Eutrophication Indicators in the Hutt River Estuary, New Zealand

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Abstract

The Hutt River estuary near Wellington New Zealand has a luxuriant intertidal band of green macroalgae growing throughout the year. Investigations of water chemistry suggested that the upstream freshwater river was likely P-limited and passed on watershed nitrogen nutrients to the estuary. P fertilization of the estuary from marine waters led to crossing N and P nutrient loadings that lead to the observed macroalgal proliferation. Chemical analyses of nutrients, macroalgae and barnacle and mussel consumers were used to further understand the mix of factors controlling eutrophication and food webs in this urban estuary, with $\delta^{15}N$ and $\delta^{13}C$ helpful respective indicators of watershed N inputs and C cycling between benthic and pelagic parts of the food web.

Keywords: *Ulva*; nitrogen isotopes; nutrients; carbon isotopes; urban estuary; consumers; food webs

Introduction

Estuaries are complex ecosystems at the land-sea interface, an interface that is increasingly used by the global human population. Both oceanic and riverine inputs are important for estuaries, but watershed development by humans typically has been the major axis of recent change impacting these systems. Urban estuaries are becoming increasingly common as the global human population is now >50% urban and >60% concentrated within 100km of coasts (http://esa.un.org/unup/index.asp, Vitousek et al.. 1997). Urban estuaries typically are channelized for flood control and navigation, often becoming narrow water conduits with only remnant connections to historical floodplains. Nonetheless, these highly modified systems are important contact points where humans encounter nature by walking, swimming and fishing. For these reasons, urban estuaries and urban ecosystems are receiving increasing scientific attention (Pataki et al.. 2005, 2010).

Urbanisation and watershed development worldwide has resulted in increases in water column nutrient concentrations, pollutants, and particulates in estuarine systems (GESAMP 2001). Nutrient increases lead to eutrophication characterized by increased nutrient and organic matter cycling. Increased nutrients can alter ecosystem function because growth rates of algae in spring and summer on temperate coastlines are predominantly limited by the availability of nitrogen and/or phosphorus (Hanisak 1983; Galloway et al.. 2003; Pedersen et al.. 2010). Increases in the availability of these nutrients can result in faster growth of plants and algae, reduced water clarity, algal blooms, changes in sediment chemistry and near-sediment water chemistry, and smothering of benthic biota (Sfriso et al.. 1991; Heip 1995; Cloern 2001). Hence, increases in nutrient availability have led to changes in interactions between organisms and loss of benthic biodiversity (GESAMP 2001; Savage et al. 2002).

Terrestrially derived surface runoff can further alter coastal systems by directly increasing the organic content of benthic sediments, toxic effects, and physical effects including the smothering of benthic organisms by particulates (Airoldi 2003; Steger & Gardner 2007; Jartun & Pettersen 2010). Urban estuaries tend to be particularly susceptible to these impacts; surface runoff in built-up areas tends to be higher due to the proportion of watershed ground covered by impermeable surfaces.

The Hutt River is the main freshwater input to Wellington Harbour that is adjacent to the capital city of New Zealand. The river channel has been heavily engineered and constrained within levees and jetties, and the historical floodplain is now occupied by residential, commercial and industrial developments. Headwaters of the river include the major water reservoir for the city of Wellington, and there are few direct nutrient inputs into the Hutt River. Sewage from the surrounding Hutt Valley is treated separately and discharged via pipeline into offshore waters of the Cook Strait. The freshwater Hutt River is used for fishing and swimming and had no readily observed green algal growth during the course of this study, but in the downstream estuary, the intertidal zone was heavily populated by the bloom-forming macroalga *Ulva intestinalis*.

This study investigated the nutrient dynamics of the Hutt River system as a possible cause for the luxuriant band of *Ulva* and included measurements of chemical bioindicators in algae, and in intertidal barnacles and mussels that might record longer-term average conditions than conventional water column chemistry. These chemical indicators included tissue N, P and Mn content as well as C and N stable isotope compositions used in other investigations of nutrient loading to New Zealand coasts (Barr 2007, Dudley and Shima 2010, Dudley et al. 2010). Study of nutrients and plant indicators led to a bottom-up assessment of estuarine condition; we also

included some primary consumers to study the food web. We conducted field sampling in the summer and winter of 2010 to test 1) whether nutrient dynamics could account for macroalgal proliferation within the estuary, and 2) whether chemical indicators in macroalgae and animals could be helpful in monitoring efforts for better water quality. These questions are considered in the context of possibly reducing nutrient loading from the Hutt River watershed to the downstream estuary and Wellington Harbour.

Methods

Study sites were arranged across a salinity gradient in the Hutt River estuary, Wellington, New Zealand (Fig. 1). Samples were collected mostly in austral summer 2010, January-March, with one set of samples also collected in austral winter on July 31, 2010. In order to provide comparison for nutrient dynamics in the Hutt River, seawater nutrients and salinity were examined at two further study sites in the nearby and relatively unimpacted Porirua Harbour, about 20 km north of Wellington. Thirty samples were collected over several ebb-flood tidal cycles from the mouths of the two arms of Porirua estuary during austral summer February and March 2010

Water samples were collected at 20 cm below the surface and frozen within two hours, later thawed and salinity and nutrients measured in the laboratory. Salinity was measured as conductivity with a Hach HQ 40d multimeter, then converted to practical salinity units (psu) using a standard seawater solution containing 35g/l NaCl and a measured conductivity of 55.2 mohms/cm. Nutrient samples were not filtered because previous work with New Zealand waters has shown little difference between filtered and unfiltered estuarine samples (Barr and Rees 2003). Nutrient samples were analysed in duplicate for ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-) and

phosphate (PO_4^{3-}). Ammonium was determined as described by Koroleff (1983a) and nitrite by Parsons et al. (1984). Nitrate was converted to nitrite by cadmium reduction, and then determined using the method described above for nitrite. Phosphate was determined as described by Koroleff (1983b) as dissolved reactive phosphorus (DRP), hereafter abbreviated as P. Total dissolved inorganic nitrogen (DIN, hereafter abbreviated as N) concentrations were calculated as the sum of ammonium, nitrate and nitrite. P and N concentration values are expressed in mmol/m^3, and N/P and P/N ratios are given as molar ratios.

Green macroalgal samples were collected as either filamentous scrapings from rocks or as larger (>30cm long) foliose *Ulva intestinalis* thalli, with N = 5 collections made at each site then pooled for one composite sample to represent the site. Mussels were similarly collected for a composite sample of N = 5 individuals at each site, and barnacles were removed from mussel shells for analysis, or collected separately where mussels were not present. Because of their small size, 50-100 barnacles were combined as a composite sample at each site. Single composite samples were collected to represent sites, with t tests used to establish mean differences among groups of sites.

Macroalgae and animals were frozen within 2 hours of collection, then later thawed and washed in deionized water. Animals were dissected into separate tissue and shell fractions, with tissues treated for 5-15 minutes with mild (1 N) HCl to remove carbonates. Tissues included gut material that usually comprises only a small fraction of the total organic matter present in animals. Shells were soaked overnight in household bleach (6% sodium hypochlorite) to remove organic matter. Tissue and shell samples were rinsed again with deionized water, then respectively freeze dried and dried at 60^{o}C. Dried tissue samples were pulverized with mortar and pestle, with

liquid nitrogen added to the pestle bowl to help fracture samples in production of fine powders. Shell samples were pulverized with metal rods in glass containers or using a SPEX mill (SPEX Industries, Metuchen New Jersey). Dried, pulverized samples were combusted for elemental and isotope compositions, as determined with an ANCA SL elemental analyser coupled to a GEO 20-20 isotope ratio mass spectrometer, both manufactured by Europa Scientific (Crewe, UK). Results are reported as %C and %N by dry mass and as $\delta^{13}C$ or $\delta^{15}N$ (‰) = $(R_{SAMPLE}/R_{STANDARD} - 1)*1000$ with R = $^{13}C/^{12}C$ or $^{15}N/^{14}N$ and standards are respectively VPDB (Vienna PeeDee Belemnite) and nitrogen gas in air (Rogers 2003, Sharp 2007). Several international standards were used as calibration reference materials for the isotopic determinations and a standard deviations averaged $\pm$0.2‰ based on analysis of replicates. Mn and P contents of macroalgae were determined with proton-induced x-ray emission, PIXE, using bovine liver as a reference material (Kennedy et al.. 2008).

Results

Summer and winter surveys of the Hutt estuary showed that the Hutt River estuary extends about 3.5 km at low river flows, from the head of tides 50m upstream of the Ewen Bridge in Lower Hutt down to the end of the south jetty in the industrial region of Seaview (Fig. 1). Green macroalgal mats comprised mostly of *Ulva intestinalis* encrusted rocky intertidal surfaces across the entire estuary; areas both upstream of the Ewen Bridge and also downstream of the tip of the eastern jetty at 1.5 km in Wellington Harbour were free of this algae (Fig. 2). The central estuary area between the Ava Railroad bridge (-1.3 km vs. the Hutt Estuary Bridge that represents 0 km) and the end of the north jetty (+1.5 km) had the densest mats of green *Ulva*. Salinity transects showed that this central estuarine area had moderate mesohaline

salinites (Fig. 3), and intertidal marine barnacles (*Chaemospio* sp.) and blue mussels (*Mytilus galloprovincalis)* also were abundant. Salinities decreased upstream of this central zone into a 1 km oligohaline reach, and increased downstream into Wellington Harbour where strong tidal flushing keeps salinities high near 35 psu.

Examination of available nutrient data for the freshwater Hutt River showed relatively high average N concentrations but very low P concentrations (Perrie 2009), while the reverse was true at the marine end of the estuary in Wellington Harbour, i.e., N nutrients were low but P levels were relatively high (Barr 2007 and Barr unpublished 2009 data for Mahanga Bay in Wellington Harbour). These data suggested the possibility that the freshwater Hutt River is P-limited, but that marine waters entering the estuary could supply P to balance the riverine N. Nutrient samples were collected in summer and winter along the Hutt River estuary to test this possibility of crossing nutrient supplies supporting macroalgal growth, and measurements indicated substantial P supply from marine sources to balance the river N supply (Fig 4). Especially N concentrations and molar N/P ratios decreased sharply through the oligohaline zone, while P concentrations and molar P/N ratios increased with salinity towards Wellington Harbour. Conservative mixing of fresh and marine waters is expected to yield linear nutrient changes with salinity, and the non-linear results for especially N (Fig. 4) were consistent with strong biological N uptake in the Hutt River estuary. The salinity and nutrient dynamics varied somewhat on the three different sampling dates (Figs. 3, 4), so summer collections were made of plant and animal bioindicators to investigate their possible usefulness as longer-term average integrators of eutrophication signals.

For *Ulva intestinalis* collected from the luxuriant intertidal band of algae, P increased and N/P decreased downstream in the central part of the estuary (Table 1),

with significant differences (t test, P<0.05) among means for results from the oligohaline samples (-2.2 to -1.8 km) vs the mean from the lower more marine estuary (km -0.8 to +0.8). Average Mn contents in the oligohaline algal samples also were significantly higher in comparisons between these same stations (t test, *P*<0.05). The stable isotope work for algal $\delta^{15}N$ showed a relatively small range of 2.1‰ (Table 1), consistent with little or small overall differences in $\delta^{15}N$ values of N nutrient sources across the estuary. Tissue $\delta^{13}C$ for mussels and barnacles reached maxima in the area of the Hutt River bridge at 0-0.1 km (Table 1), while shell $\delta^{13}C$ of these animals showed minima slightly further seawards at 0.5-0.6 km (Figure 5). Average isotope differences for especially barnacles were significant (t test, *P*<0.05) for comparisons among the following means of grouped stations: 1) $\delta^{15}N$ of 10.7$\pm$0.8 (SE) vs. 8.8$\pm$0.2 for respectively upstream stations -1.4 to -0.7 km vs. downstream stations -0.5 to 1.4 km, 2) tissue $\delta^{13}C$ -17.8$\pm$0.4 vs. -19.0$\pm$0.2 for respectively middle stations -1.1 to +0.2 vs. upstream + downstream stations -1.4, -1.3, 0.7, 1, and 1.4 km, and 3) shell $\delta^{13}C$ of -0.72$\pm$.11 vs. -0.07$\pm$.11 for respectively middle stations 0.2, 0.7, 1.0 vs. upstream and downstream stations -0.55, 0 and 1.4 km.

In comparative work with the Porirua estuary, both the Pauatahanui and Onepoto arms of this estuary had relatively small freshwater inputs, high salinities >33.5, and largely lacked extensive intertidal green algal bands, although these bands were conspicuous next to local stormwater outfalls and some freshwater streams. Nutrient concentrations in thirty samples collected at the mouth of these arms averaged ($\pm$SE) 2.6$\pm$0.4, 1.0$\pm$0.1, 3.6$\pm$0.4 and 0.41$\pm$0.02 mmol m^{-3} for respectively nitrate+nitrite, ammonium, DIN and phosphate, with N/P = 9.

Discussion

Nutrients and the presence of a luxuriant band of intertidal green macroalgae were the primary eutrophication indicators in this study, and analyses of macroalgal $\delta^{15}N$ and N/P ratios supported ideas that the Hutt River estuary is currently an eutrophic estuary. Green macroalgae are common inhabitants New Zealand estuaries, but the sustained summer+winter presence of a thick intertidal band of *Ulva* in the Hutt River seemed unusual, especially since this type of growth was completely lacking in a) freshwater river reaches immediately upstream of the head of the estuary and b) marine waters immediately downstream in Wellington Harbour (Fig. 2). The thick growth of estuarine alga may reflect several factors, especially the balance between top-down grazing that removes algae and bottom-up nutrient additions that increase algae. In the case of the Hutt estuary, repeated sampling (Fig. 4) showed that nutrients were present in sufficient quantities to support regular algal growth. Observations in downstream Wellington Harbour near the mouth of the Hutt River also support the importance of nutrient controls, because nutrient seeps along beaches and seawalls regularly have visible *Ulva* growth even in the presence of a diverse snail and chiton grazer community (Rogers 2003). Also, Ulva also grows at many exposed places in the Harbour (Adams 1994), so that higher wave activity does not seem to be generally suppressing *Ulva* growth. In summary, while it is possible that reduced (and as yet unquantified) grazing occurs in the Hutt estuary, nutrient supply currently seems required and also sufficient to explain the observed luxuriant algal development.

Comparative studies are consistent with this idea of nutrient controls. New Zealand estuaries are often steep, short and strongly flushed by tides, and similar estuaries in California receiving agricultural run-off have these same diagnostic bands of intertidal green macroalgae (personal observation, B. Fry). Generally where

estuarine flushing times are short enough to prevent extensive nutrient use by phytoplankton, attached macroalgae often flourish (Valiela et al. 1997). Examination of historical photos (Wear 1988) show that these intertidal green macroalgae were present as visible bands in the Hutt estuary 22 years ago, and so are likely long-term eutrophication features of this ecosystem. Eutrophication can increase with longer-term detrimental effects such as coastal hypoxia and harmful algal blooms (Wear & Gardner 2001; Hallegraeff 2010; Rabalais et al. 2010), so minimizing anthropogenic nutrient loading seems prudent. Current monitoring assessements are that the luxuriant intertidal algal growth and sediment-related indicators in the Hutt River estuary point to fair-to-moderate ecosystem condition with concern about nutrient loading from the watershed (Stevens and Robertson 2010, Robertson and Stevens 2010).

Strategies for decreasing the macroalgal band likely lie in efforts to decrease nutrient run-off in the Hutt watershed. The freshwater Hutt River often has summer growths of toxic (if eaten by pet dogs) *Phormidium* cyanobacterial mats downstream of the Mangaroa River confluence at -29 km (Milne & Watts 2006), a confluence that also approximately trebles N nutrients in the mainstem Hutt River (Perrie 2009). Focusing some remediation efforts in the Mangaroa watershed could be a next logical step in a clean-up of the downstream Hutt estuary. However, because of the relatively high supply of P from Wellington Harbour, N supplies to the Hutt River may need to be reduced to very low levels to achieve visual elimination of estuarine macroalgal bands. Further work estimating groundwater nutrient supplies and studies of possible grazer controls of algal proliferation may be needed before undertaking efforts to lower current nutrient levels. Comparative work in other nearby estuaries also may help in setting targets for nutrient reduction, for example with the nutrient work done

in this study showing that at about one-quarter of the DIN levels of the Hutt River, the shores in the Porirua Harbor were relatively free of the ring of intertidal green algae. Future controlled nutrient manipulation experiments in Hutt River tributaries, mesocosms or flumes also could be helpful in identifying more precise nutrient reduction targets. In general, coupled nutrient work that considers both watersheds and estuaries may be important for many New Zealand systems because P-limitation is common for streams (J. Zeldis, personal communication) and watershed development is increasing DIN delivery to estuarine systems.

A summary of regional data for the lower part of the North Island shows that the Hutt River is mid-way in a eutrophication sequence, with higher N but still low P levels (Fig. 6). The eutrophication sequence also involves a relative increase in N vs. P and a consequent trend towards higher N/P ratios (Fig. 6). The eutrophication sequence may involve N loading occurring first and faster than P loading, with P absorption by watershed clays (U. Morgenstern, personal communication) delaying and somewhat protecting rivers of the region from developing both high N and P. A better understanding of land-use patterns will be needed to assess appropriate remediation steps and understanding possible threshold levels beyond which P increases start to make the freshwater Hutt River P-sufficient, with algal bands then likely appearing in the river as well as the estuary.

$\delta^{15}N$ values of macroalgae in the low-salinity reaches of the Hutt River were higher than the -2 to +5‰ values generally found for algae in streams with low anthropogenic impact (Fry 1991; Fry 2002; Fry et al.. 2003; Maxwell et al.. 2008), and lower macroalgal $\delta^{15}N$ values could be targeted to help measure decreased DIN loading. This $\delta^{15}N$ monitoring would be similar to that being conducted with marine macroalgae to detect coastal sewage inputs in New Zealand (Dudley & Shima 2010;

Dudley et al.. 2010; Barr et al.. in prep), and lower algal N/P ratios also might be targeted in nutrient reduction attempts.

Sampling of consumer mussel and barnacle bioindicators showed some different geographic patterns than nutrients and macroalgae, and relatively high $\delta^{15}N$ values observed in consumers (Table 1) was consistent with high $\delta^{15}N$ of watershed nutrients that usually accompanies eutrophication (Dudley and Shima 2010).

Stable isotopes in consumers also provided an initial baseline assessment of food web status in this eutrophic estuary. Barnacles are more selective for zooplankton than mussels that feed more on phytoplankton and bacterioplankton, and barnacles generally had higher and more variable $\delta^{15}N$ values than mussels (Table 1). Higher $\delta^{15}N$ values are expected for consumers feeding at higher trophic levels (Vander Zanden et al.. 1999), and the expanded trophic web leading to barnacles showed more variable $\delta^{15}N$ along the estuarine transect than did mussels or macroalgae (Table 1). The salinity gradient in the Hutt River estuary that occurs even while there is a continual downstream surface flow means that there must be a 2-layer circulation in this estuary, with freshwater on top and salt water along the bottom, conditions that can lead to formation of turbidity maxima and particle trapping. These features may concentrate foods and generally alter the food web leading to barnacles, possibly accounting for the significantly higher barnacle $\delta^{15}N$ values seen near -1 km.

Carbon isotope values of consumers indicated possible benthic carbon inputs to the main estuary, benthic input from a tidal mudflat at +0.2 km and benthic inputs from the Waiwhetu tributary stream that enters at +0.7 km. Relatively high $\delta^{13}C$ values are observed very commonly in benthic mudflat animals in New Zealand estuaries and elsewhere (Rogers 2003; Fry et al. 2008, unpublished observations for nearby Porirua Harbour mudflat animals, Rogers and Fry) and significantly

higher $\delta^{13}C$ values of barnacle tissues observed near the mudflat at 0.2 km would be consistent with consumption of foods such as resuspended microalgae or harpacticoid copepods originating from mudflats. The finding of low $\delta^{13}C$ in barnacle and mussel shell centered further downstream at +0.7 km near the mouth of the Waiwhetu stream would be consistent with high inputs of respired CO_2 from the stream (McAllister & del Giorgio 2008). However, there is also active dredging of sediments deposited in this area by the Hutt River, so that respired CO_2 may also come from these sediments. At the time of this investigation, the Waiwhetu was being dredged, widened and rehabilitated from several decades of use as a wastewater conduit for the surrounding Seaview industrial area. Sampling in future years can test whether shell materials rebound following this now-completed rehabilitation, or whether the $\delta^{13}C$ depression persists as expected for an in-channel source of CO_2 from river-deposited sediments.

A concluding observation is that while chemical nutrient and plant measurements help show problems in bottom-up forcing of ecosystems like the Hutt River estuary, analyses of consumers offer important additional information about food webs that can be important for fisheries management. Reducing nutrient loading (oligotrophication) may reduce algal problems but have unintended effects on consumers and depress fisheries (Nixon 2003). For this reason, management may want to consider targeting a balanced program of algal and consumer metrics (Schlacher et al. 2005) when aiming for a sustainable, near-natural but unavoidably human-influenced system. This initial study of nutrients in the Hutt River should be complemented by future fisheries studies of this ecosystem to help determine appropriate nutrient targets. Studies outlined here emphasize low-flow conditions for the Hutt, but most nutrient export likely occurs in frequent high-flow conditions and fertilization effects are expected downstream in Wellington Harbour. Watershed

nutrient loading and nutrient reduction strategies for these systems needs to be assessed against any coastal ocean upwelling that also could be quite important for nutrient dynamics in the Hutt River estuary and Wellington Harbour that are downstream of the freshwater Hutt River.

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Table 1. Chemical composition for dried samples of attached green macroalgae, barnacles and mussels collected Jan-Feb 2010 along the Hutt River Estuary. Reported values are for single composite samples collected to represent site averages.

Sample	km	%N	%P	N/P_{MOLAR}	Mn	$\delta^{15}N_{ORGANIC}$	$\delta^{13}C_{ORGANIC}$	$\delta^{13}C_{SHELL}$
Green macroalgae, *Ulva intestinalis*								
	-2.2	2.9	0.16	41	1220	6.0		
	-1.8	2.4	0.15	36	824	6.2		
	-1.6	1.8	0.10	39	602	6.0		
	-1.3	2.1	0.19	25	779	6.2		
	-0.8	1.7	0.22	17	149	7.5		
	-0.5	2.0	0.18	25	166	6.8		
	0.0	2.7	0.24	25	113	7.4		
	0.6	2.7	0.25	24	145	5.7		
Barnacles, *Chaemospio* sp.								
	-0.8					10.5	-18.9	
	-0.8					11.8	-19.3	
	-0.7					10.8	-17.8	
	-0.5					9.7	-17.9	
	-0.4					8.0	-18.5	0.00
	0.0					8.2	-17.4	-0.28
	0.1					8.9	-17.5	-0.42
	0.5					9.2	-18.9	-0.69
	0.6					9.5	-18.9	-1.05
	1.5					9.1	-18.9	0.07
	2.2					10.1	-19.5	0.05
Blue mussels, *Mytilus galloprovincalis*								
	-0.4					8.2		
	0.0					8.2	-19.0	-0.67
	0.1					8.2	-19.2	-1.15
	0.5					8.4	-20.1	-1.54
	0.6					8.7	-19.7	-0.83
	1.5					8.1	-20.2	-0.44
	2.2					8.2	-19.5	-0.09

Figure 1. Map of the Hutt River estuary, with 0 km at the Hutt Estuary Bridge, -2 km near the head of tides that is about 50m upstream of the Ewen bridge, and 1.5 km at the end of the south jetty at Port Road that is the seaward end of the Hutt River estuary. Closed circles indicate sampling sites where *Ulva intestinalis* plants were abundant and collected on rocky intertidal shores. Salinity and nutrient samples (Figs. 3,4) were also collected at these sites. Barnacles and mussels listed in Table 1 were collected at a subset of these sites (the more marine sites, – 1 km to 1.5 km) and also from sites marked by open circles. All samples were collected in austral summer, January and February 2010.

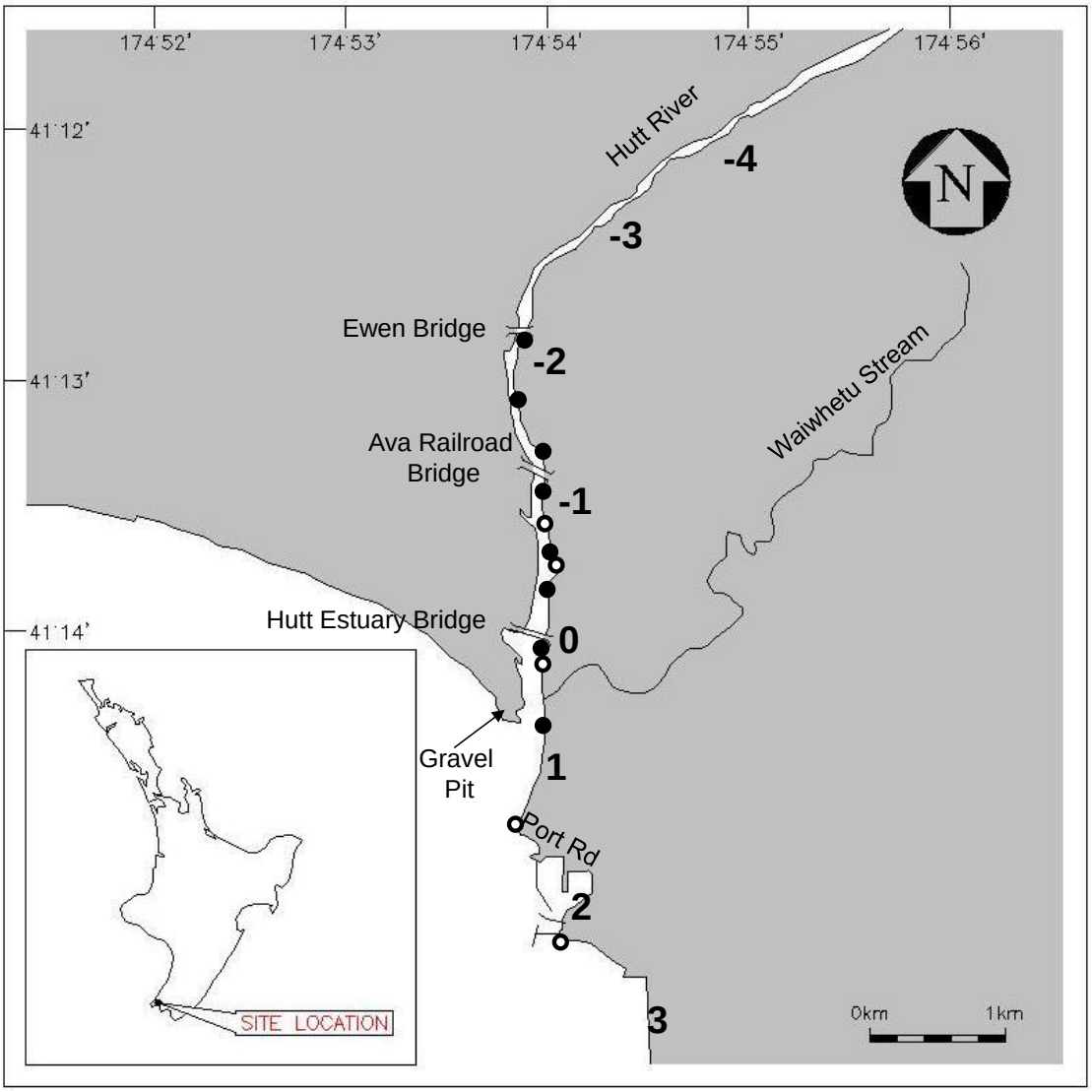

Fig. 2. Views of the mouth of the Hutt River at low tide at the tip of the eastern jetty at the end of Port Road (Fig. 1, 1.5 km sampling station). Left views are looking SE across Wellington Harbour towards Cook Strait, with little algal cover on rocks. Right views are taken at the same location but just rotated 180 degrees to look back along the south jetty of the Hutt River, with abundant green algal cover on rocks. Algae were *Ulva intestinalis*. Bottom panels are close-ups of larger pictures

Fig. 3. Salinity measured during low flow conditions on 2 summer days and 1 winter day in 2010, and general salinity zonation of the Hutt River Estuary. diamonds = summer collections March 8, 2010; squares = summer collections March 28, 2010; triangles = winter collections July 31, 2010.

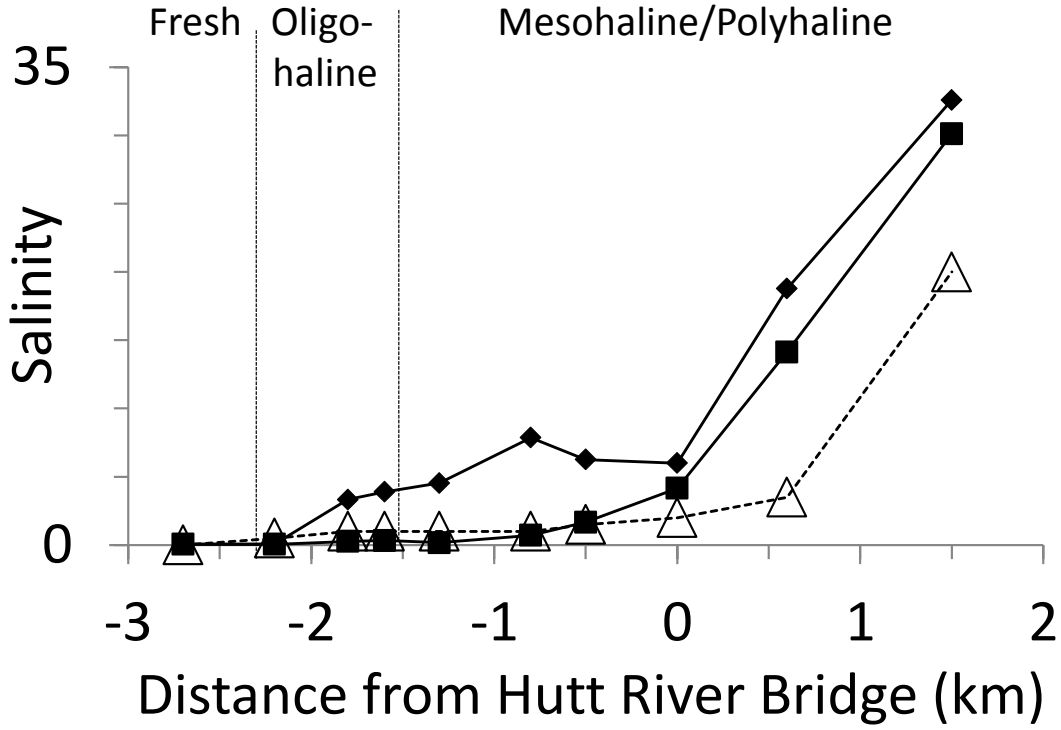

Figure 4. N and P nutrients (DIN and SRP) sampled on 3 days from the Hutt River estuary, symbols as in Fig. 3. Units for N and P are mmol m^{-3}; N/P and P/N are molar ratios.

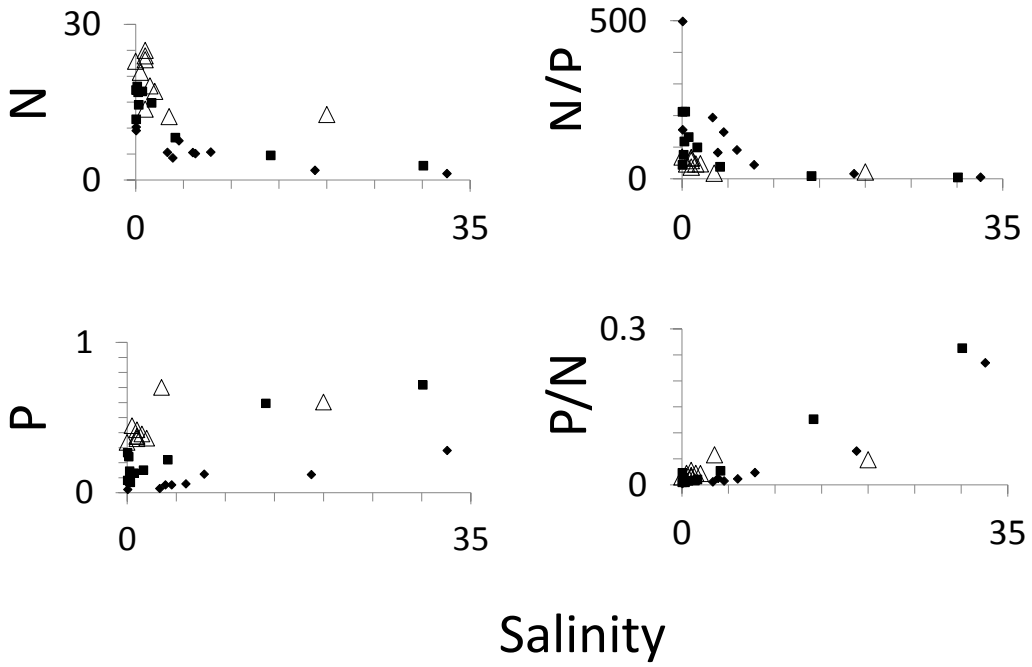

Figure 5. Carbon stable isotopes in carbonate shells of estuarine consumers collected along the Hutt River jetty near the mouth of the Waiwhetu tributary at 0.5km. Circles = barnacle shells, squares = mussel shells (from Table 1).

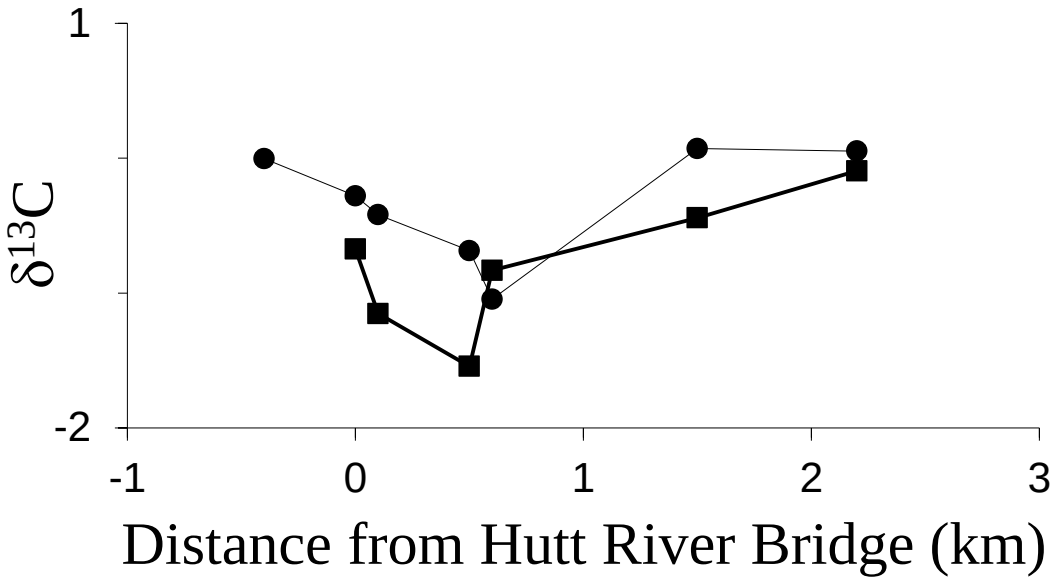

Figure 6. Average water quality in rivers and streams of the lower North Island. Data are summarized from Perrie (2009) for 56 water quality stations sampled by the Wellington Regional Council, with N = 14, 22 and 17 sites respectively in the low, medium and high nutrient categories. Data for Wellington Harbour (WH) are from Barr (2007). N (DIN) = open bars, P (SRP) = black bars, errors are SE, average N/P and P/N is given above bars.