1983). There has been no survey of plankton species in Pauatahanui Inlet since, and such a survey of the Onepoto Arm has never been undertaken.

Benthic fauna

There have been numerous studies on the sub-tidal benthic fauna of Pauatahanui Inlet. Porirua Harbour is the most southerly habitat for some benthic species (Bell et al. 1969). Copepods have been studied several times for species diversity, habitats, distribution, methods of movement, response to changes in sediment surface, daylight, tidal fluxes and impact of predation (Hicks 1985, 1986, 1988, 1989, 1992; Bell and Hicks 1991), giving a comprehensive although somewhat fragmented account of the types of species present in the Harbour. Population dynamics and species assemblages of polychaetes in relationship to environmental conditions have also been studied in Pauatahanui Inlet (Read 1984a, 1984b). Some species (a polychaete, a snail and six copepod species, including the super-abundant *Parastenhelia megarostrum*) were first described and identified in Porirua Harbour (Ponder 1972; Kudenov and Read 1977; Wells et al. 1982). The diet of the crab *Ovalipes catharus* has been studied at Paremata and Plimmerton (Haddon and Wear 1987; Wear and Haddon 1987).

Pauatahanui Inlet has been described as a healthy system, in terms of density and diversity of meiobenthos[20] and comparable to muddy estuarine sediments from other parts of the world (Coull and Wells 1981).

Hicks' studies of the copepod *Parastenheli megarostrum* focussed on one of the most common and important species in the Pauatahanui Inlet, with a density of around 263,000 individuals per square meter (PICT 2001). The distribution of meiobenthic copepods in Pauatahanui Inlet varies according to the environment, with higher densities of copepods occurring in subtidal than intertidal sediments. The greatest density occurs at the mouth of Ration Creek. Mana Bank supports a variety of species assemblages, reflecting the environmental variations in vegetation and tidal exposure. Eleven species occur at Mana Bank, whilst only two occur at Ration Point, and three at Ration Creek (Iwasaki 1993).

Systematic surveys of the benthic fauna in both arms have only more recently been completed, in 2004, 2005 and 2007-8 (Stephenson and Mills 2006; Milne 2008). Of all individuals counted, polychaetes were most abundant followed by bivalves. The most abundant bivalve was *Arthritica* sp. then *Nucula hartvigiana*. By biomass, the bivalve *Cyclomactra ovata* was the most abundant (Stephenson and Mills 2006). The 2007-8 survey showed a similar benthic community structure with polychaete worms dominating (>50%), then bivalve molluscs, crustaceans, and gastropod molluscs (Milne 2008).

Data from 2004, 2005 and 2008 indicates that there is a difference in the benthic species composition between Pauatahanui Inlet and Onepoto Arm. However, Stephenson and Mills (2006) suggested that this difference was an artefact of different sampling effort and the location of sites, as Porirua sites were in deeper water. The later survey (Milne et al. 2009) also found a much higher diversity in Pauatahanui Inlet, but sampled only two sites in Onepoto Arm. In examining the combined 2004 and 2005 surveys, Stephenson and Mills (2006) concluded that that there was nothing about the nature of the variation observed between the surveys to suggest the populations were unstable. Differences in communities between the two arms were probably due to textural difference in the sediments. Comparison of the 2004 and 2005 data shows that all sites experienced 'gains' and 'losses' in species. The species responsible for the changes in faunal composition were spread across all the major taxonomic groups encountered and no one species was involved at all sites. So, the gains and losses were not the result of the loss of a single species across the whole Harbour (Stephenson and Mills 2006).

The fine sediment community is stable because there is a diverse fauna with numerical dominance shared by a number of species. Observed changes between 2004 and 2005 were restricted to species that are uncommon or rare. The structure of the community is determined by wave disturbance and sediment texture and the population structure is consistent with the nature of sediments at each site (Stephenson and Mills 2006). The two Onepoto Arm sites sampled in 2008 showed higher metal contaminant levels in their sediments than in Pauatahanui Inlet but the mud and organic carbon contents were also higher in the Onepoto Arm sites.

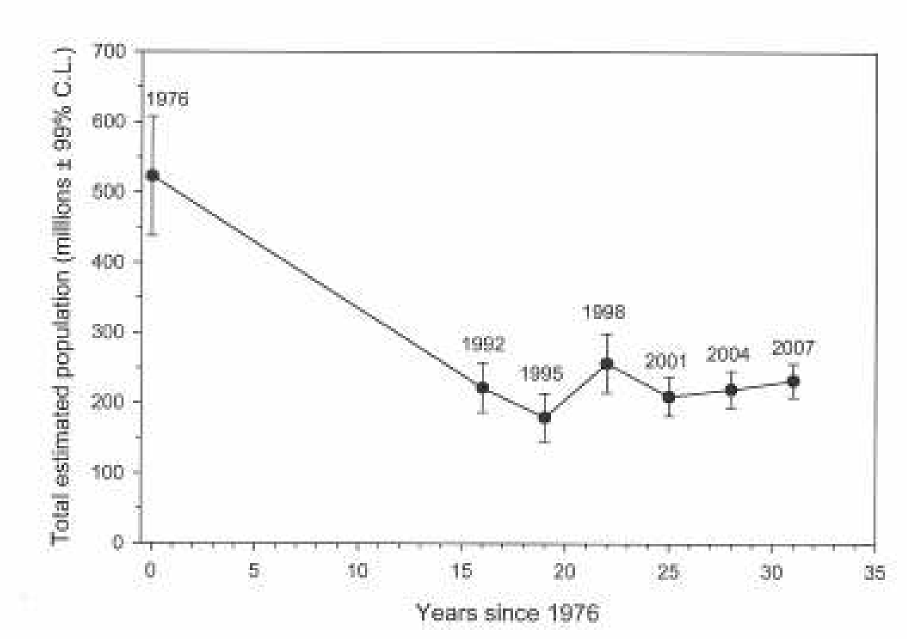
[20] small (0.5-0.044mm) bottom dwelling fauna

Cockle surveys

In Pauatahanui Inlet in 1976, the common cockle comprised around 80% by number of the living material in the Harbour, excluding fish and birds (Healy 1980; PICT 2001). Cockle populations were surveyed in 1976 (Richardson et al. 1979), 1992 (Grange 1993), 1995 (Grange et al. 1996), 1998 (Grange and Crocker 1999), 2001 (Grange and Tovey 2002), 2004 (Horn et al. 2005) and 2007 (Michael 2008). In 1976 the number of cockles was estimated at 400–600 million, which equates to 5,000 tonnes on each km^2 of inter-tidal area. The 1995 survey revealed that cockle numbers had fallen by two-thirds from 1976. Since then densities of cockle in Pauatahanui Inlet have roughly stabilised at a lower level of about 220 million (Figure 3). The reasons for the 1970s to early 1990s reduction have never been proven, although suspected to be linked to a reduction in the extent of eel grass beds in the Inlet, in turn linked both to higher sedimentation rates and to natural fluctuations (GOPI, nd).

The largest decreases in number between 1976 and 1992 occurred at Duck Creek, Kakaho and Motukaraka Point. The least successful recruitment site is at the Kakaho Estuary. Juveniles more frequently occur at low tide, where there is a greater food supply and longer feed times (Grange 1993). The proportion of juveniles in the population has differed widely between surveys (Michael 2008; GOPI nd).

Figure 3 Trend in total cockle population within Pauatahanui Inlet, 1976-2007 (Michael 2008)



Throughout the sampling period the highest densities of cockles were found at the eastern end of the Inlet, from east of Motukaraka Point to the mouth of the Pauatahanui Stream. Lowest densities were consistently found at sites alongside Grays Road from Camborne to Kakaho, at Motukaraka Point and at the mouth of Duck Creek. Recruitment was variable in intensity, with 1976 and 1992 being very poor years. In all years recruitment was highest at the eastern end of the Inlet, but also at Browns Bay in 1998 and 2007 and on Mana beach in 2007. Lowest recruitment occurred consistently at Camborne, Motukaraka Point and (except in 2007) at Mana beach. The very large decrease in the total population after 1976 was reflected at all locations but possibly was greatest at the eastern end of the Inlet between the Horokiri Stream and Duck Creek. These data were summarised by Michael (2008, Figs. 15 and 18).

Fish

The Harbour is widely recognised as an important feeding ground and nursery area for many species of fish, especially coastal flatfish. Healy (1980) recorded 30 species in Pauatahanui Inlet, to which Jones and Hadfield (1985) added three more. Jones and Hadfield list a total of 43 species of fish that have been identified in Porirua Harbour, considered to be a relatively high diversity. This list includes three species of whitebait that undoubtedly occur in Pauatahanui Inlet but are not listed by Healy. Jones and Hadfield recorded 20 species in Onepoto Arm, but this is likely to be an underestimate as they only used gill nets. Only 14 species were recorded in both arms. The relative abundance of species has not been assessed. Additionally, the lower stream reaches provide spawning and rearing grounds for whitebait. There are also sea-run brown trout in both main arms. However, there is an acknowledged lack of local data on abundance, trophic interactions and estimations of biomass and secondary production (Hicks 1985). To our knowledge, the effects of fishing and shellfish gathering in the Harbour have not been assessed.

The very abundant copepod *Parastenhelia megarostrum* is the dominant food source for young flatfish (Hicks 1984). Study of flat fish predation on copepods at Mana Bank indicated that although predation was high, there was little impact on overall abundance of the copepod (Hicks 1985). Yellow-eyed mullet have been sampled in Porirua Harbour as part of a study of the species across New Zealand (Curtis and Shima 2005). Growth and population studies for New Zealand rig have been undertaken in Onepoto Arm and Pauatahanui Inlet (Francis and Francis 1992; Hendry 2004), based partly on re-analysis of Jones and Hadfield's 1985 survey data.

The degree of contamination of biota by toxic contaminants

As concentrations of heavy metals have been reported as elevated in the sediments of Onepoto Arm (even though they are below guideline levels), there has been concern that these toxicants are affecting the benthic biota. There is also a likelihood of faecal contamination of edible shellfish species, due to the high faecal coliform counts frequently encountered in water quality tests. Several studies have looked at the contamination effects of the biota (Stephenson 2003).

The flesh of the common cockle was analysed for toxic contaminants in regards to human consumption from five sites in both arms of Porirua Harbour (Berry et al. 1997). The only four samples from the Wellington region to test positive for faecal coliforms came from Porirua Harbour, but were still below the guidelines for edible tissue. Cadmium, chromium, copper, nickel, lead, mercury, and zinc were all present in the shellfish, but not above guideline concentrations for consumption. Cockles sampled from different localities in the Wellington region had similar concentrations of these heavy metals. Cockles were tested for organochlorides and PAHs, with negative results (Milne 2006a). This result is an improvement as an earlier report found faecal coliforms in cockles up to 2.4 times higher than the food guideline values, and recommended against consumption.

Concentrations of zinc, lead and manganese have been measured in the mud snail *Amphibola crenata* from Onepoto Arm and Pauatahanui Inlet (Kennedy 1986). Although the analysis undertaken would yield higher concentrations than usual toxicity analysis (as sample was analysed for species of metals that are not bioavailable), the high lead concentration was recommended to warrant further investigation (Kennedy 1986).

Benthic ecology data from 2004 and 2005 show that although the total concentration of several contaminants (notably DDT, zinc, and to a lesser extent copper and lead) are above sediment quality guidelines there is no clear evidence any of the contaminants have resulted in significant adverse effects on the benthic ecology. There were no benthic community groups that changed with increased concentration of contaminants. The toxicant thresholds for effects are not known (Stephenson and Mills 2006).

The above study highlights the difference between testing ‘total’ metals (which includes those locked away in minerals) and the ‘bioavailable’ metals (which are those metals loosely bound to sediment). As noted above, no bioavailable concentrations for metals have been above the recommended guidelines, whereas ‘total’ metals (which can include chunks of pure metal) sometimes breach the guideline.

A earlier study of parasites, diseases and lesions affecting the common cockle and the common estuarine bivalve *Macomona liliana* within Porirua Harbour revealed that the picture of how pollution is affecting estuarine fauna is quite complex. The most severe pathology found, a massive systemic congestion of the mantle, gills and gut, affected 20% of cockles in Pauatahanui Inlet, but none from the Onepoto Arm (Hine, no date). The surfaces where the inflammation occurs were all exposed to the environment, suggesting an environmental cause, the nature of which was unknown. This result is inconsistent with pollution studies which suggest that Onepoto is more polluted with higher concentrations of metals, DDT and PAHs, whilst Pauatahanui Inlet is believed to be relatively uncontaminated. The pathology data challenges this assumption, and hints at the possibility of road-sourced PAHs causing cockle inflammation. Hine’s study provided no conclusive evidence of this, but other recent work (Rogers, 2009) has shown high levels of PAHS at some sites influenced from road wash.

Interestingly, an earlier study of the meiobenthos off Ration Point revealed a very high density and diversity of fauna collected, indicating a healthy environment, compared with the Hutt River (where sediments contain raised concentrations of zinc and lead) which had a very low faunal density and diversity (Coull and Wells 1981).

Alien biota

In a catalogue of newly introduced marine algal species to New Zealand, one new algal species was described inhabiting Porirua harbour, *Chondria harveyana*, which is a red alga originating from Australia (Nelson 1999). This species is not considered invasive (WWF no date).

A few individuals of the invasive kelp species *Undaria pinnatifida* were observed in the harbour in 2008 (Stevens and Robertson 2008). It was first noted in Porirua in 1992 (MoF 2001) and by 2000 it had colonised Pauatahanui Inlet up to end of Seaview Rd, along Camborne shore and across to Motukaraka Point. It was also present on some vessels moored in the Inlet's main channel and in boats moored in Mana Marina (BML 2000). Originally from Japan, this species is officially classed as an 'unwanted organism', as it is an invasive, opportunistic seaweed that can form dense stands in the subtidal and intertidal zones preferring stable substrates such as rocky shores, boats or even shelly habitats. Potentially it can displace native plant and animal species due to competition for light and space. It spreads mainly by fouling on boat hulls (MAF 2008).

Stevens and Robertson (2008) note a few individual plants observed in both arms. However, there have been no systematic surveys of *Undaria*, and information on the extent of its current habitat, any newly invaded areas and any declines is lacking. The long term impact of *Undaria* on the Harbour's marine ecosystem is also unknown.

Patterns and quantity of human use

Maori use

There are many sites of historical significance to Maori in the Harbour catchment[21]. Appendix 1 in BML (2005) identifies many important sites in the region, including early settlement sites.

Sites near Paremata Point, close to the current Ngatitoa Domain, are among the most significant and best known early Maori sites in Wellington (Brodie, in Healy 1980). They are believed to trace back to at least 600 years ago and have been permanently settled since then (BML 2005; PCC no date a). The stone anchor Maungaroa was left by Kupe (the first of the Polynesian ancestors) as proof of the discovery of the new land. The anchor stone lay near Paremata for many centuries until it was removed and placed in the Dominion Museum (BML 2005). Other Maori archaeological sites are recorded at Whitireia Park (Walton 2002).

[21] Te Runanga o Toa Rangatira on behalf of Ngatitoa iwi have conducted extensive research in relation to Treaty of Waitangi claims, but this research is not currently publicly available and has not been drawn on in the preparation of this review.

Before the 1820s Ngati Ira were in possession of the district and had a substantial Pa at Motu-Karaka and another east of the mouth of the Horokiri Stream. The main areas of occupation for Ngati Toa Rangatira have been: Pukerua (Wairaka, Waimapihi); Plimmerton (Taupo, Turi Kawera, Motuhara, Hongoeka); Paremata; Papakowhai and Aotea; Te Ura Kahika and Takapuwahia; Kaitawa and Whitireia area; Komanga Rautawhiri and Mana Island. The use of resources by tangata whenua in the study area is focused within the coastal waters and foreshore areas, offshore islands, harbour edges, inland rivers and forest edges, with both main arms of the Harbour considered to be inextricably linked (BML 2005).

The coastal zone is an area of traditional and continued use for the local iwi. The Harbour is important for gathering of food. Species from the harbour that have been identified as important are: flounder, herrings, conger eel, shark, dogfish, snapper, paua, mussel, pipi, tuangi, oysters, and pupu. Ngati Toa Domain is considered to be a specific area of significant importance. A plaque in Onepoto Domain recognises Ngati Toa's use of the harbour resources during the 1930s depression (BML 2005).

Harvesting

The northeastern coast of Pauatahanui Inlet was historically known to Maori as a food gathering area (Owen 1984). The southern end of Onepoto Arm was also an important source of seafood, but one which has declined to nothing over the course of the twentieth century (T. Parai, Ngati Toa iwi, address to Wellington Restoration Workshop, May 2009). Whitebaiting occurs at stream mouths, whilst collection of sea lettuce (*Ulva* spp) and eel grass occurs in Pauatahanui Inlet (Owen 1984). There have been no quantitative surveys of fisheries in the Porirua Harbour but there is thought to be increased shellfish harvesting pressure on the Pauatahanui Inlet (Guardians of Pauatahanui Inlet, in: Grange and Crocker 1999; Maysmor 2000).

Access

Artificial structures such as roads, culverts or boat ramps border most of Pauatahanui Inlet and the Onepoto Arm, and the terrestrial land-cover border (defined as 200 m from the water line) is dominated by residential, and commercial/industrial developments and grassland (Stevens and Robertson 2008). The proportion of the terrestrial border which is unmodified remains low. All these modifications directly impact on the marginal native vegetation and potential native wildlife habitat, and have the potential to contaminate Harbour waters. Many of these issues and methods for remediation for Pauatahanui Inlet are highlighted in the Pauatahanui Inlet Restoration Plan (Stages I and II) (Blaschke and Anstey 2002, 2004).

Water sports

Water sports are popular within Porirua Harbour (Stirling 1983; Berry 1998a). The Harbour is home to several yachting, rowing or boating clubs, with the Mana Cruising Club alone registering 800 members and 400 boats in 1983 Water skiing takes place on two designated ski lanes in Pauatahanui Inlet, whilst yacht races take place on courses on both arms. Several commercial fishing boats also operated out of Porirua Harbour (Stirling 1983). Bathing is common in summer, especially at Plimmerton beach, whilst windsurfing is popular both at Plimmerton Beach and Pauatahanui Inlet (Berry 1998a). Various parts of the Harbour (Outer Harbour as well as both arms) are also popular for recreational fishing, kayaking, boating, and jet-skiing.

For several of these activities, Pauatahanui Inlet is a significant site within the lower North Island (Blaschke and Anstey 2002). There is potential conflict between water-based activities and the Pauatahanui Wildlife Refuge (both windsurfing and one ski lane occur within its boundaries). There has been some recent erosion of sea rush habitat between Ration Point and Pauatahanui (EMS and Blaschke 2008) but whether boating activity is exacerbating this is uncertain. No quantitative assessment of the amount and effects of water sports has been undertaken for Porirua Harbour.

Other activities

Other recreational activities undertaken on or at the edges of the Harbour include picnicking, bird-watching, dog-walking, nature studies, horse-riding, cycling, recreational driving, and running. The presence of humans (and in particular dogs) can be detrimental to the potential of wildlife habitat. The current Pauatahanui Inlet pathway project could lead to a greater disruption of wildlife though increased interaction. However, the proposed pathway is relatively well screened in areas of bird nesting and feeding, making bird disturbance minor (EMS and Blaschke 2008).

There have been no specific studies regarding the impact on the Harbour ecology of any of these existing activities. Recreational activities (especially sailing and walking) have been either encouraged or tolerated even in the managed reserves.

The effects of roading

In this section we comment on all aspects of roading as it affects the catchment, including contaminant inputs, effects on the hydrology of the catchment, public use of the Harbour affected by roading and impacts on the natural character of the coastal environment.

Porirua Harbour is probably the most completely hard-edged estuary in New Zealand; i.e. the most completely ringed by road, rail and walkway/cycleway embankments. There are many actual and potential effects of roading on estuarine ecosystems, including pollution from vehicle emissions, tyres, brake pads, and road run-off; wave refraction; estuarine erosion and loss of absorptive capacity from storm surges along Harbour edges; direct coastal habitat loss; and loss of potential habitat for estuarine species retreating from rising sea levels (Kennedy 2003). Other effects include loss of visual and natural character and reduced public access. Broad-scale habitat maps (Robertson and Stevens 2008; Milne 2008) show clearly that in both arms of the Harbour there is little to no terrestrial vegetation buffer.

As safe pedestrian access to the edge of both inlets is limited, a series of walkways are proposed that will basically encircle the Harbour (PCC no date b). The overall impact on native fauna of increased human access to the Harbour edge has not been assessed. It may be wise to select key habitats (rocky intertidal, marsh and mud flat areas) which are screened from human use as many bird species are easily disturbed. For example, species at Pauatahanui Wildlife Reserve which forage in intertidal areas, close to Grays Road, are easily disturbed by human activity (EMS and Blaschke, 2008).

A specific proposal for a pathway from Ration Point to Pauatahanui was assessed for environmental impacts. In this area, potential disturbance to birds is assessed as minor, and the main impact is vegetation removal during construction. The proposal is likely to enhance the area as native plantings will help ameliorate coastal erosion (EMS and Blaschke 2008). Away from the Harbour, a recent proposal for a walkway and cycleway along the lower Porirua Stream has progressed to the point of initial environmental effects assessment, principally in terms of effects on flood control considerations (Opus 2008).

Under the Western Corridor Transportation Study planning balance sheet assessment, the impacts on air quality, noise, landscape, ecology, built heritage, archaeology, severance, community disruption and active travel under specific route options were assessed (Maunsell 2005). These roading assessments have largely drawn on the same information base that has been drawn on for this review.

Stormwater draining SH1 has been sampled and indicated that pollutants are not likely to cause an adverse impact on the receiving ecosystem. However, the close correlation of PAHs and metals with suspended sediments indicates the potential of road runoff to provide polluted sediment that could accumulate in depositional environments within the harbour, resulting in high pollutant concentrations in the sediments (Sherriff 1998).

Localised impacts of potential bridge and road development on Pauatahanui Inlet's physical and biotic processes have been investigated (WRC 1989a, b). Porirua Harbour was used as a pilot for a GIS study of sensitive receiving environments at risk from road runoff (Gardiner and Armstrong 2007). The inner end of Onepoto Arm was identified as a significant 'hot spot', due to cumulative effect of pollutants from five sub-catchments with moderate to high traffic density. Several recommendations in the Pauatahanui Inlet Restoration Plan (Blaschke and Anstey 2002, 2004) specifically address potential adverse effects of roads on the Inlet, recognising that the options for this were very limited because of the minimal width of the road-to-Harbour edge.

Summary of literature on Inlet exchange and outer harbour dynamics

Tidal inflow and outflow dynamics

The tidal height above Mean Sea Level at Mana is 1.42 m on the spring tide and 0.34 m on the neap tide. In Pauatahanui Inlet the tide is attenuated, with a spring of 1.4 m and a neap of 0.3 m (Stirling 1983).

A description of flow characteristics for the area around the Mana Marina was developed for the Mana Marina environmental impact statement (Stirling 1983). The entrance ("throat") to the two main arms is narrow, creating strong currents. On the flood tide, rapid flow occurs at the entrance and a strong eddy develops in midstream caused by the rocky reef that extends out from the south shore off Deepwater Point on the Whitireia Peninsula. A 20m trench has been scoured as a result in this area (Stirling 1983). Prior to the construction of the Mana Marina, on the flood tide a reverse eddy would occur over the tidal flats in front of the Mana Cruising Club. On the ebb tide, similar high velocities of flow are experienced through the entrance. Prior to the marina's construction the site experienced eddies in a reverse flow (Stirling 1983). Stirling's description highlighted flow around the Mana Marina site, but did not quantify flow or describe flow further in either arm.

Further basic hydrodynamic data has only been collected for Pauatahanui Inlet. The long term mean discharge of freshwater to Pauatahanui Inlet is 16litres/km^2, and the maximum mean discharge is ~600 litres/km^2 (Curry 1981, in: Swales et al. 2005a). The average tidal current speed is ~1 m/s, and there is an approximate 3-day residence time in Pauatahanui Inlet. Spring tides move 3.9 million cubic metres in and out of the Inlet, whilst neap tides move 1.2 million cubic meters. About 2.6 million cubic meters of water remains in the Inlet at low tide.

A mechanical hydraulic model of Pauatahanui Inlet was constructed in 1975 to test prediction about changes likely to be caused by proposed reclamation and dredging (Berwick 1978, in: Healy 1980).

Gibbs & Cox (2009) have given an estimate of the tidal share between the arms of the harbour. In 2009 64% of the spring tidal flow was into Pauatahanui Inlet and 36% into the Onepoto Arm. Beyond this, no information is available concerning the dynamics of flow between the two arms, the tidal capacity share, between the two arms, or flow recapture between the two. No quantitative measurements of tidal prism or residence time in Onepoto Arm are available.

Effects of Mana Marina on the inlet and both arms of the Harbour

Construction of the Mana Marina in the mid 1980s removed about 0.4% of the harbour areas and a similar percentage of tidal flats. There is no literature concerning the actual or potential impact of the Mana Marina on tidal flows, sediment transport, or water quality (BML 2000).

Impacts boats and moorings may have in either arm of the Harbour

Undaria pinnatifida, an invasive Asian seaweed (see section on alien species above), is present on boats and moorings at the Mana Marina, and could act as a future source of invasion (BML 2000). Other than this, no specific information is available.

Patterns and quantity of human use

No specific information is available.

Beach development and coastal erosion

Environmental features between Karehana Bay and Plimmerton Beach, including substrate characteristics, flora, fauna (macroinvertebrate abundance and diversity) and degree of modification, were mapped into a GIS layer. The mapped area extends from the far side of the marina, north to the end of Karehana Bay (Stevens and Robertson 2006).

Between Karehana Bay and Plimmerton Beach the sediment is dominated by an extensive boulder field (51% of the area mapped), whilst sand beaches are 35% of the area mapped. A band of cobbles is present at low tide and at Karehana Beach a narrow band of cobble is present at the south near the Marina (Stevens and Robertson 2006). The sediment-dwelling fauna at both Karehana and Plimmerton was fairly sparse, with only one individual sea louse present in the upper beach samples from Plimmerton, and on the lower shore, a mix of scavenging amphipods and isopods. There was a similar assemblage at Karehana, with the addition of one single bivalve species. Residential development was regarded as the most significant potential impact on these coastal areas: Plimmerton beach was rated as very highly modified, whilst Karehana was ranked as highly modified (Stevens and Robertson 2006). The next most significant pressures were erosion/flood protection, and loss of nearshore habitat.

The beach at Ngatitoa Domain has been forming since the sea level rose ~6,000 years ago. Analysis of aerial photos shows that the Domain advanced 18m at 0.3 m/yr between 1900 and 1960. However, from 1960 to 1979 there has been erosion along the Domain of 6-22 m, at a rate of -0.32 to -1.16 m/yr. The maximum erosion has occurred northwards adjacent to the railway line where 22 m of shoreline has retreated (Gibb 1993; TT 2005).

Dominant west-northwest seas mean that there is a net southward longshore drift between Plimmerton and Mana Marina (Lewis 1988 in: Gibb 1993). Sand is moved during northwest winds along the Ngatitoa Domain shore into the Harbour throat. The flood tide moves sediment further inwards. On the ebb tide, sand is carried in a well-defined channel extending towards Goat Point and is deposited in the bay. It is then moved shorewards by long period wave action. Prior to the Mana Marina construction, sand was deposited where the marina is now located. This sand accumulation was removed by dredging, and net loss occurred at Ngatitoa Domain (Stirling 1983). More recently, sand accumulated along the northern break wall of the marina and at its entrance, and the marina entrance shallowed from 5-6m depth to 2-3m depth (Gibb 1993).

Erosion at Ngatitoa Domain was also associated with the reclamation of 1.71 ha of sea bed at the north end of Ngatitoa Beach by New Zealand Railways in the 1950s. The reclamation is heavily armoured with a revetment of concrete and rock to protect the railway. This reflects breaking waves and focuses wave energy onto the northern part of the Domain. It is this area that is experiencing the greatest amount of coastal retreat (22m) and also an accumulation of gravels. The gravels indicate how the reflected wave energy is scouring out the sandy seabed and is preventing sand from naturally accumulating (Stirling 1983; Gibb 1993; Stevens and Robertson 2006).

There is no input of new sand from other areas. Mana is cut off from being replenished by sand from the Kapiti Coast littoral drift from the north. Pukerua Bay deflects the flow of sediment offshore toward the north end of Mana Island. The sand on the sea bed in the Mana Basin is finite and non renewable. Essentially the movement of sand into the Mana area is a one way valve, with no sediment returning or replenishing Ngatitoa Domain (Gibb 1993; Gibb and Cox 2009).

Currently erosion of Ngatitoa Domain is at a rate of -0.5 to -1.0 m/yr. This rate is likely to accelerate in response to a dwindling supply of sand, the focus of wave energy and wave reflection off the New Zealand Railways reclamation to the north and an accelerated rate of sea level rise (Gibb 1993). Two reports have recommended management of erosion at this location (Gibb 1993; BECA and CCNZ 2003).

Beaches within Pauatahanui Inlet and the Onepoto Arm are protected from ocean swell, and thus the only erosive forces at work are wind waves and tidal currents. Short-period wind-waves, generated when wind blows across the surface of the water, tend to be erosive in nature, and are quite effective at undermining banks and roads. However, these wave types do not have the power of ocean swell and are easily dissipated by features such as a long sloping nearshore environment (as found in the head of inlets), vegetation (e.g. rushes) or gravel/cobble beaches (Dawe 2007).

The Dolly Varden Beach shoreline is undergoing erosion caused by wave action, except in locations where there is a strong root mat (Blaschke and Anstey 2004). Estimates of rates of sand removal were not available. A mixture of hard engineering and revegetation was recommended in this area to prevent erosion (BECA and CCNZ 2003; Blaschke and Anstey 2004).

Sand bar dimensions and dynamics

In the PEP, the sand bars in Pauatahanui Inlet were mapped using 31 years of aerial photos. The bars and channels of Pauatahanui Inlet showed little to no change over a 31 year period between 1942 and 1973. The most change occurred at stream outlets where birdsfoot deltas developed (Irwin 1976). Monthly monitoring during the study revealed that the surface underwent both erosion and accretion, with most changes at around 2 mm. The intertidal surfaces appeared to be stable, whilst bayhead deltas and beaches at high tide underwent a greater rate of change (Irwin 1976). Most intertidal surfaces in Pauatahanui Inlet were stable, with most cross sectional profiles oscillating around zero change. There was a mean rate of deposition of 2.9 mm/yr (Pickrill 1979).

These earlier studies indicated that storm events did not change Pauatahanui Inlet bathymetry significantly, with no significant erosion or accretion occurring, with the exception of bayhead deltas, which did experience scour and deposition. The lack of change indicated that sediment from storms was delivered elsewhere, or was lost to the system (Pickrill 1979). In contrast, the more recent sedimentation studies (Swales et al 2005a; Gibb and Cox 2009) showed changes between 1974 and 2009 and showed net accumulation on most sand flat areas in that time, particularly on the northern Pauatahanui Inlet sandbars. Swales et al estimated that there was an increase of about 12 ha (15%) in the intertidal area during the last 150 years.

Sand bars have not been mapped in the Onepoto Arm, and have not been monitored for stability. For both arms, there is no study of the processes which influence sand bar dynamics, and how they are likely to respond.

Effluent dispersal characteristics and potential impacts on the Harbour from the wastewater treatment pipeline discharges

There is no specific information on how effluent disperses in the Harbour. Information of the impact of the quality of effluent is discussed below.

Stormwater management

The effects of catchment land use on sedimentation and water quality

Rural impacts

Rural land use impacts on stormwater in the Porirua Harbour are characterised by high faecal coliforms in water bodies, a high delivery of sediment from bare or disturbed land[22], and contamination of soil by DDT. There is also some evidence of elevated nutrients (see section on freshwater quality).

Agricultural clearing and grazing since 1850 is thought to be responsible for an increase in sediment accumulation rates (SAR) into Pauatahanui Inlet, from ~0.7mm/yr (pre-European) to ~2.0-2.4 mm/yr (see further discussion below). The sediment from the Horokiri samples is dominated by sands, unlike the eight other cores taken in Pauatahanui Inlet which are generally composed of finer sediments (Swales et al. 2005a).

Total DDT[23] (i.e., DDT and its equally toxic breakdown products DDE and DDD) has been found in the sediment of Porirua Harbour above the ANZECC 'low' trigger value. The major constituent of the Total DDT in the harbour sediment was DDE, which is produced when DDT degrades in aerobic conditions (i.e, exposed to the air). This suggests that the major source of the contamination is agricultural soils. The beds of six streams examined for Total DDT have yielded concentrations in the sediment that are greater than the ANZECC 'low' trigger value. These were Pauatahanui, Kenepuru, Porirua, Browns and Mitchell Streams and Duck Creek (Milne and Croucher 2005). This highlights that the streams are transporting these contaminants from soils to the Harbour. The use of DDT in agriculture effectively ceased in the 1970s (previously it was used to control the grass grub in pastures), but its use in urban areas was not banned until the late 1980s. The research confirms that significant sources remain in the environment and that inputs to the Harbour are likely to be on-going (Cameron 2001; Williamson et al 2004). Continued surveys of streambeds would be useful to determine trends.

Water draining rural land in the Porirua catchment is characterised by slightly elevated nutrient levels and high levels of faecal coliforms (see freshwater quality section). For example, in Belmont Stream, water had fairly high nutrient concentrations, particularly nitrogen. This reflects the rural nature of the Belmont catchment upstream (BML 2004a). Pauatahanui Stream has had consistently high levels of faecal coliforms, with stock

[22] Typical sources of disturbance include steep grazed slopes, farm or forestry roads, forestry harvesting operations, quarrying.

[23] DDT is found in the environment as a parent compound (DDT) and two derivatives of that parent (DDE and DDD), and all of these can occur as two isomers. As a result ANZECC has separate guidelines for "Total DDT", DDD, and DDE. All the GW studies report "Total DDT" and compare it with the relevant guideline, then give the percentages of the three compounds.

crossings, piggeries and chicken farms the most likely sources. Similar influences on Takapu Stream have also led to high levels of faecal coliforms (Berry 1996a).

The concentration of bacteria along Plimmerton Beach decreases with distance from Taupo Stream, indicating that the stream is the contamination source (McBride et al 1995, in: Berry 1999). Taupo Stream is likely to receive faecal material from animals grazing on surrounding pastures, which impacts on the water quality of Plimmerton Beach (Berry 1999). Rural runoff is suggested to be one of the two main causes of high microbial concentrations in coastal waters (Williamson et al. 2001).

Urban impacts

Stormwater inputs from urban areas are characterised by poor water quality, specifically high concentrations of faecal coliforms, the heavy metals zinc, copper and lead, PAHS and nutrients. Sediments also contain elevated concentrations of metals. The initial construction period of urban development in the Harbour catchment delivered a large amount of sediment (see below), but this declines as the residential area matures and revegetates. Currently, the catchment with the strongest urban influence is Porirua Stream, and, overall, the Onepoto Arm has a greater urban influence than the Pauatahanui Inlet (Fig 2).

Sewage contamination is suggested as the other main degrader of the microbial quality of coastal water (Williamson et al. 2001). The occasional high counts of faecal coliforms in Horokiri Stream are most likely from leaking septic tanks in the catchment, whilst in Porirua Stream sewer/stormwater cross connections is a likely source, although diffuse urban runoff can also be a microbial source (Berry 1996a). However, high microbial levels are not a result of the outfalls of the sewage treatment plant (McBride et al. 1995); if sewage is a source it is via uncontrolled leaks.

Onepoto Arm visually appears more polluted as it also has a significant amount of rubbish polluting the upper area of the Harbour closest to Porirua CBD (Stevens and Robertson 2008). Concentrations of zinc, lead and copper are higher in Onepoto Arm (Glasby et al. 1990; Stephenson and Mills 2006). This is especially so in the vicinity of Porirua CBD, pointing to both the Porirua Stream and the city stormwater as a source of these contaminants.

Water quality at the head of the Onepoto Arm near the discharge point of Porirua Stream to the Onepoto Arm is generally poor, as it is the receiving environment for stormwater from almost all the urban and industrial areas of Porirua City (Berry 1997a, 1999; Stephenson 2001). Concentrations of nutrients are also at levels likely to cause nuisance algae (Cameron and Wall 1992; Cameron 1993; Berry 1995; Stansfield 1999; Warr 2001; Perrie 2007). The densest covering of macroalgae in the Harbour was present near Porirua Stream mouth (Stevens and Robertson 2008), suggesting a high nutrient input from the stream. Porirua Stream occasionally records pH in the ‘basic’ range, which is thought to be a function of concrete surfaces as they ‘cook’, or of unauthorised industrial discharges (K Calder, PCC, pers. comm., June 2009).

There is evidence that the urban catchment delivers a pulse of polluted water to the catchment in rain events, which is adversely affecting the benthic community. These pollution pulses associated with rain events bring high concentrations of zinc, lead and copper (Cameron 2001). This is discussed further below. Sediments of Porirua Stream contain elevated concentrations of metals. Stormwater discharges in the Greater Wellington Region have been characterised by elevated concentrations of zinc and copper. In 2005-6 stormwater pollutants from Porirua Stream showed high levels of total zinc and lead (Milne and Watts 2008).

Organo-chlorine pesticides and polycyclic aromatic hydrocarbons (PAH) are present in high concentrations in urban streams. All have elevated concentrations of DDT (which may also be sourced from rural catchments), while Kenepuru and Porirua Streams have high concentrations of PAHs and lindane respectively (Croucher and Milne 2005; Milne and Watts 2008). These man-made chemicals are a reflection of the chemicals present within the catchment. A common source of PAHs is car emissions (ANZECC 2000).

Urbanisation of the Browns Bay and Duck Creek sub-catchments led to an increased SAR since 1950, but during this period the SAR was lower between 1985 and 2004 as the urban area matured, and erosion stabilised (Swales et al. 2005a). The high sediment yield (1200 t/km^2/yr) of the water coming from Browns Bay catchment in the 1970s showed the impact of urbanisation on sedimentation rates, as it yielded 10% of the sediment load for Pauatahanui Inlet from 1% of the catchment area (Curry 1981, in: Swales et al. 2005a).

Concentrations of zinc, lead and copper in Pauatahanui Inlet sediments decrease with depth. This is caused in part by historical changes in catchment land use (from pasture to urban) and in part by a decrease in grain size towards the surface (Swales et al. 2005a).

Industrial impacts

There are small industrial activities in the catchment, and occasional industrial spills are noted in the annual water quality monitoring reports (Cameron and Sando 1990; Cameron 1991). However, there is no assessment of industrial land use impacts on water quality.

Sewerage infrastructure overflows and stormwater outfalls discharging into the Harbour

No published data has been found identifying sewage infrastructure overflows and stormwater outfalls. Indeed on the Ministry of Fisheries Interactive web mapping of New Zealand's marine environment and biodiversity, storm water outfalls from Porirua have not been included in the national data set. This is because the sewer system data were supplied but did not include outfalls, i.e. location of pipe junctions, overflow pipes etc. In some cases this was because the council did not have a coastal sewer outfall or it was not clear if an object was an outfall or not (NABIS no date). Porirua and Wellington City Councils have maps and GIS information on stormwater and sewerage infrastructure.

No information has been found regarding the effectiveness of steps taken to manage or minimise stormwater and sediment movement and contaminants in the Harbour.

Current knowledge of impacts of stormwater on the Porirua Harbour and catchment

The possible effects of stormwater discharge on the environment depend on both the quality of the stormwater and on the characteristics of the receiving environment. Urban stormwater in the Greater Wellington area contains a wide range of contaminants, including heavy metals, PAHs and organochloride pesticides (OCPs) (Milne and Croucher 2005; Milne and Watts 2008). Concentrations of pollutants found in stormwater of the Wellington region are generally similar to stormwater in other New Zealand studies (KM 2005). Recent analysis of pollutants from stormwater outfalls in the Porirua Harbour catchment has given us sufficient information to indicate that stormwater is adversely impacting on water and sediment quality in the catchment.

The entrance to Porirua Stream and the southern end of the Onepoto Arm receives inputs from drains at Semple Street and Te Hiko Street. It commonly has high counts of enterococci bacteria (Berry 1997a, 1999; Stephenson 2001), and a dense covering of macroalgae (Stevens and Robertson 2008) which suggests a high nutrient input.

Concentrations of zinc, lead and copper are especially high in the vicinity of Porirua CBD, pointing to both the Porirua Stream and the city stormwater as a source of these contaminants (Glasby et al. 1990; Stephenson and Mills 2006; Sorenson and Milne 2009). Sampling of marine sediments in Porirua Harbour in 2004 identified elevated concentrations of heavy metals in some harbour sediments, particularly those located in close proximity to stream and stormwater outfalls (Milne and Croucher 2005). An analysis of the spatial distribution of sediment contaminants of the Onepoto Arm also identified the Semple St drain and Porirua Stream as significant sources of metal and PAH pollution. The Onepoto Stream, which drains an urban catchment, was also highlighted as contributing polluted stormwater to the Harbour (Sorenson and Milne 2009). Analysis of sediments for copper, lead and zinc in sediment showed that concentrations decreased with distance from the Semple St drain (Botherway and Gardner 2002).

Porirua Stream experiences a pulse of polluted water associated with rainfall events. Wet weather events result in high concentrations of zinc, copper, lead and chromium being delivered to the water column (Cameron 2001). This pollution explains the loss of sensitive macroinvertebrate taxa (MCI indicator species) from parts of Porirua Stream (Cameron 2001).

In Belmont Stream, the concentrations of metals (zinc, copper and lead) are below ANZECC guideline values. However, one site that receives stormwater input shows concentrations slightly elevated above the other sites monitored (BML 2004a).

Information regarding how stormwater is impacting local flora and fauna is more sparse. As mentioned above, it was concluded (Cameron 2001) that the pulse of poor water quality delivered to Porirua stream has adversely affected the macroinvertebrate community. Milne and Watt (2008) demonstrate exceedance of acute toxicity criteria at some sites. The composition of inter-tidal communities in the Onepoto Arm changes with distance from the Semple St drain, but it is unknown if this is caused by the influence of fresh water, stormwater pollutants or the scouring effect on bottom sediments (Botherway and Gardner 2002). Sorensen & Milne (2009) suggest the cause is stormwater contaminants.

Benthic ecology data from 2004 and 2005 show that although the total concentrations of several contaminants (notably DDT, zinc, and to a lesser extent copper and lead) are above sediment quality guidelines there is no clear evidence that any of the contaminants have resulted in significant adverse effects on the benthic ecology. There were no clear relationships between the composition of benthic community groups or presence of keystone species and increased concentration of contaminants (Stephenson and Mills 2006).

The quality of stormwater for the Greater Wellington Region has been assessed in terms of pollutant loads including sediment. Eleven sites were sampled in total, including Browns Stream, the Semple St drain and Duck Creek, but results were combined to highlight stormwater quality throughout the region. It was concluded that urban stormwater has the potential to contribute to sediment contamination through the deposition of suspended sediment in stormwater (KM 2005).

One study has been undertaken to specifically assess the impact of road transport on water quality. A drain at Tawa, which only collected runoff from a section of State Highway 1, was sampled during rainfall events (Sherriff 1998). The concentration of metals and PAHs was generally at low levels (when compared to urban run-off data) and suspended sediment content was very low. Contaminants from transport did not exceed ANZECC (2000) water quality guidelines, indicating no adverse impact on the local ecosystem. However, metal and PAH concentrations were closely associated with suspended sediment as they have a propensity to attach to sediment. There is a possibility that stormwater could deliver polluted suspended sediments to the receiving environment that may accumulate in depositional areas (Sherriff 1998).

This information indicates that stormwater is adversely impacting on water and sediment quality. However, analysis of the pollutant loads from stormwater outfalls in Porirua Harbour has not been extensive, with only a narrow range of temporal or spatial scales being covered. For example, the KM (2005) study only covered a few outfalls in the harbour, and only sampled one event. Stormwater pollution undergoes significant temporal variation, often with the nature of a rainfall event. A full picture as to the quality of stormwater would need to sample a greater number and range of rainfall events. The possible impacts on flora and fauna are also unclear, i.e. it is not known if there are negative biological effects occurring within the Harbour caused by polluted stormwater.

Sediment and nutrient transport

Catchment erosion and inputs to streams

The topography of the Porirua catchment is varied (Figure 1), giving rise to unequally distributed potential for erosion. Slopes are generally steepest in the north and east of the catchment. Nearly 30% of the slopes in the Pauatahanui catchment are more than 25º (BML 2000; Handford no date), especially slopes in the upper Horokiri, Kakaho and Pauatahanui sub-catchments. Most of the steepest slopes in the Porirua Stream catchment are below the highest peaks on the western and eastern edges of the catchment (Blaschke et al. 2009). Elsewhere in the catchment, because of generally gentle slopes and the moderately- to well-drained soils, erosion risk is generally low. The silt and clay loam soils, however, are easily mobilised by wind and rain once their vegetation cover is removed, making their way into streams and damaging freshwater and marine ecosystems. It is estimated that a typical hilly subdivision site in the Wellington region, once cleared of vegetation, could lose up to one thousand tonnes of soil per hectare per year (GWRC 2006).

Although there is evidence of catchment erosion and movement of sediments downstream to the Harbour (outlined below), there is very little literature regarding the amount and quality of sediments delivered from the catchments to the streams. Some information on areas of erosion in the Wellington region up to 1990 is available from the New Zealand Land Resource Inventory Page (1995). This information for the Pauatahanui catchment was summarised in BML (2000. There has been no assessment of erosion since the New Zealand Land Resource Inventory, and no assessment for other parts of the Porirua Harbour. The percentage of erosion per sub-catchment was also assessed by BML (2000, section 5.1), and shows some variation between sub-catchments. There is no estimation of the per hectare sediment run off under varying catchment covers.

There is generalised information on the movement of nutrients or contaminants from the catchment into streams. Nitrogen and phosphorus inputs from streams into Pauatahanui Inlet were assessed as part of the PEP study. Yields of nutrients per unit area did not differ between rural and developed catchments (Healy 1980). Nutrient inputs from varying catchment covers has not been assessed in the Onepoto Arm or assessed in Pauatahanui since the PEP study. Because of the aerobically decomposed nature of DDT found in catchment streams, it is evident that the DDT is sourced from eroded soils (Cameron 2001; Milne et al. 2004; Croucher and Milne 2005; Milne and Croucher 2005, Milne and Watts 2008). However, the location of DDT in catchment soils and the nature and quantity of its transportation into local streams is unknown. The movement of other contaminants (metals or other organic pollutants) is unknown.

Sediment transport and delivery to the Harbour

Streams act as a transport mechanism for water, sediments, nutrients and contaminants. However, streams can also store some of the sediments delivered to them from the catchment, and then deliver a proportion of these inputs to the downstream estuary. There is no literature concerning the sediment carrying capacity of streams in the catchment, nor of the in-stream sediment generation. There is no specific information on the percentage of hill-slopes or stream lengths in different catchments undergoing erosion, although there is recent information on slope distribution and land use in the Pauatahanui Inlet catchment which gives some idea of potential erosion (Handford, no date).

The movement of sediment within Porirua Stream has been touched on in terms of gravel accumulation. Since flood protection works commenced in the 1960s, Porirua Stream has experienced a large amount of gravel accumulation. Between 1996 and 2000, over 2,000m^3 of gravel accumulated (WRC 2001). It was estimated that the future rate of gravel supply will occur at a rate of 520m^3/yr. Most excavation has taken place in the lower reaches of the Kenepuru Stream in naturally depressed areas where gravel was infilling pools in the stream (WRC 2001). It is probable that gravel is accumulating as a response to the flood protection works, but further information on the gravel source, the flow rate and the ability of the stream to adjust its morphology is needed.

Some information on the amount and type of sediments that are delivered to the Harbour from various catchments is available, but this information is ad hoc and does not provide a consistent picture of sediment in the whole catchment. Pauatahanui, Horokiri and Kakaho streams on average deliver around 500 mg/litre of sediment to Pauatahanui Inlet. During residential development in the Browns Stream catchment in the 1970s, one flood in July 1976 deposited 1600 tonnes/day of suspended sediment, which was 35 times that delivered by the Ration catchment and 22% of the total sediment delivered to the catchment. The sediment sourced from Browns Bay has a higher silt content than other sources (Curry 1981, in: Swales et al. 2005a). The sediment load delivered from individual streams into Pauatahanui Inlet has not been remeasured since the PEP study[24] and no information of this type is available for the Porirua catchment.

Two recent studies provide detailed information regarding the amount of sediments accumulating in Pauatahanui Inlet. In the first of these studies (Swales et al. 2005a), average sediment accumulation rates (SAR) for Pauatahanui Inlet were calculated from isotope and pollen dating of five sediment cores. Results from these cores showed a significant increase in SAR since European deforestation and a rise in SAR ever since that time. Changes in SAR, averaged over the whole inlet, are summarised in the following phases:

- Last 2,000 years. SAR at ~0.7 mm/yr.

[24] The detailed study of Swales et al (2005a) examined the accumulation of sediments in the Inlet, not the contribution of individual parts of the catchments.

- Post 1850. SAR ~2.0-2.4 mm/yr, (including whole time of European settlement and deforestation of the catchment).
- Post 1950. SAR ~3.1-3.7 mm/yr, (including most time of urban development around the Inlet and ongoing rural activity).
- Post 1985. SAR ~ 4.6 mm/yr (including most recent urban development around the Inlet and ongoing rural activity including pine afforestation).

From 1950 onwards, cores taken near sub-catchment outlets have higher SAR than those of the central mud basin. This indicates not only that the sediment source is the catchment, but also that the supply rate has exceeded the ability of estuarine processes to redistribute sediment (Swales et al. 2005a). The infill of Pauatahanui Inlet can be described as a progradation and build up of stream deltas into the Inlet, and a slower accumulation of sediments in the central basin.

Monthly monitoring of changes in bed level at Pauatahanui in the late 1970s showed a mean accretion of 2.9 mm/yr, but with many fluctuations (Pickrill 1979). This value is similar, but slightly less than the 3.1-3.7 mm/yr estimated from cores for the post-1950 period by Swales et al. (2005a). Monthly changes in bed level highlighted that sediment accumulation is not a steady process, but is characterised by periods of erosion and accretion (Pickrill 1979).

Previous depth surveys were analysed in detail by Gibb and Cox (2009) in the second recent study. They studied the pattern and rate of sedimentation on the Porirua Harbour seafloor over the last 160 years, based on a comparison of hydrographic surveys made between 1849 and 2009. Detailed comparison of the surveys of 1974 and 2009 suggested that both arms of the Harbour have progressively shallowed from deposition of mud and sand, despite the offset of recent sea-level rises. Since forest clearance and land development began, rates of sedimentation have progressively increased. Between 1974 and 2009, they increased to 5.7 mm/yr in the Onepoto Arm and 9.1 mm/yr in the Pauatahanui Inlet. The tidal prism reduced by 1.7% and 8.7% respectively during that time. Gibb and Cox suggested that at current deposition rates Pauatahanui Inlet will have ceased to exist as an estuary within 145-195 years and Onepoto Arm within 290-390 years.

The two recent sedimentation studies both conclude that there has been a progressive increase in sediment accumulation rate (SAR) since European settlement, including a continuing increase in the last 25 years[25]. Current sedimentation rates are several times greater than historical rates and if continued will result in the infill of the Porirua Harbour much sooner than would have occurred naturally. SAR will almost certainly continue to increase at much higher than background rates into the future under current trends. Both studies also show there was a significant pulse of sedimentation in the Pauatahanui Inlet

[25] It should be understood that SAR presented in both studies are averages which may be influenced by the choice of time period over which the average is calculated. Also, because of the inherent limitations in the techniques used, both studies (especially that of Gibbs and Cox) have a limited ability to provide confidence limits for their estimates of SAR.

after urban development in the Browns Bay catchment in the 1970s, but the rate of sedimentation from this source has decreased. The studies differ in their conclusions about the rate of deposition, Gibb and Cox's results showing almost twice the rate of SAR for the last two to three decades. This difference is accentuated by allowance for local sea level rise (LSLR). Gibb and Cox's rates integrate LSLR, but the rates in Swales et al (2005a) are offset by corrected average LSLR of 1.5mm/yr. Net SAR differences could also be accentuated by different conclusions of the rate of uplift in the Pauatahanui Inlet (see earlier notes on uplift rates). Hence there is a significant difference in the net calculated effective SAR. These differences flow into different calculations of the available tidal prism and sediment yields.

Both studies also address the way in which Pauatahanui Inlet hydrodynamics influence sediment accumulation. Note that both studies only address a proportion of the sediments delivered to the Inlet, as a large proportion is lost from the system through tidal flushing, as discussed below. Both reports show that there is a significant amount of flushing and re-distribution of sediments in Pauatahanui Inlet and considerable spatial variability in the processes and rates of sedimentation in the Inlet. However, the pattern of variability mapped in the two studies shows very little resemblance.

There is considerable uncertainty about the potential influence of a rising sea level. Further, it is the natural evolution of an estuary to infill over time, with the extension and development of bayhead deltas and central basin infill, which eventually creates a coastal plain (Roy 1984). The sedimentation risk is described only as moderate (Stevens and Robertson 2008; Milne 2008). Such considerations do not negate the fact that anthropogenic uses of the catchment have significantly increased sediment input to the Harbour, and should be prevented or reduced as much as possible. Stevens and Robertson (2008) have recommended that habitat monitoring should include an expanded network of intertidal and subtidal sediment plates in to provide another measure of sedimentation.

In the 2004 sediment samples, Browns Bay still had a high sedimentation rate compared with its catchment size, even though the documented previously high sedimentation rates (Healy 1980) have declined since the phase of active urban development in the 1970s. This suggests that the area is a sink for sediment sourced elsewhere (Swales et al. 2005a). Sediments in Browns Bay are predominantly fine clay, contrasting with coarser sediments from elsewhere in the Inlet. These sediments are most likely sourced from 1970s residential development (Healy 1980). Sediments sourced from Duck Creek catchment are delivered to the Harbour in a flood; the bulk of sand and some mud are deposited on the subtidal flat near the Duck Creek catchment outlet. Waves can re-suspend this fine sediment and relocate it elsewhere, as in 1974 where 5 cm was deposited from Duck Creek into Browns Bay (Swales et al. 2005a).

It has been inferred from the broad, shallow nature of Porirua Stream as it enters the harbour, and the lack of channels or associated depositional banks or levees, that the sediment load of the stream is low (Williamson et al 2004). However, the sediment input of the stream has not been quantified at any time, and now the presence of flood control measures on the lower stream will probably have changed sediment delivery processes and rates. A study of sediment origin, transport and delivery would shed light on the nature, place of origin and rate of the gravel accumulation, indicating if this process is occurring at an increased modern rate, and whether it is a new human-influenced processes. A relatively simple analysis of depth and distribution of the gravels would help to highlight some of these issues.

In summary, there is only a limited (and dated) amount of information about how much sediment is delivered to the Harbour. The processes and rates of accumulation in Pauatahanui Inlet are now well understood, but not those of Onepoto Arm.

In terms of delivery of pollutants to the Harbour, the transport of DDT residues found in the sediments of Porirua Harbour was discussed in earlier sections. The likely source of most DDT residues is agricultural soils (Milne et al. 2004; Williamson et al. 2005, in: Swales et al. 2005a). Studies of stream sediment quality showing concentrations of DDT above ANZECC ISGQ ‘low’ values (Croucher and Milne 2005, Milne and Watts 2008) suggest that the DDT-contaminated sediments in the Harbour are predominantly transported there by streams. However, there is no quantification of relative stream contributions to the Harbour totals.

There is no information about the movement of other contaminants (such as heavy metals) from the streams to the Harbour, nor on the movement of nutrients from the streams into the Harbour. The characteristics of DDT contamination movement are known, but have not been quantified.

Estuarine inputs and Harbour discharge

Sediment can be moved by a variety of process into, out of, and around the Harbour. The major sediment sources for the Harbour are: the sea floor and coast outside the harbour, moved by flood tide and wave action; and the contributing catchments. Sediment is also moved along the floor of the estuaries on the flood and ebb tides (Stirling 1983). The top 5 cm of sediment undergoes extensive mixing and reworking by physical (wind waves) and biological (faunal burrows) processes. Waves often resuspend estuarine sediment (Swales et al. 2005a). As discussed elsewhere, there is very limited information on the movement of contaminants around the Harbour.

Some information for Pauatahanui Inlet is available concerning the amount of sediment delivered in a flood event which is lost to the open coast. It was estimated that, overall, around 70% of sediment coming into Pauatahanui Inlet is later flushed from the inlet (Pickrill 1979). From two individual monitored storm events in the 1970s, around 20% of the 3300 tonnes of sediment delivered to Pauatahanui Inlet was flushed from the Inlet (Healy 1980). However, since the PEP study there has been no quantification of the amount of fluvially-delivered sediment which moves through the Harbour to the open coast. Catchment land use changes and Harbour shallowing may have altered the proportion that is flushed from the Harbour.

In the Onepoto Arm, the dominant wind blows down the length of the harbour and is likely to cause a considerable reworking of sediments. It is likely that a significant proportion of finer sediment deposited at the south end is reworked and redeposited in the central mud basin or lost to the open coast (Williamson et al. 2004). This has been inferred by the prevalence of sand at the southern end of Onepoto Arm, but has not been verified or quantified.

There is no known information concerning the possibility of erosion of deposited Harbour sediment being redistributed to the coast by tides. As such, there is no quantification of the net movement of sediment out of the Harbour. Sediment movement out of the Onepoto Arm has not been quantified, in terms of either the net movement or from flood event delivery.

There is no known information on the movement of nutrients or contaminants from the Harbour to the open coast.

The relationship between sedimentation and Harbour hydrodynamics

Pickrill (1979) found that most intertidal surfaces in Pauatahanui Inlet were stable, with most cross sectional profiles oscillating around zero change. There was a mean rate of deposition of 2.9mm/yr. Irwin (1976) found that the position and shape of the banks and main channel within Pauatahanui Inlet had generally remained very stable. There is no more recent detailed study.

As discussed in a previous section, storm events do not appear to significantly change Pauatahanui Inlet bathymetry (Pickrill 1979). The lack of change indicates that sediment from storms is delivered elsewhere, or is lost to the system. It was estimated that of the suspended sediment delivered to the system, probably around two thirds is delivered to the sea, while one third stays within the Inlet.

In Pickrill's study the bed morphology of Pauatahanui Inlet was monitored at monthly intervals, revealing that the surface undergoes erosion and accretion, with most surface changes involving only the top 2 mm of sediment. Swales et al (2005a) found rapid mixing of surficial sediments (<5cm) by physical and chemical processes, and deeper and more gradual sediment mixing by bioturbation over periods of years to decades. The intertidal surfaces appeared to be stable, while bayhead deltas and beaches at high tide underwent a greater rate of change (Irwin 1976). The effect of these changes on hydrodynamics is unknown. For the Onepoto Arm, no information is available on either bed morphology stability or the effect on hydrodynamics.

Climate change and sea level rise

Predicted changes and sea-level rise characteristics for the Harbour catchment

Expected impacts of a higher sea level include dune erosion, increased hazard from storm events, flooding of lowland areas and beach recession (IPCC 2007). The changes in global sea level that have occurred in the recent past and projections of future sea-level rise trends up to the year 2099 are summarised in recent reports from the Intergovernmental Panel on Climate Change (IPCC) (Bindoff et al. 2007). The average global rise for the entire 20th century was 1.7 ± 0.5 mm/year. More recent satellite records of sea level change from 1993 to 2003 give a higher average rate of rise of 3.1 ± 0.7 mm/year. A mid-range emission scenario for global sea-level rise (A1B) predicts rates of 4 mm/year, with global sea level reaching 0.22–0.44 m above 1990 levels by 2090–2099. This rate excludes rapid melt of glaciers, and accounts mainly for thermal expansion of oceans (IPCC 2007).

Sea level has been monitored at Wellington since 1891 (Dawe 2007). The monitored rate of sea-level rise at Wellington is 1.8 mm/yr (Swales et al. 2005a). Based on the calculated regional uplift for Pauatahanui (maximum 0.3 mm/yr) and the monitored sea level rise at Wellington (1.8 mm/yr), the relative sea-level rise is 1.5 mm/yr (Swales et al. 2005a). Gibb and Cox (2009) adopt a higher relative sea-level rise of 1.95 mm/yr for their calculation of sedimentation between 1849 and 2009.

Within this climate-induced sea-level rise, there is significant decadal variability. In the southern hemisphere sea level is strongly affected by El Nino Southern Oscillation (ENSO) fluctuations. For example, ENSO-driven variations in mean sea level occurred at the Port of Auckland during 1999–2000 when sea level rose 50–75 mm (Kennedy 2008).

Other factors that can influence local sea level include tidal fluctuations and storm surge. An 18.6 year tide cycle produces what is known as the highest astronomical tide (HAT). The next HAT is forecast to occur in Wellington on 10 April 2012, causing high tides up to 20cm higher than mean high water springs, on this date and in the months leading up to and proceeding this date (Dawe 2007). Storm surge results from a combination of three factors: wind set-up, wave set-up and barometric lift.

In the Wellington region storm surge is most commonly associated with southerly storms and ex-tropical cyclones that bring with them strong winds, large waves and low air pressure. The Wahine storm (an ex-tropical cyclone) of 1968 and the southerly storm of 1976 produced storm surges in exposed areas in the order of 0.8-1.0 m, and a storm tide of 0.72 m above normal High Water observed in Pauatahanui Inlet (Gibb 1978). NIWA has presented unpublished information about a large storm recorded in Wellington during 1936 that produced a storm surge in the order of ~1.20 m. These storms are all recognised as being 1:100 year events. If a similar magnitude storm occurred on high tide in Pauatahanui Inlet it could elevate water levels to around 1.5 m above MSL (Dawe 2007).

Table 6 Summary of future mean water level indices for Porirua Harbour coast using measured and projected sea level rise rates (Dawe 2007)

Projection	Date	Sea Level Rise (m)	Mean High Water Mark (m)	Highest Astronomical Tide (m)
	Present	---	0.700	0.890
Measured linear	2012	0.009	0.709	---
Measured linear	2050	0.077	0.777	---
Measured linear	2100	0.166	0.866	---
Satellite Accelerated	2100	0.30	1.00	---
IPCC – low	2100	0.18-0.38	0.88-1.08	---
IPCC – mid	2100	0.21-0.48	0.91-1.18	---
IPCC – high	2100	0.26-0.59	0.96-1.29	---

Likely impact of predicted climate change and sea-level rise on the Harbour and catchment

The potential impacts of sea level rise are difficult to assess, as there is no information regarding current storm surge, or tidal oscillation heights around the Porirua Harbour. To be able to predict the impact of a storm surge or a king tide under a higher sea level, it is necessary to have information on the effects of those processes at present. There is no known information on the impact of sea-level rise on rocky coast habitats, the physical dynamics of the Harbour (such as tidal exchange or flooding events), or coastal erosion.

The documented increase in sediment accumulation in the Pauatahanui Inlet (see discussion above) is a function not only of increased sediment delivery, but also of changes in accommodation space for the sediment, as sea level changes. Characteristically New Zealand estuaries infill quickly, after which sediment bypasses the system and is delivered to the open coast (see next section). The current SAR cannot continue indefinitely, as once accommodation space has been filled, sediments will be flushed elsewhere. Sea-level rise will increase the amount of accommodation space available. Sea level has been rising 1.8 mm/yr over the last century in Wellington, giving a total rise at present of 19 cm (Swales et al. 2005a). This provides a significant increase in accommodation space for sediments. A greater accommodation space means that a higher SAR is possible instead of sediments being lost to the system. Hence the measured increase in SAR may also be a consequence of the Harbour being able to store more sediment from the catchment (rather than it being lost to the Harbour), as well as a response to greater sediment supply from the catchment. This could continue, or even accelerate, under future sea level rise. However, Gibbs and Cox's (2009) calculations of net SAR take both sedimentation and sea level rise into account.

Gibb (1993) predicted that the current rate of erosion at Ngatitoa Domain would increase under a higher sea level rise. However, estimates of the rate of erosion increase have not been made.

Stevens and Robertson (2008) have argued that the salt marsh vegetation will suffer from 'coastal squeeze' with a rising sea level. As most of the Harbour is bounded by artificial structures and there is often a physical separation between the terrestrial buffer and the Harbour, salt marsh vegetation is essentially hemmed between the water and artificial boundaries. A rising sea level may 'squeeze' this habitat, as salt marsh can not migrate landward in response to increased inundation.

International literature has shown a landward movement of salt marsh species that can tolerate grater levels of inundation, and hence a decrease in habitat size of less inundation-tolerant species. However, some studies indicate that salt marsh species are able to keep pace with sea-level rise, by means of vertical sediment accretion (Reed 1990). The response of a marsh to sea-level rise varies according to local conditions reflecting the local supply of organic (sourced from the marsh) or inorganic (sediments from the catchment) sediment supply (Reed 1990). As long as marsh accretion rates can keep pace with sea-level rise, and the rate of rise is not too quick for marsh plants to respond, 'coastal squeeze' may not occur. The process of vertical sediment accretion has not been investigated at Porirua Harbour, where, in any case, salt marsh habitat appears to be under threat from wave-driven erosion, as well as from rising sea level (EMS and Blaschke 2008).

It would be useful to determine rates of salt marsh accretion or retreat in Porirua Harbour (which can be done by isotopic analysis) to determine the current rate of marsh accretion, and to investigate whether salt march species are keeping pace with the rising local sea-level trend.

Summary of relevant New Zealand soil erosion literature and knowledge

Catchment erosion and sedimentation

Catchment land use practices heavily influence the sediment load, water quality and nutrient export loads to streams and ultimately the downstream estuary. The natural background characteristics, such as soil type, geology, slope steepness and climate will also influence the rate and characteristics of erosion and nutrient and sediment export to streams. In this chapter we summarise highlights of recent literature on soil erosion, sedimentation and catchment studies in New Zealand that are relevant to processes occurring in the Porirua Harbour and its catchments. Recent relevant New Zealand reviews include those of Blaschke et al. (2007), Maclaren (1996) and Fahey et al. (2004).

As most of the Porirua Harbour catchment is composed of greywacke it likely that the dominant erosion types will be cumulative surface processes (sheet erosion, shallow landslides etc) and fluvial erosion processes (gully and streambank erosion etc) (BML 2000). However, parts of the catchment are also composed of quaternary sediments and have a loess cover. Loess has a significant erosion potential with loess deposits on the Banks Peninsula experiencing severe tunnel erosion (Hughes 1972). There has been no recent information on loess erosion, and very little published information on the typical erosion patterns of loess in the North Island. It can only be surmised that given the significant amount of erosion and deposition from the Whitby area (and subsequent deposition in Browns Bay) (Healy 1980), the loess deposits in Pauatahanui Inlet are prone to erosion once disturbed.

The influence of catchment land use on water quality, habitat, periphyton, benthic invertebrates, and sediment and nutrient export, was studied for the tributaries of the Waipa River, near Hamilton (Quinn et al. 1997; Quinn and Stroud 2002). This area is comparable to the Porirua Harbour catchment as it is dominated by a similar rock type (sedimentary sandstones and siltstones, greywacke and argillite), although some volcanic ash deposits are present in the study area. Streams draining native forest had lower temperature, sediment and nutrient concentrations, algal biomass, and higher water clarity than those draining pine forest and pasture (Quinn et al. 1997; Quinn and Stroud 2002). Streams draining pasture had sediment loads between 100 and 320 tonnes per square kilometre per year ($t/km^2/yr$) compared to native vegetation which yielded 30 $t/km^2/yr$. Streams draining pasture also showed the greatest variation in water quality attributes in relation to changes in season or flow (Quinn and Stroud 2002). Interestingly, invertebrate taxa richness did not differ between land uses but community composition did differ. Streams draining pasture were dominated by chironomids and snails at high densities, while mayflies, stoneflies and caddisflies were the most dominant in native streams (Quinn et al 1997). In terms of sediment and nutrient input to streams, pastoral land use contributes higher loads than pine and native forest plantations (Quinn et al. 1997; Quinn and Stroud 2002).

Comparable land use impacts were found in the Avon-Heathcote estuary in Canterbury. Sediment yields were least for partly forested rural land use (40 t/km^2/yr), higher for mature residential urban use (70 t/km^2/yr) and were highest for unforested rural land use (320 t/km^2/yr) (Hicks 1993). The higher yield from the unforested catchment reflects historical erosion problems associated with replacement of the natural vegetation, overgrazing, burning and animal pest influences. New urban subdivisions on hill spurs, and market gardening areas are expected to yield more sediment per unit area than are undisturbed rural or mature residential catchments. Quarries also yielded large amounts of sediment. However, all these land effects were overridden by the location of an area – whether on hill or flat land - with yields from hill country being several times higher (BML 2000).

The impact catchment land use has on fish species has only been touched upon in the literature, with most changes in fish distribution attributed to changes in physical in-stream habitat (such as channel depth, width, etc) (Jowett et al 1996). Fish may be adversely impacted in pasture catchments due to the decrease in stream shade, and increases in suspended sediment (Ryan 1991; McIntosh and McDowall 2004). It is notable that a recent national review of the effects of land use on coastal fisheries (Morrison et al 2008) drew strong conclusions about the potential for adverse land use effects (such as have been reviewed for Porirua Harbour in the present report) on various aspects of the fisheries, but drew no material from the Porirua Harbour, even though it is thought to be an important North Island nursery area.

Suspended sediments have many impacts on New Zealand streams. Suspended sediments can decrease primary productivity, increase the drift fauna, or reduce habitat for fish and invertebrates, and thus may reduce benthic fauna densities as well as alter community structure. Fish community structure may also alter in response to interferences to run-riffle-pool sequences (Ryan 1991; McIntosh and McDowall 2004). Excessive levels of nutrients in both streams and estuaries can cause symptoms of eutrophication such as nuisance algal blooms (MFE 1992; Biggs 2000).

The downstream effects on estuaries of increased erosion and suspended sediment input have been determined for a number of estuaries in New Zealand. Increased sediment delivery has led to increased sediment accumulation rates. Typically SAR are <1 mm/yr under native land cover, and increase to several mm/yr following European settlement (Hume and Gibb 1987; Goff 1997; Swales et al. 2002; Fahey et al. 2004). Whaingaroa (Raglan) Harbour is probably the New Zealand estuary which is most comparable to Porirua Harbour and was identified as such in the BML (2000) review of Pauatahanui Inlet. The climates of both are similar, being similarly exposed to the west rather than eastern ex-tropical cyclonic storms, but Whaingaroa is somewhat warmer and wetter. Both estuaries are predominantly steep and drain catchments containing greywacke although Whaingaroa varies in that it is partly composed of volcanic rocks.

Whaingaroa Harbour experienced very rapid sedimentation, with all but the top 2 m of sediment deposited before 6,000 years BP (Swales et al. 2005b). In the Waitetuna Arm, the pre human SAR was 0.5mm/yr. However, corresponding to catchment deforestation, from 1890 onwards the SAR increased to 1.1 mm/yr, later increased to 2.5 mm/yr and by the 1990s had reached 8 mm/yr (Swales et al. 2005b). This recent rate of sediment deposition is much higher than Swales et al (2005a) recorded for the post-1985 period at Pauatahanui Inlet.

In the Waingaro Arm of Whaingaroa Harbour, sediment has not been deposited for the last 150 years, and probably longer. Because of the shallowness of the estuary, the small, short period waves initiated by prevailing southwesterly winds initiate are able to resuspend and remobilise tidal flat sediments, with the result that these sediments leave the harbour; its trapping efficiency is therefore lower now than in prehistory. These processes have been observed in other New Zealand estuaries, as mud is winnowed from tidal flats and redeposited in low energy fringing marshes and tidal creeks (Swales et al. 2005b). They have also been described in Pauatahanui Inlet, with sediment being winnowed from Duck Creek bayhead delta and redeposited in Browns Bay (Swales et al. 2005a), and localised erosion being observed on various parts of the shoreline (EMS and Blaschke 2008). Areas that are less exposed to wave action (i.e. they are sheltered) are more susceptible to the effects of future changes in the quantity and type of sediment runoff associated with human activities (Swales et al. 2005b).

Catchment use in Whaingaroa is dominantly rural, native forest or exotic pine plantation, with minor residential areas. Because of Porirua Harbour's exposure to a major arterial road and significant urban development, comparison with more urbanised estuaries such as the Avon-Heathcote estuary, or Pakuranga estuary is also appropriate.

Pakuranga Estuary is a small urban estuary in Auckland. For most of its history this estuary infilled slowly (0.2-0.5 mm/yr). Catchment deforestation and subsequent agricultural land use increased sediment accumulation to 0.8-1.6 mm/yr, lower than for many New Zealand agricultural sedimentation rates because of much gentler slopes. Urbanisation has accelerated estuary infilling overall, but sedimentation is not constant across the various subtidal environments, with the upper estuary bayhead deltas accumulating at a greater rate (32.6 mm/yr) than the lower estuary rate (1.7-3.8 mm/yr), which is comparable to that of a central mud basin (Swales et al. 2002).

Sediment delivery to the Pakuranga estuary has occurred in pulses that coincide with peaks in urban construction (rather than with years of higher than average rainfall). Urbanisation was particularly intense during the late 1960s and late 1980s, with one third of the total catchment sediment load between 1953-1995 being delivered to the estuary in the last decade of that period. Urbanisation has resulted in a three-fold increase in soil erosion over that estimated for the catchment under 100% pasture (Swales et al. 2002). This contrasts with Porirua Harbour sedimentation where because of the steep greywacke topography, erosion rates under pasture are much higher.

In the Avon-Heathcote estuary, where the catchment is mainly flat, urbanisation has led to a widespread deposition of a 30cm thick layer of muddy sediment (Macpherson 1979).

In Pakuranga urbanisation also resulted in the deposition of finer-grained material than under the previous land use cover (Swales et al. 2002).

Urbanisation has brought about substantial environmental changes in the upper Pakuranga Estuary through the continued infilling of shallow, intertidal areas (Swales 2002). Tidal creeks (or bayhead delta areas) at the heads of these estuaries are particularly susceptible to rapid sedimentation due to their close proximity to the catchment outlet and small volume (Swales et al. 2002). The ultimate fate of sediments and contaminants in Auckland's estuaries is uncertain because the estuaries are largely infilled, and therefore a larger proportion of catchment sediment inputs from contributing streams is not being trapped in the estuary but transported straight to the open coast (Swales et al. 2002).

Therefore, results from these northern estuaries may not be applicable to Porirua Harbour as the latter is largely subtidal, rather than intertidal (Stevens and Robertson 2008). Porirua Harbour may need to become infilled to the current intertidal level before such extreme uncoupling of sedimentation environments occurs. However there is already some separation between sedimentation rates at bayhead deltas and the central mud basin (Swales et al. 2005a). The effects of different catchment characteristics such as slope and rock and soil type must also be brought in any comparisons.

In summary, the Whaingaroa, Avon-Heathcote, and Pakuranga estuaries are comparable examples that give some good indications of the impacts of sedimentation on New Zealand estuaries, under different land uses. Sedimentation is likely to increase under pastoral land use, and is likely to further increase as urban areas are being developed. It is important to note that Porirua Harbour is dominantly subtidal, unlike most New Zealand estuaries which empty almost completely at low tide (Stevens and Robertson 2008), and this may influence SAR and affect these comparisons, since differences in hydrodynamics may affect sedimentation.

Methods for assessing estuarine health

We suggest there are four key issues in regards to monitoring estuary health: sedimentation; loss or fragmentation of estuary vegetation; biodiversity; and pollution and eutrophication.

Knowledge of sedimentation rates is important in order to understand sedimentation effects on an estuary and its biota. Increased sedimentation rates can signal to management that erosion issues in the catchment need to be addressed. An understanding of long term sediment rates (such as the studies by Swales et al. 2005a and Gibb and Cox 2009) is useful to put modern sedimentation in context. Modern rates can be measured using a variety of methods, such as sedimentation plates, stakes and marker layers (Kennedy and Woods 2008). Effects of sedimentation on ecosystem properties requires more complex investigation, including the documentation of ecological changes such as a shift in habitat type or species composition from pollution-sensitive to pollution-tolerant species or assemblages.

Changes in biodiversity and the spatial distribution of estuarine vegetation can identify loss of key species or the degradation of habitat. Measuring the extent of saltmarsh and seagrass habitat, as done recently in the Harbour by Stevens and Robertson (2006, 2008) is a useful measure as loss or fragmentation of vegetation equals a decline in habitat area and quality, which should be addressed to maintain estuary health. An assessment of the health of vegetation (such as percentage cover, or burial by sediment) can also give a warning if that vegetation is under stress.

Biodiversity assessments give an important overview of species diversity and abundance within the various habitats of an estuary. Changes in species composition or abundance over time can indicate if the habitat of an estuary is changing, especially if sensitive species are lost.

Assessment of pollution levels is useful to assess potential toxic effects on biota and human health, as well as to determine the need for upstream catchment management to control inputs. However, most water quality parameters are not particularly useful to assess the overall environmental health of an estuary. This is because the large fluctuations caused by tides or freshwater inputs will dominate any samples collected, and under many conditions pollutants are likely to be diluted below detection levels.

In contrast, assessing toxicity in the sediments gives a good indication of pollution, and provides a longer pollution record. Analysis of the concentration of metals, PAHs and organochlorides gives a good indication of pollution. However, total metal content is not indicative of pollution unless corrected for against a background (Alloway and Ayres 1993). Once corrected, total metal content gives the total amount of pollution, but not the bioavailable fraction. "Total metals" gives an indication of possible pollution, but cannot show definite adverse impacts on specific species of biota. For the latter, *bioavaiable* content assesses the amount of pollutants which have the potential to adversely impact biota.

Assessment of some parameter of the fauna (abundance, biomass etc), rather than measuring the pollutants themselves, potentially provides a more direct method to indicate if changes in the environment are causing an adverse ecological impact.

Eutrophication issues are difficult to monitor. Measuring the concentration of nutrients in the water column is not particularly useful in determining eutrophication, as increased nutrient content may not be indicative of an algal bloom. The same issues of dilution and tidal fluxes altering concentrations as outlined above also apply. In our opinion, a better indication of eutrophication is to measure chlorophyll-a concentrations. This measures the amount of algae present in the water column, and thereby assesses if nutrients are having an adverse impact. A simpler but less precise measure is to assess the presence of nuisance algae cover.

Integrated catchment management studies

Developing effective management actions on a catchment basis requires that any actions are linked to an understanding of ecology and environmental system processes, and also that they have community endorsement. "Integrated catchment management" is a framework for assessing water quality in streams, rivers and estuaries using a catchment-wide approach (Bowden et al. 2004; Atkinson et al 2009). Primarily it is based on the concept that issues in the estuary or stream (i.e. the receiving environments) cannot be properly rectified without management of the catchment. It is also based on having strong iterative consultation processes and involvement with stakeholders. Scientific studies proceed after discussion with stakeholders to identify what to study, to justify why such studies are important and to advise how these studies should proceed.

In the South Island, an intensive Integrated Catchment Management Plan (ICMP) is being undertaken in the Motueka Catchment. This plan arose mainly from the need to manage dwindling water resources, in the face of potentially conflicting land uses (Bowden et al. 2004). However, the plan was extended to other important issues including the effects of land use on in-stream values and the cumulative effects of land and river management practices on coastal processes and values (Bowden et al. 2004).

Successful ICM plans in Australia have recognised that participation and leadership from the community are key issues in successful outcomes (GLC 2006). In the major oyster-growing regions (Wallis Lakes, Clyde River and the Shoalhaven River) improvements in water quality have come about through the cooperation of dairy farmers and oyster growers (GLC 2006). This joint sectoral approach has also been sought in the Whaingaroa and Motueka catchments, specifically including estuary fishers.

We conclude that each catchment management plan for each estuary will be inherently different, as it will reflect not only the unique characteristics of the catchment, but also will address the issues and concepts that are of primary concern to stakeholders in that area. Thus it will have social and economic as well as biophysical contexts. For example, a particular issue for integrated catchment management in Porirua Harbour is the effects of the encircling of the Harbour by roading, and management responses to this factor. The effects of this extent of encirclement, which appears to be unique in New Zealand, and would be a major consideration in an ICM approach to the Harbour, do not appear to have received significant research attention, with the partial exception of the Sherriff's study (1998) of roading effects and Gardiner and Armstrong's review (2007) of the lower Onepoto Arm as a particularly sensitive receiving environment.

Conclusions and recommendations

What is the sum of our knowledge?

Pauatahanui Inlet and catchment

Our knowledge of Pauatahanui Inlet and catchment is considerably greater than that of the other parts of the Porirua Harbour system, as a result of the major research project in the 1970s (the PEP), the consolidation of that knowledge through the development of the Inlet Action Plan (PIAG 2000), the formation of the Pauatahanui Inlet Community Trust, the research review undertaken at that time (BML 2000) and the filling in of some of the gaps identified in that review.

Highlights in the increased knowledge and understanding gained since 2000 include:

- Intensive sediment survey using a variety of methods has given us detailed knowledge of past and current sedimentation rates (including a range of estimates).
- Cockle surveys have been carried on long enough to give us reasonable confidence about current population trends.
- Additional water quality results give us a better (although still patchy) understanding of the ambient condition of the estuarine environment and current water quality status and issues.
- Work on restoration principles and priorities has summarised catchment issues and established some of the linkages between headwaters and coastal portions of catchment, land and water, and different parts of the catchment. However, this work is based on incomplete knowledge and many assumptions.
- Surveys of plants, animals, pests and ecological sites provide a broad outline of their distribution in the catchment and harbour.

In spite of this progress, there are still major gaps in knowledge or areas where changes are likely to have occurred but not studied, as highlighted by discussion in previous sections. It should be remembered that the benchmark PEP studies are now 30 years old and it is dangerous to rely indefinitely on this information when we know that sedimentation rates have increased significantly and suspect that there are related changes in Inlet bottom topography, tidal prism and hydro-dynamic patterns.

Onepoto Arm and catchment

Research on the Onepoto Arm and its catchment has been much less than that on Pauatahanui Inlet and catchment but has increased significantly in the last five years, to the point that there is a reasonable amount of information available.

Highlights of our knowledge and understanding include:

- Water quality testing and sediment chemistry studies give us a patchy understanding of current water quality status and issues.
- We have some information on sedimentation and bathymetry.

- Flow readings, and limited modelling, give us a patchy understanding of current stormwater movement and management.
- Surveys of plants, animals, pests and ecological sites provide a broad outline of their distribution in the catchment and harbour.
- Stream studies give a limited knowledge of condition and trends in parts of the freshwater environment. There is a better knowledge of freshwater habitats than terrestrial or marine habitats.

Outer Porirua Harbour and catchment

Knowledge and understanding of this part of the Harbour and catchment is very limited, principally comprising:

- Surveys of plants, animals, pests and ecological sites provide a limited outline of their distribution in the catchment and harbour.
- Knowledge of geomorphic and uplift processes (Taupo catchment)

We also note, in relation to the whole Harbour and catchment, that there is no consolidated central collection of material pertaining to the Harbour and catchment, a situation that has required considerable bibliographic searching for this review. It would be desirable, as part of the Porirua Harbour and Catchment Management Programme, for Porirua City Council to gather and maintain a consolidated reference collection of all published and known unpublished reports on Porirua Harbour and catchment, to be made available for reference purposes to interested parties as appropriate.

Synthesis and conclusions from previous chapters

Physical setting

Due to the high level of faulting, the whole catchment has a significant earthquake hazard. The fault structure may also be one of the main drivers of environmental differences between the Onepoto Arm and the Pauatahanui Inlet, especially as a strong driver of the tidal flushing regime. A study of the geomorphic and historical differences between the two arms of the Porirua Harbour, and especially on the recent uplift history and the evolution of the flushing regime in the two arms, may help to reveal the historical and current drivers of significant environmental trends and issues, e.g. sedimentation trends, effects of rising sea levels, earthquake hazard, etc.

There are other fundamental and significant differences between the two main arms. Firstly there is a difference in orientation, (and hence exposure to coastal processes) with Pauatahanui Inlet facing west, and Onepoto Arm facing northeast. This difference may also influence flushing regimes and contribute to the differing characters of each arm. There is only one significant fluvial input into the Onepoto Arm, compared with several into Pauatahanui Inlet. This may influence flushing and pollutant movement, although to what extent is unknown. Onepoto Arm catchment is less steep and there are also important land use differences, with the Onepoto Arm catchment being more urbanised and having much less farming than the Pauatahanui Inlet catchment.

Both arms are in turn very different from the outer harbour. There are apparently fewer contemporary pressures on the outer Harbour; however, this information is based on limited knowledge.

These fundamental differences between the three main parts of the Harbour and catchment have important implications for management. It may not be necessary to understand all the drivers of these differences, but rather to accept that they are different. In management planning, they should not be directly compared in terms of estuarine health, nor treated as a single management unit. This does not negate the need for integrated planning, but such planning should be founded on the different nature of the resources, identifying different sections for management.

The consequences of high loess content in catchment soils may have been insufficiently appreciated by managers. In general, catchment soils are relatively erodible and mobile, but also have potential for suspension and re-suspension in water, both in freshwaters and the Harbour.

Our discussion of rates of previous uplift is crucial to current management considerations. If there has been no recent uplift, then there has been higher sea level in the past, which if studied would give an indication of the effects of previous higher sea level (e.g. old shorelines etc). On the other hand, if there has been greater uplift than previously thought, this means that calculated past sediment accumulation rates (SAR) may be inaccurate.

Catchment

The geomorphology of streams in the Porirua Harbour catchment is largely undescribed except in relation to major fault movement. More work is needed on the characterisation of the sub-catchments of Porirua and Pauatahanui Streams and other “minor” streams, and to understand the geomorphic and hydrological consequences of stream straightening and other flood control works on the lower Porirua Stream, including the sources of gravel coming into the catchment streams.

Assessing the suite of water quality results from streams in the entire Porirua Harbour catchment, we conclude that the overall water quality situation has remained basically the same from the period 1987- 2008, with relatively minor fluctuations between years. We also note that water quality studies in the streams, although providing an excellent information resource, rarely discuss or investigate specific causes of water quality issues, based on assessment of catchment properties. Nor do they propose ways to ameliorate the issues raised. Investigation of the specific sources of pollution is required, with the information from these investigations used in catchment planning and design.

In Porirua Stream, persistently poor water quality parameters (especially nutrient and faecal contamination) indicate that the pollution pulse delivered by rainfall events has somewhat decreased the life supporting capacity of the stream. This pollution explains the relative loss of the sensitive macroinvertebrate “EPT” taxa from some sites, even though overall stream health is still reasonable, at least comparable to results from comparable urban streams elsewhere in the region. The suggestion that Porirua Stream tributaries (Belmont, Stebbings) are at or near their "tipping point" needs urgent investigation, initially based on close analysis of any trend data available and the presence/absence of indicator species. On a more positive note, the potential for enhanced inanga habitat in the lowest reaches of Kenepuru Stream seems to be significant, and should be explored further. Enhancement of the spawning habitat for inanga (a key species) would benefit the whole lower catchment system.

We now have good information on past and present sediment accumulation rates in Pauatahanui Inlet, and some for Onepoto Arm. Catchment land uses and physical properties differ significantly between the Onepoto Arm and Pauatahanui Inlet catchments, so it is not surprising that SAR in the catchments appear to be different, especially taking into account possible differences between hydro-dynamic processes between the two arms.

Furthermore, we know very little about the erosion-storage-sediment delivery system in the catchment, and the variations in this system between sub-catchments. For example, how much of the eroded material remains in storage on hillsides, how much goes into storage in and near waterways, and how much is delivered straight into the Harbour? Answers to these questions are vital to prioritising erosion and sediment management. For a full understanding of the whole catchment-harbour system, we would need a full sediment budget for all parts of the catchment, including in-stream measurement of sediment loads in the lower reaches of all the streams. This would require continuous monitoring of flow and turbidity, with the latter calibrated by suspended sediment samples under various flow regimes. A representative sub-catchment budget, based on more limited sampling supplemented by field measurement of terrestrial sediment volumes, would be more feasible.

Any sediment budget work needs to take account of sediment movement within the Harbour as well as what is delivered to the Harbour. It should be remembered that sediment arriving at the Harbour comprises gravel, sand, loess and clay, each in varying volume according to the part of the catchment that it came from and the type of land use that precipitated its transport. In this respect, the consequences of sometimes high loess content in catchment soils could be significant: these soils are erodible, but also have potential for suspension and re-suspension in water (freshwater and estuary).

Although various biological surveys now provide a broad outline of plant and animal distribution in the catchment, our knowledge of the catchment's biodiversity is far from complete. The first priority is to complete biological inventory and ranking of significant terrestrial sites in Wellington City, and where necessary update inventory and rankings of Porirua City ecosites, in order to obtain complete information on priorities for terrestrial site protection and management in the whole catchment. Habitat and indicator species mapping has been very useful to assess the current distribution of key species and habitats around the Harbour. Trend information will become increasingly useful over time, as shown by the cockle surveys. Habitat mapping of Harbour edges should be continued, in particular trends in the distribution of sea grass and sea rush. It may also be possible to extend habitat mapping back in time by incorporating reliable historic records where possible.

The Harbour

Physical setting: Many of the physical and biological processes of the Porirua Harbour are related not only to the underlying geomorphology but also to the hydrodynamics of water movement within and between the two main arms. Water movement is probably the most poorly understood element of the physical basis of environmental issues. Although we have knowledge of changes in the bed morphology (and hence erosion and accumulation) of sediments for Pauatahanui Inlet, the effect of these changes on hydrodynamics is unknown. For the Onepoto Arm, no information is available on either bed morphology stability or the effect on hydrodynamics. Sediment movement in general is poorly understood, and needs to be better understood, including environmental impact assessment of any proposed future dredging. There is some limited recent evidence of localised erosion of Harbour edges (especially in the Pauatahanui Inlet) during storms.

There is little understanding of water exchange between the two arms, including the effects of the bridges at Paremata in altering tidal flow into and out of Pauatahanui Inlet. There is also little understanding about how much (and for how long) fluvial discharge and any associated pollutants are retained in the Harbour. An understanding of the tidal flushing capacity of the Onepoto Arm would also be useful in determining the effects of pollutant loads at the mouth of the Porirua Stream.

Sediment and contaminant movement: There is now conclusive evidence of increased rates of sedimentation over the last 150 years into Pauatahanui Inlet and Onepoto Arm, consistent with trends seen elsewhere in New Zealand. The sediment research has not established conclusively whether rates have continued to increase right up to the present. However, evidence of continuing sedimentation into many parts of the Harbour, including from parts of the catchment where there is no residential development or large-scale earthworks, suggests a continuing input from agricultural land uses such as steepland grazing. Continued monitoring of sediment generation, transport and delivery from steepland agricultural land is required, as well as monitoring of the effectiveness of programmes such as the Pauatahanui Vegetation Framework in reducing sediment generation. As discussed above, better knowledge of the variation in erosion potential in different parts of the catchment (e.g. the effect of different amounts of loess in catchment soils) is a background requirement for this work.

There is very little information on the movement of contaminants around the Harbour. Little is known about how the hydrodynamics in the Inlet influence sediment accumulation, and even less about the likely effects of a rising sea level. There is also the possibility of sedimentation rates increasing even further as the tidal prism and flushing capacity decreases, or from continuing urban development. With the knowledge gained from recent sediment studies, regular monitoring of sedimentation using sediment plates, now underway within the habitat mapping programme, should provide sufficient information on sedimentation in the short to medium term.

There have been no broad-scale studies of the Harbour's subtidal (benthic) habitats since the survey of the Pauatahanui Arm reported in Healy 1980 (Fig. 59). Subtidal habitats in the Onepoto Arm have never been surveyed. Up-to-date information on both the subtidal sediments and the benthic fauna would be very useful, particularly that for the channels, flood-tide and ebb-tide deltas, because these would be key habitats if dredging were to be undertaken in the future. Updated information on the distribution and characteristics of the sub-tidal sediments of the Harbour would also shed light on the sediment flows experienced in Onepoto Arm compared with Pauatahanui Inlet, and contribute to an understanding of tidal flushing capacity in the Harbour (see below).

Biota: Recent data suggest that there is a difference in the benthic species composition and diversity between Pauatahanui Inlet and Onepoto Arm. Comparison of the 2004 and 2005 data shows that all sites experienced gains and losses in species. The changes in the composition of fauna were spread across all the major taxonomic groups encountered and no one species was involved at all sites. Thus, the changes were not the result of the loss of a single species across the whole Harbour. Differences in communities between the two arms are probably more directly related to geomorphic and related sediment textural differences, rather than to the presence of pollutants. There is no data for change in the composition of benthic fauna in both arms of the harbour prior to 2004.

Cockle numbers in the Pauatahanui Inlet dropped markedly between 1976 and 1992, but have stabilised at the 1990s levels. Although reasons for the declines were not proven they have been linked to a reduction in the extent of eel grass beds in the Inlet, in turn linked both to higher sedimentation rates and to natural fluctuations. Although there are indications that populations of some estuarine fauna, such as cockles, are being exposed to anthropogenic-sourced contaminants, there is no clear evidence that contaminants of any kind have resulted in significant adverse effects on the benthic ecology, even if there may be small effects on individual species. The composition of benthic community groups in Pauatahanui Inlet does not appear to have changed with changes in concentration of contaminants. However, the toxicant thresholds for effects on the species exposed are not known.

As a number of studies in both Harbour and freshwater habitats have referred to impacts of certain processes on specified indicator species, it would be timely to develop a definitive list of indicator species for the catchment and Harbour. For Harbour habitats, this list would probably be based on the indicator species monitored in Robertson and Stevens (2008), extended where necessary to include key estuarine fish species. There appears to be little recent knowledge of coastal marine fish populations and trends. In view of the likely importance of the Harbour as a nursery area for coastal fish species as well as an important fishery in its own right, it is important to gain new information on estuarine fish habitat and fish populations in the Porirua Harbour, especially the outer Harbour, and to research the effects of Porirua Harbour fishing and catchment land use on the Harbour and adjacent coastal fisheries. Recent review of land-based effects on coastal fisheries supporting biodiversity in New Zealand confirms stresses on coastal fisheries, especially from sedimentation, but does not provide information from Porirua Harbour.

Water quality: Generally it seems that the Onepoto Arm has lower water quality than Pauatahanui Inlet, with higher concentrations of macroalgal cover, and more frequent and higher breaches of recreational guidelines for enterococci. This is likely to be related to storm water inputs (probably including sewer cross-connections) to Onepoto Arm, as these poor water quality indicators generally occur at the city end of the inlet. However, while it has been long thought that tidal flushing processes are more pronounced in the Pauatahanui Inlet than in Onepoto Arm, the role that tidal processes and hydrodynamics have in flushing or pooling of pollutants is unknown. This reinforces the need for detailed knowledge of hydrodynamics in the whole Porirua Harbour, including the Outer Harbour, and the movement of nutrients, sediments and contaminants from the Harbour to the open coast.

It is likely that the high levels of faecal-derived bacteria found in Porirua Harbour water testing are sourced from within the catchment, as the Porirua, Pauatahanui and Horokiri Streams also have consistently high faecal coliform counts. The two likely within-catchment sources are farm stock and leakage from sewer and septic tank systems (or a combination of both). As yet a conclusive understanding of the source of microbial contamination is not available.

Concentrations of zinc, lead and copper are higher in Onepoto Arm, especially in the vicinity of Porirua CBD, pointing to both the Porirua Stream and the city stormwater outfalls as sources of these contaminants. In turn the most likely original sources are vehicle brake pad wear, lead residues from petrol and unpainted galvanised iron roofs and claddings. There are also persistent elevated levels of DDT and derivatives. Continued monitoring of DDT and its derivatives in the catchment and Harbour will be required, as well as understanding of the catchment sources.

Any conclusions about pollution in the Harbour need to take into account natural (background) levels of pollutants, i.e. substances that occur naturally but are now present at higher concentrations from anthropogenic sources. To obtain background information on water quality of Porirua Harbour it would be useful to monitor turbidity, salinity, dissolved oxygen, temperature and pH, as well as pollutant and nutrient concentrations. Assessments of eutrophication should be undertaken by monitoring chlorophyll-a concentrations. Sample sites should be strategically located at sites around the Harbour, and sampled on both rising and falling tides, to assess the relative influence of fluvial inputs, tidal flushing and harbour morphology. A background sample of metal levels in catchment sediments would also be useful to compare natural and anthropogenic contributions of metals.

An analysis of bioavailable metals would give an indication of whether existing concentrations are likely to affect biota. As yet there is no specific local evidence as to what concentrations of pollutants in sediment are toxic to local biota, or if the local fauna is adversely impacted by these concentrations. In general, assessment of parameters of Harbour biota (abundance, biomass etc), rather than measuring the pollutants themselves, potentially provides more direct methods to indicate if changes in the environment are causing an adverse ecological impact. A list of recognised plant and animal indicator species should be developed and routinely used to assess effects of contaminants or changes in the Harbour environment.

The long-term monitoring of sediment chemistry and benthic ecology at sample sites in Onepoto Arm and Pauatahanui Inlet should be continued, taking into account the effects of sediment size and previous rainfall. Sediment samples that are above ANZECC (2000) guidelines should be analysed for their bioavailable fraction to determine if high concentrations could affect biota.

Human use: There is considerable anecdotal evidence of changed patterns of use of the Harbour and some lower streams by locals for recreational fishing. It is known that the Onepoto Arm was an important kaimoana area in the nineteenth and first 70 years of the twentieth century. But as far we are aware, this knowledge has not been systematically recorded, or made specifically accessible. Changes in human use of Porirua Harbour, especially Onepoto Arm, over the last 100 years would be an important topic for investigation through the gathering of traditional Maori and recreationalists' knowledge.

Porirua Harbour may be the most completely hard-edged estuary in New Zealand; i.e. the most completely ringed by road, rail and walkway/cycleway embankments. There are many actual and potential effects of this situation, including pollution from vehicle emissions, brake pads, tyres and road wash, wave refraction, estuarine erosion and loss of the absorptive capacity of the Harbour edges from storm surges, direct coastal habitat loss, and loss of potential habitat for estuarine species retreating from rising sea levels. The only harbour in New Zealand we can suggest as being anywhere close to Porirua Harbour in terms of proportion of its total perimeter directly fringed or very close (<20m) to hard surfaces (sea walls or road, rail or cycleway/walkway embankments) is Wellington Harbour. Wellington Harbour is many times the area and volume of Porirua Harbour, so pollution effects from encirclement are presumably much smaller. Because of the uniqueness of Porirua Harbour's circumstances, further study of the implications of this degree of encirclement, and options for management responses, seems to be an important priority.

Overall: There is strong evidence that the rate of sedimentation has increased in the last 150 years. There is also considerable evidence of persistently elevated levels of some contaminants, and some evidence of moderate eutrophication. However, there are few clear indications of significant ecological effects of these changes. Biological indicators are likely to be at least as reliable as water quality indicators to indicate pollution and estuarine health, as water quality parameters fluctuate so greatly. It is important to remember, however, that biological indicators also fluctuate naturally over time (as shown well by the Pauatahanui Inlet cockle studies), and that we need long term records to establish an equilibrium or "normal" situation. Ideally, we would want to be able to look at trends over time of both water quality and biological indicators, related to changes in land use. Better understanding of the hydrodynamics of the whole Porirua Harbour system is also key to interpretation of results of studies of water quality and sedimentation.

Climate change

The potential impacts of sea level rise on Porirua Harbour are difficult to assess, as there is no information regarding current storm surge, or tidal oscillation heights around the Harbour. To be able to predict the impact of a storm surge or a king tide under a higher sea level, it is necessary to have information on the effects of those processes at present. In Pauatahanui Inlet, some salt marsh habitat appears to be currently under threat from wave-driven erosion, a trend that would be exacerbated by predicted changes in sea level. It is too early to say what effects that changes in storm frequency will cause, but they are likely to include changes in sediment delivery from the different parts of catchment to the Harbour.

It would be useful to determine changes in salt marsh accretion, where the salt marsh has room to expand, to determine whether it is keeping pace with local sea-level changes. However, it is reasonable to assume that habitat will be significantly restricted as sea level rises and outward expansion of habitat is blocked by roads, embankments and seawalls.

It is possible that rising sea levels will largely negate the current rates of infill, through providing a greater volume of water in the Harbour, but that possibility is discounted by the most recent calculations of net SAR that take both sedimentation and sea level rise into account. In addition, rising sea level, through creating more space for sediments, could increase sedimentation rate. Higher deposition of sediments is also likely to continue to smother benthic biota. In our view, the possibility of rising sea level negating sedimentation does not permit inaction on managing sediment inputs. The best recourse is to try and correct for the increased inputs, rather than relying on any option that assumes that ‘rising sea level will make it OK’.

Other consequences of climate change for Porirua Harbour will mainly arise from increased storm intensity. These include coastal erosion, streambank erosion, and delivery of pulses of sediment from hillslopes into and down the streams to the Harbour, altering rates of sedimentation. We have drawn attention to research requirements to better understand sediment generation and transport to Porirua Harbour. Other than this, management action and planning is urgently required, including the highest statutory management standards for all vulnerable sites, e.g., where earthworks and forestry harvesting are taking place, grazing on steep slopes etc.

Information from other New Zealand estuaries

Relevant information from elsewhere in New Zealand highlights catchment land use which adversely impacts stream water quality and Harbour condition. Streams draining agricultural land (cleared pasture) experience greater sediment loads, are warmer and have less shade than streams draining native or planted forest.

Other estuaries on the North Island (such as Whaingaroa and Pakuranga) have experienced similar increases in sedimentation rates since the arrival of European settlement and the development of agriculture and plantation forestry and more recently, the intensification of urbanisation. The highest sedimentation rates occur where catchments drain steep grazed land or on urban land undergoing development. Various studies highlight the need for a catchment management approach to problem areas upstream, and the implementation of riparian buffer areas to slow sediment and nutrient inputs. For the Porirua Harbour, a focus on maintaining all remaining estuarine vegetation, and restoring it where possible, are important priorities.

Recommended research priorities for Porirua Harbour and catchment

In this final section we suggest research areas that in our judgement are the top priorities for immediate information-gathering and research. These are by no means all the gaps in our current knowledge and understanding, but the ones that seem to us to be the most important and urgent to enable effective management action.

We also repeat that, as implied in the previous paragraphs, these research gaps should not be used as a reason to delay management action. Although these research priorities are important and should be addressed, we also consider that there is already enough information from the Porirua and other catchments to at least begin the development of a catchment management strategy or plan which begin to counteract some of the identified adverse indicators and trends. For example, in broad terms, we know sedimentation is increasing: action should be taken to reduce erosion and introduce riparian buffers. We know there is stormwater pollution even though there are still many questions about the distribution of pollutants: action should be taken to reduce pollution, using both engineering and planning options. The proposed Porirua Harbour and Catchment Strategy, for which this review is an input, represents such an important opportunity to address some of the management needs through integrated planning. Recent work on the Porirua Stream catchment, including a recommendation to develop a statutory catchment plan for that catchment (Blaschke et al 2009), is another example of the recognition of this planning need.

The research priorities listed below are not in any particular order of importance or cost/difficulty of implementation. It includes items for which there is already a recognised need and which in some cases have begun to be addressed, as well as items that to our knowledge are new to the research agenda. In addition to these listed priorities, we consider that a key priority is to continue gathering information from the community about their environmental concerns, and then to use planning processes that address those concerns and involve stakeholders.

Recommended research priorities

1. Gather and maintain a consolidated reference collection of all published and known unpublished reports on Porirua Harbour and catchment, to be housed at Porirua City Council and made available to interested parties.

2. Improve understanding of the transfer of pollutants and sediments within Porirua Harbour, by undertaking an integrated Porirua Harbour hydrodynamics study, focussing on Onepoto Arm, and the exchange processes between Pauatahanui Inlet, the Onepoto Arm and the Outer Harbour.

3. Obtain background information on water quality at sites across the entire Porirua Harbour in order to understand natural variation within the system. Parameters measured should include turbidity, salinity, pollutant and nutrient concentrations, dissolved oxygen, temperature and pH. Sample sites should be located to enable assessment of the relative influence of fluvial inputs, tidal flushing and harbour morphology.

4. Continue to monitor changes in Porirua Harbour bathymetry over time, and relate changes to estuarine hydro-dynamic processes.

5. Characterise the catchment in terms of geomorphology and stream morphology, and document recent changes e.g. channel straightening. In particular, investigate the effects of Porirua Stream (and tributaries) flood control and other engineering works on stream and harbour processes.

6. Identify the sub-catchments which urgently need erosion control, and prioritise amelioration works, based on representative sub-catchment sediment budgets and field measurements, and continued assessment of sediment inputs into Porirua Harbour using already installed sediment plates.

7. Complete biological inventory and ranking of significant terrestrial sites in Wellington City, and where necessary update inventory and rankings of Porirua City ecosites, in order to obtain complete information on priorities for terrestrial site protection and management in the Porirua Harbour catchment.

8. Continue habitat mapping consistently over the entire Porirua Harbour, and extend to sub-tidal areas, along with broad-scale description of the benthic communities.

9. Derive a definitive list of indicator species for Porirua Harbour and catchment, including key estuarine fish species.

10. Extend the monitoring of cockle populations in Pauatahanui Inlet, to include the monitoring of key indicator species in all relevant parts of the Harbour.

11. Continue long-term monitoring of sediment chemistry and benthic ecology at sample sites in Onepoto Arm and Pauatahanui Inlet. Sediment samples that are above ANZECC (2000) guidelines should be analysed for their bioavailable fraction to determine if high concentrations could affect biota.

12. Investigate the hypothesis that some Porirua Stream tributaries are at or near their ecological "tipping point", initially based on a close analysis of any trend data available and the presence/absence of indicator species.

13. Investigate sources of gravels in the Porirua Stream and Harbour, especially those that are removed by dredging. Investigate the effects of all current dredging activities in the Porirua Harbour.

14. Document changes in human uses of the Porirua Harbour over the last 150 years, in particular focussing on the extent and use of cockle and oyster beds.

15. Investigate adaptation and mitigation strategies for the environmental consequences of the high degree of road/transport encirclement of the Porirua Harbour.

16. Investigate the potential and preferred methodology for enhancing inanga habitat in the lowest reaches of Kenepuru Stream.

17. Obtain and analyse further information on fish habitat and fish populations in the Porirua Harbour, especially the Outer Harbour. Research the effects of Porirua Harbour fishing and catchment land use on Harbour and adjacent coastal area fisheries and ecosystems

Appendix 1 Sites of cultural importance in the Porirua Region[26]

Section	Sites and areas
Porirua to Paremata	Horopaki Aotea Papakowhai Tamanga a Kohu
Paremata to Plimmerton	Paremata, Taupo Whitianga Pa Paremata Pa Thoms Whaling Station Moa Bone hunting sites Burial ground Dunes Paremata Barracks Gallows Military Camp Ngati Toa Domain Pauatahanui Inlet Porirua Harbour Te Whata kai o Tamairangi Taupo Pa and kainga Proximity to Turi Kawera Te Whata kai o Tamairangi Te Punga o Matahorua Burial Hill Plimmerton Domain (former Taupo Swamp) Plimmerton railway (urupa)
Plimmerton to South of Pukerua Bay	Taupo swamp

[26] Source: BML (2005)

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Glossary of terms and scientific names of organisms

Terms

aggredational (also accretional): A process where sediment is added to a surface over time.
ANZECC: Australian and New Zealand Environment and Conservation Council. Interim Sediment Quality Guidelines (ISQG) are contained within the ANZECC "Australian & NZ Guidelines for Fresh and Marine Water Quality" (ANZECC 2000).
bayhead delta: a delta is a triangular landform found where a stream meets a body of water (estuary or lake) composed of sediment which the stream has transported but drops as the energy of the water flow falls. A bayhead delta is a delta at the head of an estuary.
benthic: bottom dwelling
bioavailable: describes pollutants that are easily absorbed by biota. Hence, pollutants that pass through the digestive system of a creature and are not absorbed are not bioavailable.
bioturbation: the displacement and mixing of sediment particles by benthic animals or plants
birds-foot delta: a delta with long projecting distributary channels that branch outward like the claws of a bird
BP: years before present
CBD: Central Business District
copepod: minute marine or freshwater crustacean (aquatic arthropods of the class **Crustacea**, including lobsters, crabs, shrimps, and barnacles)
co-seismic: refers to an event that occurs with seismic activity, i.e. movement of a fault that ruptures with an earthquake
DDT: **d**ichloro**d**iphenyl**t**richloroethane. A synthetic pesticide once used extensively and now banned, due to its far reaching poisoning effects and its persistence in the environment.
degradational: refers to any landform formed by the wearing down of a landsurface by erosion and weathering
diatoms: single celled algae
EC: Electrical conductivity
EIA: environmental impact assessment (also known as *EEA:* environmental effects assessment)
enterococci: bacteria found in the human lower intestine, and used to detect sewage contamination of water.
eustatic: global, referring to global change in oceanic water level due to a change in the total volume of water in the oceans
eutrophic water body: characterised by: high nutrient inputs; dense algal concentrations often called algal blooms (and hence high chlorophyll-a concentrations); dissolved oxygen concentrations in the surface waters which fluctuate according to light exposure; low dissolved oxygen in the lower water column which can suffocate fish; and anaerobic sediments
faecal coliforms: bacteria found in faecal matter
flushing regime: the process of water moving in and out of a confined embayment/estuary
fluvial: refers to a river or stream. A fluvial channel is a stream channel.
integrated catchment management: a process through which people can develop a vision, agree on shared values and behaviours, make informed decisions and act together to manage the natural resources of their catchment
intertidal zone: the coastal zone between the lowest to the highest tide mark
kaimoana: seafood

KNE: Key Native Ecosystems, referring to a Greater Wellington Regional Council programme aimed at identifying and protecting ecosystems vital to the long-term viability of the region's unique biodiversity

longshore drift: movement of sand in the surf zone parallel to the shore

macroalgae: types of algae visible to the naked eye, commonly known as seaweed

macroinvertebrates: animals without backbones that are visible without magnification

MCI: Macroinvertebrate Community Index which ranks sites according to fauna diversity and taxa susceptibility to pollution

meiofauna: catch - all term for animals about one millimetre long

nearshore: the area comprising the swash, surf and breaker zone in waves are forced to break owing to the shallowing of water

organo-chlorine: Any organic chemical that contains at least one chlorine atom. Organo-chlorides are used extensively in the production of plastics (especially PVC), for dry cleaning, and in pesticides. One important organo-chloride is DDT.

PAH: polycyclic aromatic hydrocarbon. PAHs are common aromatic solvents used for adhesives, resins, fibres, pesticides and ink, as industrial cleaners and degreasers, as thinners for paints and lacquers and in the rubber industry. They are also constituents of asphalt and of crude oil and are products of oil refining.

PEP: Pauatahanui Environment Programme, an intensive three-year integrated study of the Pauatahanui Inlet and catchment carried out by the former Department of Scientific and Industrial Research between 1975 and 1977

periphyton: a complex mixture of algae, cyanobacteria, heterotrophic microbes, and detritus that is attached to submerged surfaces.

pH: measure of acidity (pH 1-7) or alkalinity (pH 7-14).

phenols: a class of organic compounds, used in many industrial applications such as the manufacture of herbicides and cosmetics

polychaetes: marine worm

porewater: water filling the spaces between grains of sediment

progradation: seaward build up of a beach, delta or fan by deposition of sediments

residence time: in relation to flushing processes, a measure of the rate of exchange between an estuary and the adjacent coast

salt marsh: a marsh located in the intertidal zone, between the land and the coast. Characterised by sea rush and jointed rush

sediment accumulation rate (SAR): the rate (usually in millimetres per year) at which sediment has accumulated at a location.

seepage area: depression in the ground where water collects, on or below the surface

subtidal (sub-littoral) zone: The sea-shore zone lying immediately below the intertidal zone, generally extending to about 200 m depth or to the edge of the continental shelf

surficial: refers to the surface

TSS: Total Suspended Solids. Refers to particulate concentrations in water.

Scientific names of organisms

Australasian harrier: *Circus approximans*
banded dotterel: *Charadrius bicinctus bicinctus*
banded kokopu: *Galaxias fasciatus*
black swan: *Cygnus atratus*
black stilt: *Himantopus himantopus leucocephalus*
blackbird: *Turdus merula*

browntop: *Argrostis capillaris*
Caspian tern: *Hydropragne caspia*
common bully: *Gobiomorphus cotidianus*
common cockle: *Austrovenus stutchburyi*
eastern bar-tailed godwit: *Limosa lapponica baueri*
eelgrass (seagrass): *Zostera muelleri*
fantail: *Rhipidura fuliginosa*
flounder: *Rhombosolea* spp, most commonly sand flounder, *R. plebeia*
freshwater shrimp: *Paratya curvirostris*
giant kokopu: *Galaxias argenteus*
glasswort: *Sarcocornia quinqueflora*
goat: *Capra hircus*
grey teal: *Annas gracilis*
grey warbler: *Pseudogerygone igata*
gulls: *Larus* spp
hares: *Lepus europaeus*
harrier hawk: *Circus approximans gouldi*
hinau: *Elaeocarpus dentatus*
inanga: *Galaxias maculatus*
jointed rush (jointed wire rush, oioi): *Apodasmia similis*
kahawai: *Arripis trutta*
kahikatea: *Dacrycarpus dacridiodes*
kereru: *Hemiphaga novaeseelandiae*
kingfisher: *Halcyon sancta vagans*
kohekohe: *Dysoxylum spectabile*
koura: *Paranephrops planifrons*
long finned eel: *Anguilla dieffenbachii*
magpie: *Gymnorhina tibicen*
mahoe: *Melicytus ramiflorus*
matai: *Prumnopitys spicatus*
mouse (house mouse): *Mus musculus*
morepork: *Ninox novaeseelandiae*
New Zealand rig: *Mustelus lenticulatus*
North Island fantail: *Rhipidura fuliginosa fuliginosa*
New Zealand kingfisher *Halcyon sancta vagans*
NZ shoveler: *Anas rhynchotis variegate*
paradise shelduck: *Tadorna variegata*
possum: *Trichosurus vulpecula*
pukeko: *Porphyrio porphyrio melanotus*
rabbit: cuniculus
rat: *Rattus* spp (Norway or brown rat, *R. norvegicus*, and ship or black rat, *R. rattus*)
rewarewa: *Knightia excelsa*
rimu: *Dacrydium cuppressinum*
salt marsh ribbon wood: *Plagianthus divaricatus*
sea primrose: *Samolus repens*
sea rush: *Juncus kraussii*
shags: *Phalacrocorax* spp.
shining cuckoo *Chrysococcyx lucidus*
short finned eel: *Anguilla australis*
silvereye: *Zosterops lateralis lateralis*
sole: *Peltorhamphus novaezeelandiae*

spoonbill: *Platalea regia*
spotted dog fish (New Zealand rig): *Mustelus lenticulatus*
spur-winged plover: *Vanellus miles novaehollandiae*
tawa: *Beilschmiedia tawa*
trout: likely to be brown trout, *Salmo trutta*
tui: *Prosthemadera novaeseelandiae*
variable oystercatcher: *Haematopus unicolor*
waxeye: *Zosterops lateralis*
welcome swallow: *Hirundo tahitica neoxena*
white-faced heron: *Ardea novaehollandiae novaehollandiae*
yellow-eyed mullet: *Aldrichetta forsteri*