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Habitats of particular significance for fisheries management: identification of threats and stressors to rig nursery areas

New Zealand Aquatic Environment and Biodiversity Report No. 150

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The limited capacity of elasmobranch populations to compensate for increased mortality, both in adult and juvenile stages, is widely recognized, and the management of these species should include protecting juvenile populations including the maintenance of healthy nursery areas, where they exist. The objective of this study was to identify threats to these nursery ground areas and recommend mitigation measures. New born rig (*Mustelus lenticulatus*) use inshore coastal and estuarine waters as nursery grounds, putting them in direct contact with human populations. The three main anthropogenic impacts are likely to be: 1) habitat degradation and loss due to coastal development and destructive practices, 2) sedimentation and pollution from terrestrial runoff, and 3) direct exploitation by fisheries. There are currently no studies linking land-based anthropogenic activities to population declines in any New Zealand elasmobranch species and the mechanisms by which specific stressors may impact on elasmobranch populations are not demonstrated. Therefore, a holistic approach has been taken, summarizing key metrics of anthropogenic stress such as land use, population size, transport infrastructure and fishing effort and assuming that the broader health status of the harbours is indicative of a greater capacity to function as nursery habitats; i.e. that harbours with better water quality, lower sedimentation rates and more pristine habitats are better able to provide adequate food resources and shelter from predators.

Based on the combination of historical and current survey information, Kaipara and Raglan Harbour are considered to be “Very High Value” and Waitemata, Tamaki, Manukau, and Porirua were among those considered to be of “High value” as rig nursery habitats. These six harbours were selected for assessment of potential threats and stressors. All are impacted by anthropogenic activities occurring in the coastal fringe as well as the wider catchment area. Deforestation and farming in the wider harbour catchment has resulted in elevated nutrient levels and sedimentation rates in all harbours. In the more heavily populated catchments, such as Tamaki, Manukau and Waitemata, shoreline hardening (land reclamation, marina and port construction), expansion of urban settlements and associated infrastructure (e.g. sewage, stormwater drainage, roads) resulting in increased impervious cover, are reflected in degraded water quality and reduced habitat benthic community diversity to varying extents. Juvenile rig may also be vulnerable to certain small mesh fishing methods, especially in Kaipara and Manukau harbours where recorded effort was significant.

The relatively high survey catches and large size of Kaipara Harbour make this potentially the most important rig nursery area in the country. The harbour is already significantly impacted by agricultural activities, and the southern area in particular may be especially vulnerable to the effects of future urbanization. Although smaller in size, Raglan and possibly Kawhia Harbour may also represent significant nursery areas that have been, and continue to be, mainly impacted by agricultural activities rather than urbanization. The success of the local harbour care group in improving the health of the estuary through stimulating improved farming practices in Raglan should have positive implications for estuary health and could serve as a template for other harbours, such as the Kaipara. .

Juvenile rig are potentially relatively tolerant to the effects of some of the land-based stressors such as increased sedimentation; they were caught in higher numbers in muddier stations and were found to be feeding on mud-tolerant species. However, a full understanding of how resilient juvenile rig are to anthropogenic impacts requires more detailed knowledge of how specific habitats are utilized and the mechanisms by which stressors such as degraded water quality, pollution levels, prey availability and

noise disturbance affect growth, survival and long term reproductive success. In the absence of this information it is recommended that rig nurseries with significant levels of either marine and/or land-based anthropogenic stressors are considered potentially vulnerable. It is recommended that MPI works with Regional Councils, public forums and community groups to raise awareness and prioritize agricultural and urban management practices that improve freshwater and ultimately estuarine and coastal water quality and reduce sedimentation rates. Identifying on a finer spatial scale the areas and / or habitats used by juvenile rig in highly vulnerable areas, such as Kaipara Harbour would assist the spatial planning process. The impact of fishing effort on juvenile mortality could be assessed by MPI directly by gathering information on the frequency of juvenile catches and combined with field assessment of damage or tank-based survival experiments.

1. INTRODUCTION

1.1 Overview

The low fecundity of many elasmobranch species limits their capacity to compensate for increased mortality, both in adult and juvenile stages, and it is widely recognized that the management of these species should aim to maintain reserves of reproducing adults, and also protect juveniles and young reproductive adults (Au et al. 2009, Kinney & Simpfendorfer 2009). Protection of the juvenile population requires identification and maintenance of healthy nursery areas, where they exist. Under the 1996 Fisheries Act, protection of habitats of particular significance for fisheries management is an environmental principle (Section 9(c)), and the Minister of Fisheries is required to take these habitats into account when managing fisheries. The National Plan of Action–Sharks, approved in October 2008, also states the following important action: "identification of areas of habitat of particular significance to shark species (e.g. spawning, pupping and nursery grounds)" and requires that "a range of actions will be implemented to ensure that fisheries management in New Zealand satisfies the objectives of the International Plan of Action–Sharks to ensure the conservation and management of sharks and their long-term sustainable use" (Ministry of Fisheries 2008). In order to effectively manage and protect habitats of significance, an understanding of the condition of and threats to those habitats is critical.

The inshore coastal and estuarine waters around New Zealand appear to be used as nursery grounds by new born elasmobranchs (cartilaginous fishes) of a variety of species, including rig (*Mustelus lenticulatus*). For rig, use of these areas is typically seasonal: adult females migrate into shallow coastal waters in spring–summer to give birth to live young (Oct-Dec), mate with males, and then depart for deeper water (Francis & Francis 1992, Jones & Hadfield 1985). Juveniles congregate in the shallow estuaries and harbours, which probably provide highly productive food resources and a refuge from predators until they depart in April - May (Francis & Francis 1992, Hendry 2004). The diet of juvenile rig consists mainly of benthic macroinvertebrates, particularly crustaceans such as pagurid crabs, thallassinids and polychaetes with highest foraging intensity at night (King 1982, King & Clark 1984).

Use of these near shore habitats puts rig in direct contact with human populations. The three main anthropogenic impacts upon rig are likely to be: 1) habitat degradation and loss due to coastal development and destructive practices, 2) sedimentation and pollution from terrestrial runoff, and 3) direct exploitation via fisheries (Knip et al. 2010). Current coastal development activities in New Zealand include those in the marine environment directly, such as dredging, aquaculture, and infrastructure such as pipelines and platforms. Future activities are likely to include further development of resource mining (minerals, sand, etc.), and increased development of energy infrastructure such as offshore wind and wave turbines, etc. Land-based activities that impact on coastal environments include shoreline hardening (land reclamation, marina and port construction), expansion of urban settlements and associated infrastructure resulting in increased impervious cover, as well as deforestation and farming in the wider harbour catchment. All these activities can have a detrimental effect on the freshwater systems and the estuarine environments they feed into.

Potentially important rig nursery grounds, according to the criteria of Heupel et al. (2007) have recently been identified in New Zealand (Francis et al. 2012). Following a review of available literature, a targeted set net survey identified the Arapaoa and Oruawharo arms of the Kaipara Harbour and Raglan Harbour as sites where 0+ rig were abundant and considered these to be “Very High Value”. In the Waitemata, Tamaki, Manukau, Porirua, Pelorus and Otago harbours, 0+ rig were present in varying numbers. They were not caught during surveys of Tauranga, Nelson, Farewell Spit, Whanganui and Blueskin Bay, although 0+ rig have been caught in the past in Tauranga, Tasman and Golden Bays, Akaroa and Lyttleton. Based on the combination of historical and current survey information, Waitemata, Tamaki, Manukau, Tauranga and Porirua harbours were considered to be of “High value”. Of these high value harbours, the three in the Auckland region, along with Porirua, Kaipara and Raglan were selected for assessment of potential threats and stressors.

The objective of this study was to identify threats to rig nursery habitats in New Zealand and recommend mitigation measures. There are currently no studies linking land-based anthropogenic activities to population declines in any New Zealand elasmobranch species and the mechanisms by which specific stressors may impact on elasmobranch populations are not demonstrated. Although juvenile rig are known to be non-visual predators of mud-associated crustaceans, and found in muddy, impacted estuarine eco-systems (Francis et al. 2012), there are likely to be limits to their tolerance of such conditions, and the ability of heavily impacted estuaries to provide effective nursery habitat. Such limits have not been quantified, and in the absence of such information, a holistic approach has been taken, making the assumption that the broader health status of the harbours, as reflected through water quality, pollution, sediment loads, and condition of habitats and benthic communities, is indicative of their capacity to function as rig nursery habitats, providing adequate food resources and shelter from predators (see next sections on Habitat degradation studies in relation to fish communities and elasmobranchs). There are currently no formal national criteria for rating overall health of estuaries in New Zealand, however, information on catchment land use, human population size and activities, as well as a range of indicator data from monitoring programmes designed to assess the health of coastal and estuarine environments, are available from a variety of sources. These data have been summarised in this report and assessed in relation to potential impacts on the functioning of selected harbours as rig nursery habitats.

1.2 Background

1.2.1 Habitat degradation, sedimentation and pollution

Land cover is now a well-documented and valuable indicator of the state of riverine ecosystems and numerous studies worldwide and in New Zealand have reported declines in freshwater quality, habitat and biological assemblages as the proportion of agricultural land in a catchment increases (Allan 2004, Meyer & Turner 1994, Quinn 2000, Quinn et al. 1997, Rowe et al. 1999). Before the development of pastoral agriculture in New Zealand, 80% of the land was covered in native forest. Through Maori and European settlement, large-scale deforestation has occurred and now agriculture, primarily sheep and dairy farming, is the dominant land use in the middle and lower catchment areas of most of New Zealand’s freshwater systems (Quinn 2000). Vegetation cover is an important moderator of erosion; in the Auckland region, for a given rainfall and slope combination, sediment yields from forested areas were two thirds those from pasture whilst Quinn & Stroud (2002), found that in hill-land catchments, export of sediment from pastoral land cover was up to 15-fold higher than from native forest cover. Historical reconstruction of rates of sedimentation in New Zealand have indicated that, under native forest land cover accumulation is less than 1 mm/year, increasing to several millimetres following European settlement, with more recent increases occurring in areas of pastoral land use and urbanization (see Morrison et al. 2009). The ingress of livestock into riparian areas and waterways also has damaging effects. Along with destabilization of banks and channels, increased suspended sediments, higher levels of nutrients, pesticides and herbicides are contained in runoff water from agricultural lands. Research indicates that freshwater streams can remain undamaged where agricultural land use makes up 30 – 50% of the catchment (Allan 2004). In New Zealand, impacts such as increases in pollution-tolerant species were seen where agricultural land comprises more than 30% of the catchment (Quinn 2000, Quinn & Hickey 1990).

Estuaries act as the receiving environment for freshwater systems and thus are also particularly susceptible to the effects of pastoral land use, including sedimentation, elevated nutrient levels and contaminants. The amount of sediment transported from the catchment will depend on rainfall patterns, erodability of the soil (dependent on slope and soil type), the nature of the freshwater system as well as the type of land use and management practices (Hicks et al. 2009). In addition, factors such as the shape, shoreline complexity and amount of ocean and river forcing within the estuary will also have an effect on sediment accumulation rates (Hume et al. 2007). Impacts include smothering of habitats, especially filter-feeding animals such as bivalves, reduced water clarity resulting in reduced light available to plants such as sea grass and phytoplankton and reduced photosynthetic activity, depleted algal food sources for benthos, damage and clogging of gills, and reduced burrowing activity (Nicholls et al. 2003, Nicholls et al. 2000, Thrush et al. 2004). These effects can result in changes to sediment chemistry and invertebrate community structure and decrease productivity of entire estuaries (Lohrer et al. 2004). Morrison et al. (2009) considered sedimentation the most important land-based stressor in the New Zealand coastal environment.

It is expected that, by 2030, 60% of the world's population will live in urban areas, and whilst urban land cover typically accounts for only a small percentage of a catchment area, it exerts a disproportionate negative influence on aquatic environments (Paul & Meyer 2001). Urbanization results in an increase in impervious surface cover (ISC) (e.g. roads, roofs, car parks etc.), which decreases infiltration and increases surface runoff; a 10 – 20% increase in ISC typically results in a two-fold increase in runoff over forested catchments, 30 – 50% ISC increases runoff three-fold and 75 – 100% increases runoff more than five-fold (Arnold & Gibbons 1996). Increases in volume and rate of precipitation runoff, as well as associated sewage, industrial effluent and other pollutants result in a degradation in water quality and other associated negative impacts in freshwater and estuarine systems. The amount of impervious surface cover (ISC) has been demonstrated to be an effective indicator of the intensity of human pressure and a useful predictor of declining health of urban aquatic ecosystems in many situations. For example, Wang et al. (2001) found that the amount of connected impervious surface was the best measure of urbanization for predicting fish density, species richness, diversity and index of biotic integrity score in 47 small watersheds in southeastern Wisconsin, USA. They found that imperviousness levels of 8 – 12% represented a threshold level above which, indices of condition were consistently poor. Across a range of other freshwater studies, a threshold of 10 – 25% ISC has been demonstrated to have a serious impact on water quality and biological integrity of the ecosystems (DeLuca et al. 2004, Limburg & Schmide 1990, Paul & Meyer 2001, Walsh et al. 2001, Wang et al. 1997). Figure 1 illustrates the Impervious Cover Model, developed and recently updated by Schueler et al. (2009), which defines four categories of urban streams. Streams with less than 10% IC (impervious cover) are able to retain their hydrologic function and generally support good aquatic diversity ("sensitive steams"), although this may also be influenced by other metrics such as forest cover and agricultural practices, as indicted by the range in Stream Quality ranking indicated in the model. Those with between 10 – 25% IC are defined as "Impacted streams", showing clear signs of declining health. Those with between 25 and 65% IC are classified as "Non supporting". Non-supporting streams are characterized by poor water quality and channel instability and are no longer able to support good biological diversity. Where IC increases above 60%, streams are often so degraded and modified, that they function only as urban drainage. The transition point between these categories (hatched areas) depends on the characteristics of each stream and can vary.

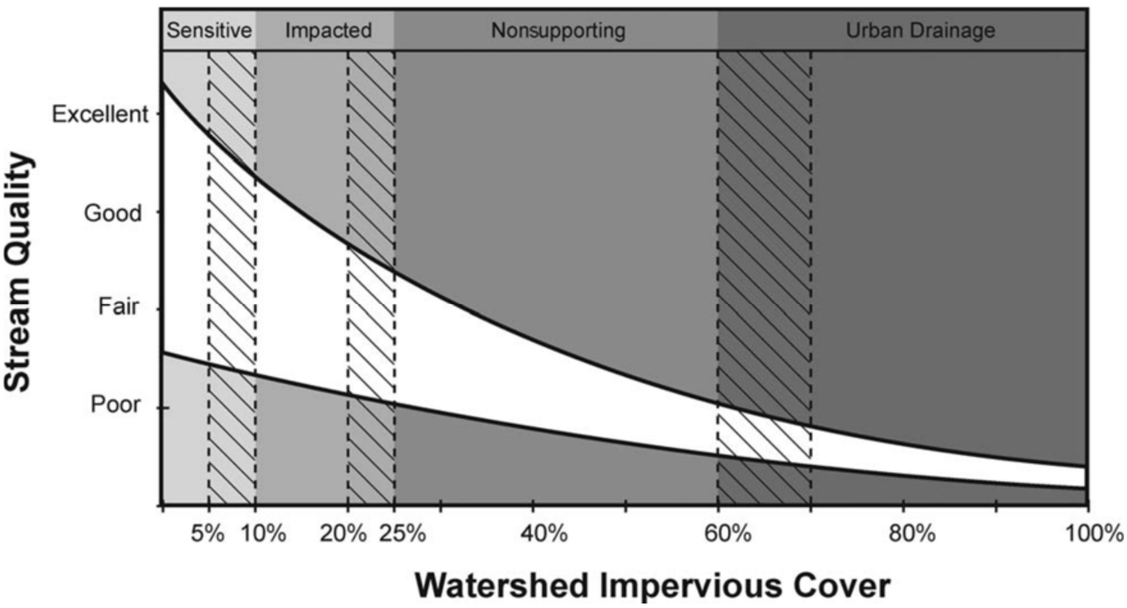

Figure 1: The Impervious Cover Model (source: Schueler et al. 2009). See above text for definitions of stream categories.

Similar relationships have been found between land use and ecosystem health in estuarine and tidal creek environments. In Chesapeake Bay, two indices of macrobenthic biological integrity were used to assess the impact of environmental and shoreline condition and riparian and watershed land use (Bilkovic et al. 2006). The indices used were the Benthic Index of Biological Integrity, (B-IBNN) and a statistical measure of the relationship between abundance and biomass curve comparisons (W-value). Shoreline condition was judged as the amount of alteration (expressed as a percentage of the total shoreline), including hardening with seawalls, revetments etc. Significant reductions in the indices were apparent when the amount of developed shoreline exceeded 10% and the developed watershed exceeded 12% of the total catchment. In a further study, subtidal habitats, shoreline condition and upland land use were linked to nearshore fish community integrity (Bilkovic & Roggero 2008). Sites with greater than 23% developed land use showed changes in fish community indices of structure and function, with lower diversity, and dominated by a few generalist species (see study for more details). Even in areas of low human development, shoreline hardening can have a negative impact as it changes the curve of the shoreline and breaks the connection between riparian, intertidal and subaqueous areas and reduces shallow water habitats. Assessment of 23 tidal creeks in South Carolina covering a range of human pressure found changes in hydrography, chemical contaminants and sediment characteristics where impervious cover exceeded 10 – 20%. At levels of 20 – 30% impervious cover, there were changes in the biological communities including declines in stress-sensitive macrobenthic species, reduced abundances of key species and altered food-webs (Holland et al. 2004).

Whilst elasmobranchs are mobile and able to remove themselves from stressed environments, species with philopatric behaviour patterns (staying near the birth place) and/or species or life stages with restricted ranges may be at greater risk to both the indirect impacts of degraded habitats (e.g. poorer foraging success, impaired growth) and direct impacts of the stressors such as pollution. Whilst few studies link elasmobranch populations directly to the catchment-scale indicators described above, a number have highlighted how increasing human populations and coastal development have had adverse impacts on populations of some elasmobranch species. In a study of thousands of underwater surveys carried out around the Caribbean between the early 1990s and 2008, the frequency of shark sightings was compared to the human population in each area and apart from nurse sharks, other species were found mainly in areas of low human population or strong fishing regulations and/or marine conservation (Ward-Paige et al. 2010). Walker (1998) described how the Geelong Arm of Port Phillip Bay, South Australia, was formerly an important nursery area for a number of shark species, particularly school shark (*Galeorhinus galeus*) with high catches of juveniles recorded in the early 1950s. These catches declined sharply by the 1990s, thought to be due in part to habitat modification through heavy industrialization of this area. Similar declines in sandbar shark nursery grounds have been reported for certain areas on the east coast of the United States, attributed to urbanization and habitat degradation in those areas (McCandless et al. 2002). A 23.5% decline in survival rate of young lemon sharks (*Negaprion brevirostris)* was linked to a 17.7% decline in seagrass habitats in the Bahamas, caused by increasing coastal development (Jennings et al. 2008). The bull shark (*Carcharhinus leucas*) has been able to adapt to and utilize urbanized rivers and estuaries (Heupel & Simpfendorfer 2011), with a recent acoustic tracking study in the Nerang River, Queensland, finding that neonates and juveniles utilized both natural and artificial (canal) habitats, although a preference for natural habitats was evident for neonates (Werry et al. 2012). However, over the course of half a century, a significant decline in juvenile bull sharks in an estuary in southeastern Louisiana (Lake Pontchartrain) was thought to be closely linked to the decline of vegetated shallow-water nursery habitats due to anthropogenic pressures, including extensive hardening of the shorelines through conversion to concrete sea walls and riprap (rock or rubble armouring) (O'Connell et al. 2007). The smalltooth sawfish (*Pristis pectinata),* has also been found to make use of seawall lined creeks linked to natural estuarine habitats (Poulakis et al. 2013), but is also critically endangered. Habitat loss and degradation are thought to be significant contributing factors (Simpfendorfer et al. 2010), and habitat restoration in the Everglades National Park is thought to have been instrumental in preventing its extinction altogether (Carlson & Osborne 2012, Carlson et al. 2007, Heupel & Simpfendorfer 2011, Werry et al. 2012). An example of previously degraded habitats being restored and benefitting elasmobranch populations is the Bolsa Chica Tidal basin in southern California, where large numbers of juvenile gray smooth-hound sharks (*Mustelus californicus*) now occupy the estuary in Spring and Summer (Espinoza et al. 2011).

Direct effects of stressors associated with anthropogenic impacts such as eutrophication and pollution have been demonstrated in some elasmobranch species. Elevated nutrient levels often cause eutrophication and associated increases in nuisance algal blooms and reductions in dissolved oxygen. Elasmobranchs have been shown to move away from hypoxic conditions (Carlisle & Starr 2009, Heithaus et al. 2009) or alter their swimming behaviour and respiration (Carlson & Parsons 2001). Being relatively long-lived, with a slower metabolism, and being a predator placed relatively high in the food chain, many elasmobranchs accumulate concentrations of pollutants that can potentially have adverse effects on reproductive, immune, endocrine and nervous systems (for a recent review see Gelsleichter & Walker 2010). For example, elevated levels of compounds such as dichlorodiphenyltrichloroethane (DDT) and other organochlorine pesticides (OCPs) have been measured in elasmobranch species, demonstrating potential for bioaccumulation, in larger pelagic and deepwater species in particular (Johnson-Restrepo et al. 2005, Strid et al. 2007, Webster et al. 2011). Smaller coastal sharks were found to contain lower levels, most likely due to their lower trophic level (e.g. Fairey et al. 1997), but in the blacktip reef shark (*Carcharhinus limbatus*), higher levels of OCPs in less than 3 month old neonates in northwest Atlantic suggest the possibility of maternal transfer to offspring via yolks and placentas (Gelsleichter et al. 2007). Organochlorines have also been linked to infertility in bonnethead sharks *Sphyrna tiburo* (Gelsleichter et al. 2005). Like OCPs, Polychlorinated Biphenyls (PCBs) and dioxins can bioaccumulate to high levels and are known to cause health effects in vertebrates such as foetal or embryonic abnormalities, reproductive dysfunction and immunosuppression, but are only recorded as reaching dangerous levels in high trophic level sharks (Strid et al. 2007). Emerging pollutants such as brominated flame retardants are likely to accumulate and could pose risks in the future along with chemicals used increasingly in pharmaceuticals and personal care products – disrupting endocrine function and inhibiting cellular defences. Of the heavy metals, only mercury is known to have exceeded thresholds associated with adverse health effects in elasmobranchs (Gelsleichter & Walker 2010).

The water-based activities of increasing human populations can also impact on elasmobranch populations either directly on their behaviour, or indirectly via degradation of habitats. Increased boating traffic, and other water-based recreational activities such as diving were found to disrupt mating activities of nurse sharks *(Ginglymostoma cirratum)* in Florida (Carrier & Pratt 1998). More broadly, increased vessel traffic, particularly large vessels, may require channels to be dredged and the development of port facilities and marinas, resulting in habitat loss, increased risks of pollution incidents and introduction of non-indigenous biota. High density marina facilities also increase the contamination of water and sediments from the metals and booster biocides leached from antifouling paints applied to the hulls of vessels. Experimental exposure to acute waterborne concentrations of tributyltin oxide has been shown to be highly toxic to yellow sting ray *Urolophus jamaicensis*, causing membrane degradation, cell loss and tissue exfoliation (Dwivedi & Trombetta 2006)

Other activities in the marine environment that have the potential to degrade habitats include aquaculture and mining activities. In their review of the ecological effects of intertidal oyster aquaculture, Forrest et al. (2007) concluded that biosecurity threats and impacts on the seabed in the immediate vicinity of the farm were the most significant ecological issues. The spread of pest organisms has the potential to lead to ecologically significant and irreversible changes to coastal ecosystems much broader than the site of the farm itself. Seabed effects such as direct smothering with biodeposition, organic enrichment and alteration of sediment grain size, lead to enhanced microbial activity and oxygen depletion and resultant displacement of large-bodied organisms and a decline in species diversity. Effects extend no more than a few tens of metres from the perimeter of the farm and impact can depend on the stocking density and extent of flushing the site experiences.

1.2.2 Fishing Pressure

Alongside habitat degradation, sedimentation and pollution, a main anthropogenic impact on elasmobranch populations is direct mortality caused by fishing pressure. In the case of juvenile rig in their nursery habitats, 0+ rig would not be targeted directly, but they may be caught as a bycatch of both recreational and commercial fishing activities. Juveniles are small, mostly 30–50 cm total length, and averse to taking baited hooks, so they are not vulnerable to all fishing methods. The most likely sources of fishing mortality are therefore set nets, drag nets and ring nets. These methods are highly length-selective: large mesh nets (greater than 100 mm mesh) will not usually retain small rig except for occasional individuals that become tangled rather than gilled or wedged. However, recreational and commercial fishers are permitted to use smaller mesh nets in estuaries for targeting grey mullet and kahawai (90–100 mm mesh), and yellow-eyed mullet, garfish, pilchards, and herrings (25 mm) (http://www.fish.govt.nz/en-nz/Recreational/default.htm). These fishing gears may be a source of juvenile rig mortality in their nursery grounds, although no data is available to enable this to be quantified.

1.3 Objectives

This report addresses the objectives of Ministry of Fisheries research project: SEA2010-15

Specific objectives:

1. Identify threats to these nursery ground areas and recommend mitigation measures.

2. METHODS

Based on the literature reviewed for assessing and scoring the health of and risks to both freshwater and estuarine ecosystems, information was compiled on the activities, potential stressors and indicators outlined in Table 1 for each of the six harbours. A variety of place names and sites are referred to, and the reader is referred to the original reports for the location of these. This information was used to score each harbour for each potential stressor using quantitative indicator data where available, and qualitative estimation where adequate data were not available. These scores were used to build an overall picture of the threat status for each harbour.

2.1 Harbour Classification, Catchment Land Use, Impervious Cover and Human Population

Definition of the catchment area and land use for each harbour was carried out in ArcGIS using information downloaded from the River Environmental Classification (REC) database (http://www.niwa.co.nz/our-science/freshwater/tools/rec.) and the Ministry for the Environment's Land Use and Carbon Analysis System (LUCAS). From the REC, polygons defining areas of land associated with freshwater catchments were used to build a shapefile which defined the total catchment area of freshwater systems draining into each of the harbours. Land Use Mapping (LUM) data as of 2008 were then downloaded from the LUCAS website. These data are derived from 10 m spatial resolution satellite imagery, processed into standard reflectance images and categorized into land use types (Ministry for the Environment 2010). For details on the methods and land use category definitions see http://www.mfe.govt.nz/issues/climate/lucas/. An intersection of the harbour catchment areas and the land use layer provided information on the proportion of different land uses which may be affecting each harbour.

Information on the characteristics of the estuaries themselves, such as the total area at high tide, intertidal area, mean annual river discharge and Catchment to Estuary Area (CER) were collated from the New Zealand Estuary Environment Classification database (Hume et al. 2007). The CER indicates the capacity of an estuary to accumulate sediment runoff. The database was also the source of estimates of the proportion of the intertidal areas classed as sand, mud and mangrove, calculated from the GIS shape files derived from the LINZ 1:50000 digital topographic database. Sand and mud are combined as they cannot be differentiated using this method.

For the Auckland harbours, the percentage of Impervious Surface Cover (roads, roofs, car parks etc.) was available from Auckland Council as a layer that could be intersected with the harbour catchment areas to estimate a proportion of the catchment that would be classified as ISC. These data were not available for the other harbours. Information on the size, intertidal area and mean annual river discharge of each harbour were also sourced from the REC database.

Human population statistics were sourced from the National Population Census (http://www.stats.govt.nz/Census/2006CensusHomePage). Population data (2006 Census, 2010 and 2031 estimates) by area units ("suburbs") were matched as best as possible to catchment areas. These boundaries did not always match the harbour catchment boundaries, but the information was considered sufficient for the purposes of assessing levels of human population pressure among harbours. Information on the number of bridges, extent of the road network, and vehicle kilometres travelled were sourced from the NZ Transport Agency website, which documents road assets by region and district (http://www.nzta.govt.nz/resources).

Table 1: Land and Water-based threats to estuarine habitats, their effects and potential indicators of the levels of these stressors.

Activity	Potential Stressor	Potential Effects	Indicators
Land use change to pastoral agriculture	Increased sediment runoff	Smothering of some habitats, increased mangrove habitat. Reduction in mud-sensitive species and diversity of biological communities	Sediment Accumulation Rate (SAR), Turbidity, % mud in sediment, mangrove cover, benthic community health indices
	Increased nutrient run-off from fertilizer applied to land, and effluent discharges.	Eutrophication, nuisance algal blooms, low dissolved oxygen	Water quality indicators, Benthic community health indices
	Stock access to waterways - damage to waterways, bacterial contamination	Habitat loss, microbial pollution	Sediment Accumulation Rate (SAR), *E. coli* counts
Land use change to urban settlement	Building and other development	Increased erosion and run off, pollution, increased turbidity, Reduction in mud-sensitive species and diversity of biological communities	Sediment Accumulation Rate (SAR), water quality and sediment contamination, Impervious surface cover, Benthic health community indices
	Sewage and storm water discharges	Elevated nutrient levels and pollution (e.g. heavy metals), Nuisance algae	Water quality and sediment contamination (e.g. levels of heavy metals), Benthic health community indices
	Industrial discharges	Pollution and potential for acute and chronic toxic effects	Water quality and sediment contamination Biological effects indices
	Shore hardening	Loss of intertidal habitat	% change in intertidal habitats
Estuary use	Fishing pressure	Direct mortality on juveniles	CPUE, catch, bycatch
	Boating traffic – noise and pollution	Disturbance, acute pollution events, contaminant build-up, non-indigenous, invasive species	Number of moorings / marinas, vessel traffic statistics, sediment contamination and count / presence of invasive species
	Invasive species	Out-compete native species, reduce diversity of biological communities	Invasive Species counts, Benthic community indices
	Dredging activities	Removal and smothering of habitats, increased turbidity, reduced diversity of biological communities, and release of contaminants from sediment	Occurrence - spatial and temporal extent, volume of sediment removed, sediment contamination and oxygenation levels, benthic community health indices

Activity	Potential Stressor	Potential Effects	Indicators
	Aquaculture	Deposition of faeces, uneaten feed, shell accumulation, elevated nutrients, invasive species and parasites, reduced diversity of biological communities	Occurrence - spatial and temporal extent, nutrient enrichment, sediment and oxygenation levels. benthic community health indices
	Power generation	Habitat loss, smothering, noise pollution, electromagnetic field effects	Occurrence - spatial and temporal extent, sediment contamination, benthic community health indices

2.2 Environmental Monitoring Data

Local and regional councils conduct environmental monitoring of rivers and estuaries to varying extents. Technical and State of the Environment reports and website summary "Report Cards" were sourced from Northland Regional Council (Northern Kaipara), the Auckland Council (Southern Kaipara, Waitemata, Tamaki and Manukau), Waikato Regional Council (Raglan), Porirua City Council and Greater Wellington Regional Council (Porirua), along with information from other literature sources. The reader is referred to the original reports for locations of the various monitoring sites.

2.2.1 Water Quality

For freshwater and estuarine water, the following indicators of water quality were available in some format for most harbours;

- Dissolved oxygen
- Turbidity
- Total phosphorous (TP)
- Total nitrogen (TN)
- Ammoniacal nitrogen (Amm. nitrogen)
- Nitrite-nitrate nitrogen (NNN) / Nitrate (N)
- *Escherichia coli* / Faecal coliforms / *Enterococci*
- Total Suspended Solids (TSS)

These monitoring data are assessed against guideline trigger values such as the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC 2000), and often reported in terms of the proportion of samples that exceeded these guideline levels. The guideline values used by each council are listed in Table 2, and did vary among regions; for instance, Auckland trigger levels were based on local reference sites believed to represent natural conditions, and Waikato Regional Council used guidelines based on a number of national and other sources (see Tulagi 2011, for more detail). Guidelines for microbial contaminants used by the different councils are based mainly on trigger values recommended in the Ministry for the Environment microbial water quality guidelines (2003), although some monitoring programmes used different values; Northland Regional council water quality monitoring programmes use trigger values recommended for livestock drinking water, as well as contact recreation.

Table 2: Guideline values for water quality. Values in brackets are for marine water where specified. Guidelines for microbial contaminants are MfE (2003).

Parameter	ANZECC (2000) Trigger value Lowland rivers	Auckland-specific values: Waitemata. Manukau, Tamaki and S. Kaipara	Greater Wellington Council: Porirua	Northland Regional Council: N. Kaipara	Waikato Council: Raglan
Dissolved oxygen (%)	98–105%	70 –140% (>78%)	> 80%	98–105% (80%)	>80%
Turbidity (NTU)	<5.6	<30 (<7.7)	< 5.6	<5.6 (5 – 10)	<5 (<10)
Total phosphorous (mg/L)	<0.033	<0.072 (0.062)	<0.033	<0.033 (0.03)	<0.04 (<0.03)
Total nitrogen (mg/L)	<0.614	<1.4	<0.614	<0.614 (0.3)	<0.5
Nitrite nitrate nitrogen (NNN)(mg/L)	<0.444	- (<0.105)	<0.444	<0.444	
Nitrate (g N/m^3)					(< 0.015)
Ammoniacal nitrogen (mg/L)	<0.021	<0.065	<0.021	<0.021 (0.015)	<0.88 (<0.91)
E. coli (cfu/100 mL)*1	<550 / <260*3	<550 / <260	<550 / <260	<550 / <260/ 126*5 (<260)	<550/<55
Faecal coliforms (MPN/100 mL)*2	<150		(median <14)*4	(Single sample <150)	(median <14)
Enterococci (cfu / 100 mL)	< 140	< 140	<140	<140	<280

*1 cfu = colony forming unit (ie viable cells). *2MPN= Most Probable Number (estimate of number of viable cells)*3MfE provides two levels; if lower level exceeded, "amber mode" requires increased sampling frequency, if higher level exceeded; "red mode" requires warnings and finding the source. *4Relates to guidelines for shellfish monitoring and refers to median of samples over a season. *5 Livestock water trigger value recommended by ANZECC (1992).

Overall water quality indices (WQI) are also used by Councils to compare between sites and years. Auckland Council (formerly ARC) use an index developed by the Canadian Council of Ministers for the Environment (C.C.M.E 2001), which is based on seven water quality parameters; dissolved oxygen, pH, turbidity, ammoniacal nitrogen, temperature, total phosphorous and total nitrogen (Neale 2010b). It incorporates the percentage of parameters that failed to meet guidelines at least once, the frequency of failure, and the amount by which values exceeded the value. The index value calculated ranges from 0 – 100, which is categorized into four levels (see below). A similar WQI has been recently introduced by Northland Regional and Greater Wellington Council, and is derived from the median values of six variables; visual clarity, dissolved oxygen, dissolved reactive phosphorus, ammoniacal nitrogen, nitrite-nitrate nitrogen and *E. coli*. The same four categories are applied, relating to equivalent numbers of median indicator values complying with the guidelines (Perrie & Cockeram 2009);

- "Excellent" when the WQI value is over 90, or median values for all six parameters are within guidelines;

- "Good" when the WQI value is 70–90, or median values for five of six parameters are within guidelines;
- "Fair" when the WQI value is 50–70, or median values for three or four parameters are within guidelines;
- "Poor" when the WQI value is less than 50, or median values for fewer than three parameters are within guidelines.

Waikato Council did not calculate an overall Index, but water quality was classified as "Satisfactory" where it meets Council-specified guideline values (Table 2) and "Excellent" where it meets more stringent guidelines derived from expert opinion (Tulagi 2011). Water quality that does not meet these guidelines is classed as "Unsatisfactory".

2.2.2 Sedimentation

Sedimentation rates are estimated by calculating the thickness of sediment between layers in cores which have been dated using complementary methods (see individual reports cited for more details). Sediment Accumulation Rates (SAR) for the different harbours were collated from various sources. The methods used included pollen profiles and radioisotopes (Swales et al. 2013; 2005b; 2002a & b; Reed et al. 2008; Abrahim 2005), radiocarbon dating (Swales et al. 2005a; Hume & McGlone 1986) and current and historical sea level and bathymetry information (Gibb & Cox 2009). In some studies a harbour wide estimate was provided whilst in other areas, rates have been estimated in particular areas or tributaries.

2.2.3 Pollution

Levels of the heavy metals zinc, copper, lead and polycyclic aromatic hydrocarbons (PAHs) were monitored in all harbours, along with a variety of other contaminants and organochlorine pesticide residues such as DDT in some harbours. Levels of heavy metals were reported as either total recoverable metals from the whole sediment sample (sieved through a 2 mm sieve to remove debris); the <500 µm (0.5 mm) fraction, which approximates to the total sediment sample; or the weak acid extractable metals from the under 63 µm silt fraction (Mills et al. 2012). The latter more closely approximates to the more bioavailable metal fraction, but was not available for all harbours. Levels of organic contaminants (PAHs) are given as concentrations "normalised" to a sediment organic carbon content of 1%. ANZECC sediment quality guidelines (Table 3) provide low and high trigger values; the ISQG-low is nominally indicative of contamination concentrations where the onset of biological effects could occur, whilst the ISQG-High value indicates concentrations where significant biological effects are expected. The Auckland Regional Council's Environmental Response Criteria (ERC) amber and red thresholds were developed as conservative early warning signs of environmental degradation, and are also used by other Councils when assessing levels of contaminants. These guideline values refer to the total recoverable metals from the 0.5 mm fraction in the settling zone (SZ), and the greater of the two values within the outer zone (OZ).

Table 3: Guideline values (ANZECC and Auckland-specific) for selected contaminant levels in sediments.

	ANZECC(2000)		Auckland Regional Council ERC	
	ISQG-Low	ISQG-High	Amber	Red
Metals (mg/kg dry weight)				
Zinc	200	410	124–150	>150
Copper	65	270	19–34	>34
Lead	50	220	30–50	>50
High Molecular Weight PAHs [1] (µg/kg dry wt)	1 700	9 600	660	1 700
Total PAHs	4 000	45 000		
Total DDT [2] (µg/kg dry wt)	1.6	46		3.9

[1]High Molecular Weight PAHs are the sum of the concentrations of fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[a]pyrene and dibenzo[a,h]anthracene.
[2]Total DDT is the sum of the concentrations of 2,4-DDE, 2,4-DDD, 2,4-DDT, 4,4-DDE, 4,4-DDD and 4,4-DDT.

2.2.4 Habitats and Biological communities

The New Zealand Estuary Environment Classification database provided proportions of the estuary classified as sand / mud and mangroves, which was supplemented with information from other sources for each harbour where available. Some form of soft sediment invertebrate community monitoring was carried out in all harbours, but methods and data presentation were not always directly comparable, ranging from species counts, abundance and diversity indices, to biotic indices based on multivariate analysis of community structure, or the overall community sensitivity / tolerance to pollution and enrichment. Benthic Health Models (BHM) (Anderson et al. 2006) and the Traits-Based functional Index (TBI) (van Houte-Howes & Lohrer 2010) have been developed for Auckland Council monitored harbours. The Benthic Health Models link macrofaunal community structure to gradients in sediment mud content and sediment heavy metal levels using Canonical Analysis of Principal coordinates (CAP) of biotic dissimilarities among sites to predict their relative position along each of the gradients (PC axes). The TBI is based on seven biological traits, representing broad categories relevant to ecosystem function, all of which had strong and significant negative responses to both mud and metals (see van Houte-Howes & Lohrer 2010 for more detail). The Index value is calculated by summing the taxonomic richness in each of the seven trait groups per site to give SUM_{actual}. A maximum expected value called SUM_{max} (i.e., a non-polluted reference value) is identified from reference information (see table 2 of Lohrer, D. & Rodil 2011), and a minimum possible value (i.e., a completely defaunated site) is set at 0. The TBI formula is $1 - (SUM_{max} - SUM_{actual})/ SUM_{max}$, which standardises the index values to fall between 0 and 1. Values near 0 indicate highly degraded sites, and values near 1 indicate the opposite (Hewitt et al. 2012). The BHMs have been found to reflect the pollution gradients well (Anderson et al. 2006), and the CAP scores (either alone, or more recently combined along with the TBI value) can be used to give an overall ecological health ranking on a five point scale from healthy (lowest CAP scores) to least healthy (highest CAP scores). Least healthy / most degraded sites, are characterized by elevated levels of pollutants (at concentrations over TEL) and tend to have fewer rare and large species, reflecting reduced biodiversity, stability and resilience of these communities, since large taxa are known to have a disproportionate contribution to ecosystem functioning such as bioturbation, oxygen, carbon and nutrient exchanges between water and seafloor sediments.

The Greater Wellington Regional Council uses the AZTI Marine Benthic Index (AMBI), originally developed by the Spanish Technological Institute for Fisheries and Food (AZTI) to assess the health of soft-bottom benthos in European estuarine environments (Borja et al. 2000), but now adapted and applied to many other regions. The index is derived from the proportions of individual abundances in five ecological groups relating to the degree of sensitivity or tolerance to an environmental stress gradient. The formula produces a Biotic Coefficient that, similar to the BHMs, can be used to grade the macrofaunal community on a five point scale from “Unpolluted” to “Azoic (devoid of life)” (Robertson & Stevens 2010).

2.3 Fishing Threats

Extracts of fishing effort using small mesh nets in coastal waters were obtained from the MFish catch-effort database *warehou*. Fishing methods extracted were set net, drag net, ring net and beach seine. Only data from the three most recent fishing years (2007–08 to 2009–10) were extracted because there have been recent changes in the distribution and quantity of set net fishing effort around New Zealand, and only recent information is relevant to this objective. Fishing effort was used instead of landings data because catches of 0+ rig are probably not reported: fishers are likely to return these small fish to the sea. However, fishing mortality of juvenile rig may be inferred from the distribution, seasonality and quantity of fishing effort using small mesh nets in relation to known habitat and timing of nursery usage by rig.

The Netting Catch Effort Landing Return that was introduced in October 2006 records latitudes and longitudes for all sets, so it provides good information on small-scale distribution of fishing effort. Unfortunately it is only used by vessels longer than 6 m, which excludes most of the smaller trailer boats which fish in harbours. Consequently data from Catch Effort Landing Return (CELR) forms which usually record fishing locations grouped into large statistical areas (Figure 2) was also extracted. Most fishing in shallow estuaries and harbours is carried out by small boats that typically fish in only one statistical area per day, so effort on CELR forms can be mapped accurately to statistical area. Set net bans were implemented in coastal waters of much of the west coast North Island out to 4 NM in 2003 and then extended out to 7 NM in 2008 (Ministry of Fisheries 2011), resulting in the cessation of most coastal set net fishing along that coast. The relationships between statistical areas and likely regions of inshore net fishing during the period analysed in this study are as follows (see Figure 2):

Statistical Area 007 – Inner Hauraki Gulf including Firth of Thames
Statistical Area 039 – Porirua Harbour and coastal waters of Manawatu
Statistical Area 041 – Kawhia and Aotea harbours and a small length of coastal waters north of New Plymouth
Statistical Area 042 – Raglan Harbour and Waikato River mouth
Statistical Area 043 – Manukau Harbour
Statistical Area 044 – Kaipara Harbour

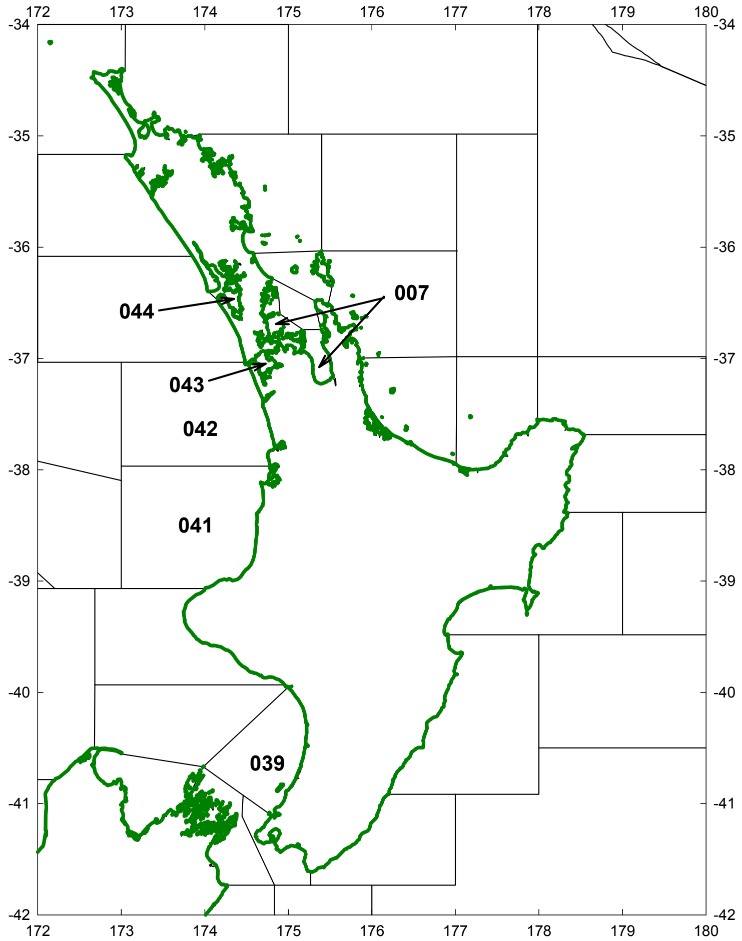

Figure 2: New Zealand fisheries Statistical Areas used for analysis of net fishing effort in or adjacent to harbours identified as rig nurseries.

Areas in the mouths of Kaipara, Manukau and Raglan harbours and Waikato River are also closed to set netting:
(http://www.fish.govt.nz/en-nz/Recreational/Fishery+Management+Areas/Auckland+and+Kermadec+Areas/Closed+and+Restricted+Areas.htm)

Mesh sizes and lengths (which are supposed to be recorded in millimetres and metres, respectively) are often recorded erroneously on CELR forms. Sometimes mesh size and net length are transposed (entered in the wrong columns), and sometimes mesh sizes are reported in inches. We groomed the mesh size and net length data to correct these obvious errors as follows:

- If mesh size exceeded 200 and net length was less than 200, the values were reversed
- If mesh size was less than 5.7, it was assumed to be recorded in inches and was multiplied by 25.4 to convert to millimetres

Set net length-selectivity curves have been estimated for the Australian gummy shark (*Mustelus antarcticus*), a species that is almost identical in body shape to rig (Kirkwood & Walker 1986). The relative selectivity (compared with a maximum of one) for 50–59.9 cm long gummy shark (the smallest size class for which selectivity was estimated) in five-inch (127 mm) mesh nets was estimated to be extremely low (0.04). However, the relative selectivity of the same size class in four-inch (102 mm) set nets was moderate (0.47). Our unpublished data show that 0+ rig are occasionally caught in 4.5-inch (114 mm) mesh set nets. In this study we included only fishing effort for set nets and drag nets with mesh sizes of 100 mm or less, because most 0+ rig are shorter than 50 cm, so larger nets are unlikely to retain significant quantities. Ring net and beach seine sets did not have mesh size measurements, so all sets for those methods were included. A fishing event was defined as a unique trip-day-method-area combination.

3. RESULTS

3.1 Harbour characteristics and human populations

The six harbours assessed varied in the size of the surrounding catchment area, size of the estuary itself, volume of water discharged and neighbouring human population (Table 4). All harbours except Porirua are classed as type F estuaries, which are described as being shallow basins with complex shorelines and extensive intertidal areas (Hume et al. 2007). The tidal prism of type F estuaries makes up a large proportion of tidal volume but the upper arms of these harbours are susceptible to sediment accumulation. Porirua is classed with type E estuaries, which are also shallow, but tend to be slightly elongate with a simple shoreline. Like type F estuaries, they have extensive intertidal areas and the tidal prism makes up a large proportion of the tidal volume, but are less susceptible to sediment accumulation. The difference in the ratio of catchment to estuary area (CER, Table 4) indicates the capacity of the estuary to accumulate sediment runoff. The higher the CER value, the larger the catchment area in comparison to the estuary area and the greater potential for infilling of the estuary with sediment. The highest CER values were for the smaller estuaries, Porirua and Raglan, indicating that these sites are more vulnerable in terms of their limited ability to accommodate sedimentation. Appendix A contains figures outlining the catchment areas of each harbour.

Table 4: Summary information on the size of harbours and their catchments. CER = Catchment to Estuary Area. Harbours are ordered according to proportions of key Landuse types (see Figure 3).

	Kaipara	Raglan	Manukau	Porirua	Waitemata	Tamaki
Catchment Size (km^2)	5676.6	522.73	1022.6	210.66	427.28	108.83
Mean Annual River Discharge (cumecs)	302	26.86	42.52	8.77	19.72	4.13
Estuary area at high tide (km^2)	743.1	31.8	365.6	7.5	79.8	16.96
Intertidal area (%)	42	69	62	11	36	40
CER	7.6	16.4	2.8	28.1	5.35	6.42
Estuary Type	F	F	F	E	F	F

The northern half of the North Island, where five of the six harbours are located, contains just over half (53%) of New Zealand's total population, with the Auckland region home to one third of the population (Statistics New Zealand).

Table 5 gives estimated population size, density and projected increases for each catchment. Boundaries used for National Census statistics do not exactly match those of the harbour catchments and so population estimates are approximate only.

Much of the Kaipara catchment area is zoned as rural with relatively low populations. Within the northern part, the Kaipara District population was estimated at 18 950 for 2010 and declining. This includes the Northern harbour towns of Dargaville, Paparoa, and Mangawhai but does not include those living in the full northern catchment which includes parts of the Far North and Whangarei districts. In its 2007 State of the Environment Report, Northland Regional Council identified coastal development in the Northern Kaipara as a key pressure as indicated by the increase in subdivision applications (1049 applications were granted between 2005 and 2007 within 1 km of the Kaipara coast). The southern part of the harbour catchment is included within the Rodney district, which has an estimated population of around 100 000. However, the majority of this population is outside the harbour catchment area on the east coast north of Auckland; the approximate estimate for 2010 within the southern Kaipara catchment area was nearly 30 000 people. This includes the Kumeu – Helensville region, with an estimated electoral population of over 25 000 and where future growth is expected to be high (3–5% per annum).

Table 5: Human populations within the regions of the selected harbours (data compiled from Statistics New Zealand and regional council websites).

Human population	2006 census	2010 Population estimate	Density at 2010 (no./km^2)	2031 Population estimate	Estimated Density Increase (no./km^2)	Projected Increase in no. per annum
Kaipara Harbour		**~ 40 – 50 000**	**<10**	**~ 62 000**	**~3**	**~1.40%**
Kaipara District (North)	18 135	18 950	6	18 450	0	0.07%
Rodney District(South)	89 559	100 000	40	139 900	16	2.24 %
-approx. Kaipara catchment		29 000	14	~40 000	~10	2.35%
Raglan Harbour		**<5 000**	**<10**	**~6 000**	**~2**	**~1.00%**
Raglan Settlement	2 637	2 760		3 190	1.86	0.80%
Waikato District	43 959	48 300	10	58 700	3.08	1.34%
Porirua Harbour		**~85 000**	**300 - 400**	**~97 000**	**~90**	**~0.90%**
Porirua City	48 546	52 100	286	55 600	38.76	0.60%
Manukau Harbour		**~450-500 000**	**450 - 500**	**>600,000**	**~200**	**~2.0%**
Manukau City	328 968	375 700	682	532 100	368.8	2.46%
Papakura City	45 183	49 800	405	64 100	153.8	1.67%
Franklin District	58 932	65 200	30	85 900	12.31	1.83%
Waitemata Harbour		**~350 - 400,000**	**~ 800**	**~500,000**	**~350**	**~1.80%**
Auckland City	404 658	450 200	425	584 500	169.8	1.77%
Waitakere City	186 444	208 100	567	272 000	235.3	1.85%
North Shore City		212 200	1632	250 000		1.55%
Tamaki Harbour		**~200 – 250 000**	**~ 2000**	**~350 000**	**~1000**	**~2.50%**
Manukau City	328 968	375 700	682	532 100	368.8	2.46%
Auckland City	404 658	450 200	425	584 500	169.8	1.77%

Raglan is a satellite urban community that experienced a significant increase in population from the mid 1980s until the mid 1990s, but growth has been slower since 2000 (Waikato District Plan). The estimate for the wider harbour catchment is fewer than 5000 people with a modest increase in population predicted. The Porirua City territorial authority population was estimated at just over 52 000 in 2010, with a 2010 estimate of around 85 000 living within the wider harbour catchment area that includes outer parts of Wellington city. This harbour catchment population estimate gives an estimated overall density for the region of around 400 people/km^2. The current wider Auckland population was estimated to be around 1.4 million people. Most of the population lives within Auckland and Manukau City regions (31 and 25% respectively). These areas border parts of the Manukau, Waitemata and Tamaki. The overall population is expected to increase to nearly two million by 2031 (Statistics New Zealand), with particularly large increases expected in the Manukau City territorial authority (375 700 increasing to 532 100), which includes parts of both Tamaki and Manukau harbour catchments. Large increases are also expected within Auckland city (450 200 to 584 500), which borders all three harbours to some extent. Using the smaller electoral area units, approximate estimates of populations living within the three catchments were made; 450 000 – 500 000 within the Manukau, 350 000 – 400 000 around the

Waitemata, and 200 000 – 250 000 within the Tamaki catchment. Population density reaches over 4000 people /km^2 in some parts of the city. Within the Manukau Harbour catchment population densities varied from nearly 700 people /km^2 in Manukau City to less than 30 along the less populated southern borders of the harbour within the Franklin District. The catchment-wide density is estimated at around 500 people /km^2. With areas of high population density found all around the Waitemata and Tamaki, current overall population densities for these harbours were estimated to be around 800 and approaching 2000 people /km^2 respectively.

Information on road density, number of bridges and traffic levels are another indicator for human impacts on aquatic environments. Table 6 gives summary information on the road and bridge density and number of vehicle miles travelled for the region(s) within which the six harbour catchments occur.

Table 6: Summary transport statistics for the Regions surrounding the six harbours (Source: http://www.nzta.govt.nz/resources/)

	Road density (km/km^2)	Bridge density (no./km^2)	VKT (Vehicle Km Travelled (millions km))
Kaipara			
Kaipara District	0.5	0.107	81
Rodney District	0.68	0.15	509
Raglan			
Waikato District	0.52	0.09	235
Manukau			
Auckland City	1.34	0.14	2720
Manukau City	2.29	0.24	271
Papakura City	2.34	0.301	1587
Porirua			
Porirua city	1.3	0.11	200
Waitemata			
Auckland City	1.34	0.14	2720
North Shore	5.27	0.47	800
Waitakere City	2.14	0.19	836
Tamaki			
Auckland City	1.34	0.14	2720
Manukau City	2.29	0.24	271

3.2 Catchment Land-Use

The estimated catchment areas of all the freshwater systems draining into each harbour were classified by their land use type (see Appendix 1), and are shown as percentages of the combined catchment area in Figure 3. Land use has changed dramatically around all harbours, either to predominantly agricultural and exotic forest plantations (Kaipara and Raglan), a combination of agriculture, forestry with some urbanization (Manukau and Porirua) or significant urbanization of large areas of the catchment (Waitemata and Tamaki). Natural forest (which includes indigenous and non-planted non-indigenous forest) represented 15 – 26% of the catchment for all harbours except Tamaki, which had less than 2% forest cover within the river catchments. Nearly 75% of the combined freshwater catchments draining into the Tamaki estuary were classed as "settlement", which includes built-up urban areas, impervious surfaces, as well as parks and other recreational spaces within those urban areas. Data on ISC

(Impervious Surface Cover) was only available for the three Auckland harbours; 24% of the Tamaki freshwater catchments, 8.75% of the Waitemata, and 6.09% of the Manukau were categorised as ISC. These levels suggest that some the freshwater catchment systems could be classed as "Impacted" or "Non-supporting" according to the Impervious Cover Model (see Figure 1, Section 1.2.1). It is likely that the Porirua catchments would have a level of ISC similar to, or less than that of the Manukau and Waitemata (5 – 10%), with the Kaipara and Raglan catchments having much lower levels (probably less than 1%). Up to date information on the extent of shore hardening was not readily available for any harbours, but was assessed for the central Waitemata in 1983, when it was estimated that 45% of the shoreline between the entrance and the Auckland Harbour Bridge had been modified by reclamation, with 24% of the shoreline claimed by wharves, breakwaters, embankments, causeways and other uses (Dromgoole & Foster 1983). Further modification of the harbour has almost certainly occurred since that assessment was carried out. In Porirua the amount of shore hardening is also significant; sea wall, road and rail corridors directly border about two thirds of each arm and have been identified as having a significant impact on the estuary function (Stevens & Robertson 2008). Similar information could not be found for the other harbours, but would be likely to be similar or less for the Manukau and Tamaki, and minimal for Raglan and Kaipara harbours.

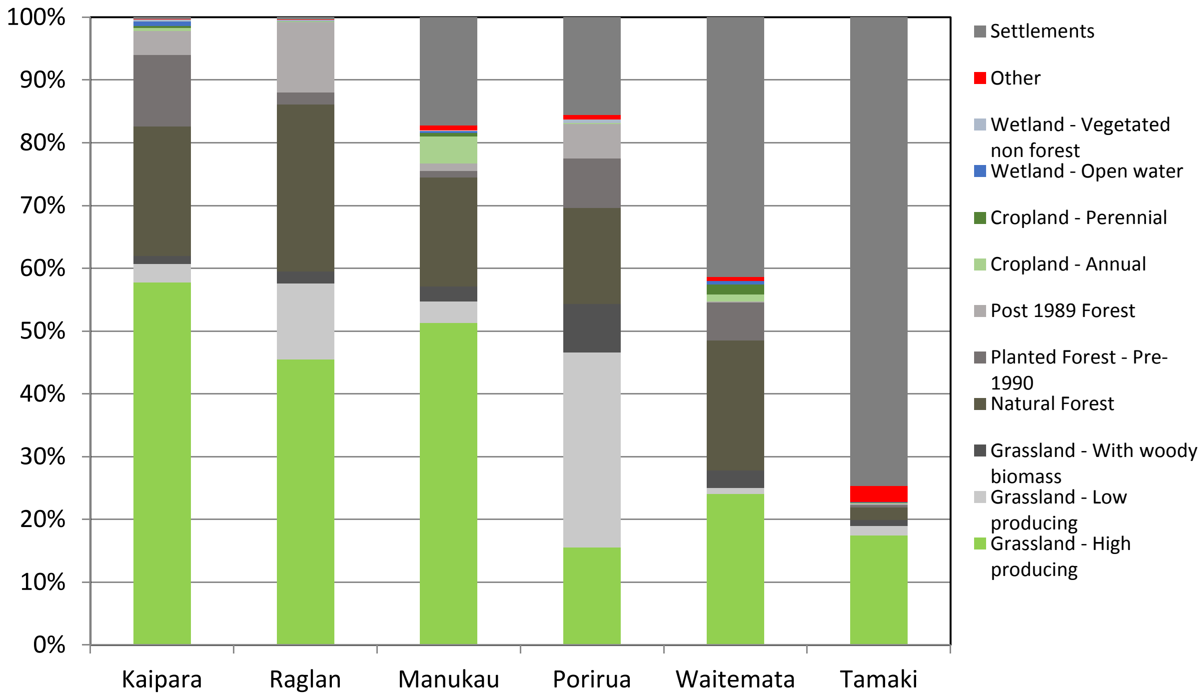

Figure 3: The proportion of each land use category in the estimated catchment of each harbour. Harbours are given in descending order of % of Grassland (pastoral agriculture). The LUC category 'Other" refers to any land that isn't classified as the main listed categories (see http://www.mfe.govt.nz/issues/climate/lucas/).

In the freshwater catchments draining into the Kaipara, Manukau, Raglan and Porirua harbours, agriculture makes up more than 50% of the area. Given the threshold values cited in the literature, it is likely that all harbours, apart from Tamaki, are negatively impacted to some degree by the effects of agricultural practices. In particular, Kaipara and Raglan harbours, although differing considerably in size, had freshwater catchments with around 60% agricultural land use, well above the 30–50% threshold at which freshwater ecosystems show signs of negative effects (Quinn 2000, Quinn & Hickey 1990). Figure 4 shows the number of dairy cows by region and illustrates the high number in the Kaipara Harbour catchment area (this includes parts of Rodney and Whangarei) and the Waikato region, which includes Raglan catchment. Dairy farming is increasing in the Waikato region compared to the Northland and Auckland regions, which have shown declines in numbers. In their review of recent land trends in the Waikato region, Cameron et al. (2009) described a recent wave of conversions to dairy farming with higher stocking rates, and more intensive farming practices, including increases in use of nitrogen fertiliser, and increased use of feed-pads and supplementary feed. Whilst appearing to decline somewhat, there are still high numbers of dairy cows (more than 50 000) in the Kaipara and Whangarei region (Kaipara Harbour catchment) and Franklin (Manukau catchment). The impacts of intensive dairy farming include elevated levels of nutrients in freshwater systems via runoff from the land as well as point source discharges and high levels of bacterial contamination where stock has access to freshwater (Larned et al. 2004, 2005, Parkyn et al. 2002). These impacts can be measured in both freshwater and estuary water quality monitoring, as well as the health of the freshwater biological community.

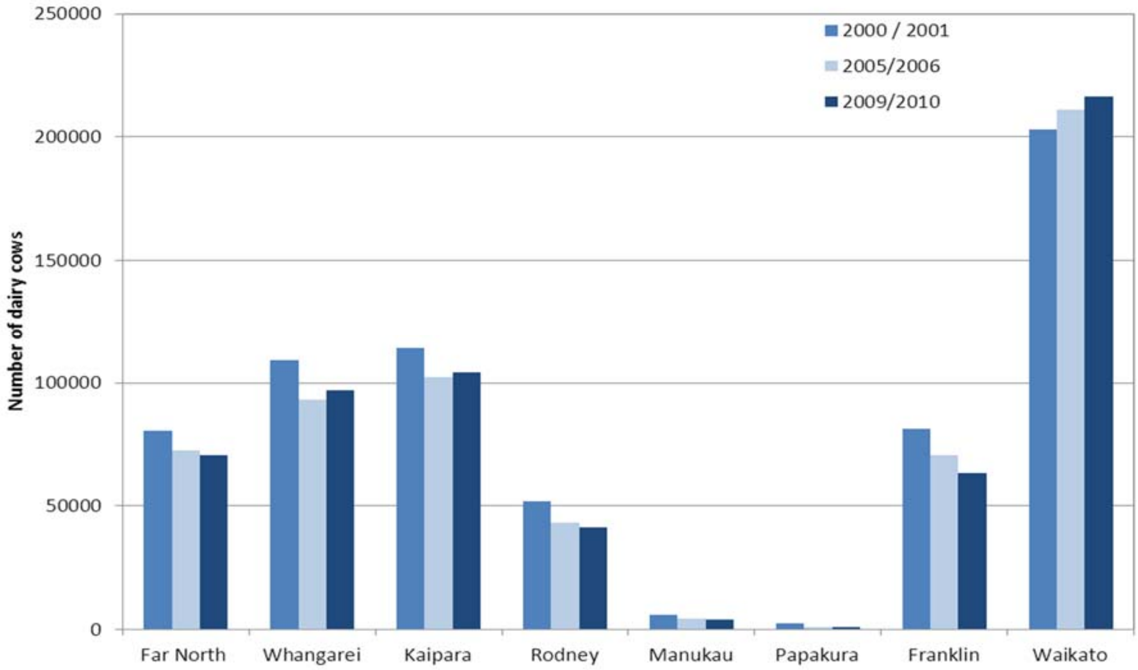

Figure 4: Number of dairy cows by regional authority for three different time periods between 2000 and 2010. Data from the Livestock Improvement Corporation (LIC) (http://lic.co.nz/lic_Publications.cfm).

3.3 Environmental Monitoring

3.3.1 Freshwater Quality

River and stream water quality monitoring is carried out by regional councils to some level in all six harbours. A selection of the physical and chemical indicators monitored are given in Table 7; each council has its own methodology in terms of assessment of water quality, but median values with maximum and minimum readings are usually reported.

In the Kaipara freshwater catchments, 12 sites were monitored in the northern area by NRC (Northland Regional Council 2010b, 2011) and three sites in the southern area by Auckland Council (Neale 2010b). Water quality was found to be variable, most sites having poor water quality on some occasion, some consistently, particularly sites near intensive pastoral farming. The three sites monitored by Auckland Council shifted from being classed as “Good” to “Fair”, to “Fair” or “Poor” in the more recent the monitoring (Lockie & Neale 2012, 2013, Neale 2010b, 2012). In the northern Kaipara, 8 out of 12 rivers monitored by NRC had a compliance level of less than 25% for dissolved oxygen, and 7 out 12 rivers had turbidity levels above the Council’s lowland river trigger value (5.6 NTU) on at least 50% of occasions in 2008/2009 (Northland Regional Council 2010b). Suspended solids were particularly high compared to other areas where measurements were available. Nutrient levels, phosphorous in particular, were elevated above guideline levels at a number of sites although this is partly due to the area’s phosphorus-rich sandstone and mudstone geology, and significant improving trends in total phosphorous and nitrogen have been observed in some rivers (Northland Regional Council 2011).

Overall water quality for the period 2007 – 2011 ranged from "Excellent" to "Poor", but was ranked as "Fair" for most sites (Northland Regional Council 2012b). Macroinvertebrate monitoring classed Kaipara sites as mild to severely polluted (Pohe 2011).

In Raglan, river water quality is measured at three sites (Beard 2010, Tulagi 2011). Turbidity was generally poor at all three sites, classed as unsatisfactory (over 5 NTU) between 75 – 90% of occasions. Total nitrogen and phosphorous were also classed as unsatisfactory on about 40 – 50% of occasions sampled, although overall median values for each river were generally below the guideline values used in the region. Environment Waikato classed these three sites as either "Satisfactory" or "Excellent" nearly 75% of the time. Vant (2008) looked at long term trends in the Waikato rivers monitored since 1987 and described an "*insidious pattern of water quality degradation, which in many cases is likely to be related to the widespread and intense use of land for pastoral farming in the Waikato region*". A recent update to this analysis found significant increases in levels of nitrogen at all three sites, which was likely to be from runoff and leaching from areas of pastoral farmland, and increasing turbidity (Tulagi 2012, 2013, Vant 2012).

The four freshwater monitoring sites within the Porirua Harbour catchment were classed as either "Fair" or "Poor" (Perrie & Cockeram 2010). Sites on the Porirua stream in particular, have recorded high levels of nitrogen (NNN, Amm. nitrogen), TP and *E. coli* that regularly do not comply with guideline values (Perrie et al. 2012).

The Auckland Council undertakes monitoring at a number of freshwater sites within the Manukau, Waitemata and Tamaki catchments (Neale 2010b). A water quality index originally developed by the Canadian Council of Ministers for the Environment (CCME) is calculated, based on seven water quality parameters and compared against reference values from the Auckland region, which differ in some cases to other region's guideline values (see Section 2.2.1). For instance, acceptable turbidity is classed as under 30 NTU and total nitrogen as under 1.4 mgl^{-1}, which are higher than other regions. Table 7 presents the range of median indicator values from the rivers sampled in these three catchments. A long term analysis in the Auckland region found water quality of urban streams was generally poor, with high temperatures, high concentrations of nutrients and suspended sediments, and high levels of faecal coliform bacteria (Scarsbrook 2007). However, there have been significant decreases over time in annual median concentrations of faecal coliforms, nitrate - nitrite nitrogen (NNN), and suspended sediments indicating an improvement in water quality since the early 1990s. Within the Manukau catchment, two sites were classed as "Fair", with the third site (Puhinui Stream) classed as having the worst water quality in the whole Auckland region in 2009, with some of the highest median values for total nitrogen of all the harbours recorded in this area at between 1 and 3 mg/L. However, monitoring since then has classed these sites as "Fair" or "Good" (Lockie & Neale 2012, 2013). Within the Waitemata catchment, streams were classed as "Fair" to "Excellent" in 2009, although in some years, a few sites have been classed as "Poor" (Lockie & Neale 2013, Neale 2010a). Streams draining from urban areas into the Upper Waitemata, (e.g. Lucas, Oakley and Oteha) had poorer water quality with lower dissolved oxygen and elevated turbidity and nutrients, whilst streams draining from the Waitakere ranges had much better water quality. Streams draining into the Tamaki estuary were all classed as "Poor" in 2008, but since then have ranged from "Poor" to "Fair". Overall, levels of Amm. nitrogen, TP, *E. coli* and suspended solids were highest in the Tamaki catchment compared to the other Auckland catchments. (Lockie & Neale 2012, 2013, Neale 2010a, 2010b, 2012).

Table 7: Summary of freshwater quality monitoring for streams within the catchment areas of the six harbours. See Section 2.2.1 for definitions of water quality ratings. Text in italics refers to a second source.

	Kaipara	Raglan	Manukau	Porirua	Waitemata	Tamaki
River Water Quality Information availability and source	Range of median values from monitoring of three rivers by Auckland Council, 2009 (Neale, 2010b) with max. and min. readings in parenthesis *Range of median values for 13 rivers monitored by NRC (2008-2009 data)*	Range of median values from three river sites sampled monthly over 2010 (Tulagi 2011)	Range of median values from three rivers monitored by Auckland Council, 2009 (Neale 2010b)	Range of median values from four sites 2009 – 2010 (Perrie & Cockeram, 2010	Range of median values from seven rivers monitored by Auckland Council, 2009 (Neale 2010b)	Range of median values from seven rivers monitored by Auckland Council, 2009 (Neale 2010b)
Dissolved oxygen (% saturation)	82.3–100.7% (53.3–118.9) *81.7–109.1%*	97–98.5%	87.2–122.7%	97.8–109.5%	80–99.8%	77.8–136.5%
Turbidity (NTU)	7.8–12.4 (5.1–67.5) *2.5–13.1*	8.2–9.7	2.4–6.5	1.2–2.3	3.2–13.2	4.5–8.5
Amm. nitrogen	0.011–0.047mg N /L (0.002–0.079) *0.005-0.045*	0.01g N/m^3	0.013–0.052 mg N/L	0.005–0.018mg/L	0.004–0.036mg N/L	0.02–0.215 mg N/L
Total nitrogen	0.052–0.83 mg N /L (0.49–1.9) *0.209–3.287*	0.34–0.56g N/m^3	0.82–3.35 mg N/L	0.41–1.35 mg/L	0.07–1.8 mg N/L	0.65–1.3 mg N/L
Total phosphorous	0.029–0.078 (0.022–0.142) mg P /L *0.01–0.104*	0.02–0.039 g/m^3	0.012–0.074 mg /L	0.015–0.036 mg/L	0.018–0.058mg /L	0.026–0.088 mg /L
E. coli	250 (70–5600) cfu/100ml *68.6–619.5 n/100ml*	385–417 no/100mL	245–2550 cfu / 100ml	210 – 1000 cfu/100ml	40–700 cfu / 100ml	405–1600 cfu / 100ml
Suspended solids (TSS)	10 (3.6–60) mg/L		2.2–6.7 mg/L	1 mg/L	1.2–4.3 mg/L	5.2–11.8 mg/L
Water Quality Rating	Fair: Poor - Good	Good: ~ 75% samples Excellent or Satisfactory	Fair -Good	Poor / Fair	Variable: 3 × Fair, 2 × Good, 2 × Excellent	Poor/Fair

3.3.2 Estuarine Water Quality

Northland Regional Council has undertaken monitoring of coastal water quality at up to nine sites a year in the northern half of Kaipara Harbour since 2009, including measurements of temperature, salinity and turbidity, nutrient levels (Ammonia, Phosphorus and Nitrogen) *Enterococci*, faecal coliforms and *E. coli* (Northland Regional Council 2010a, 2012a). Over the monitoring period, nutrient levels were elevated, frequently exceeding guideline levels in the upper reaches such as Oruawharo River and Wahiwaka Creek of Otamatea River, Kapua Point on the Arapaoa River, and Burgess Island in the northern Wairoa River arm of the harbour (see reports for site locations). Turbidity measurements were generally within guidelines, with highest values recorded close to sources of freshwater. In the southern Kaipara, long term monitoring at Shelley Beach, classed this station as "Fair" using a water quality index based on six indicators; total suspended solids, nitrate-nitrogen, ammonia-nitrogen, total phosphorous, soluble reactive phosphorous and faecal coliforms. The site was at the lower end of this category with the highest median value for total suspended solids compared to the Auckland harbours and high values for ammoniacal nitrogen and total phosphorous (Scarsbrook 2008). An additional six sites have been monitored since 2009, and these recent data have shown indications of declining overall water quality, with the number of sites rated as "Poor" increasing from one site in 2009 to five sites in 2012 (Walker & Vaughan 2013a, 2013b).

Estuarine water quality had not recently been measured in Raglan harbour, but a year-long study was carried out in 2002 – 2003 with bi-monthly sampling at four sites in low tide channels, along with sampling on two more occasions after heavy rainfall (http://www.waikatoregion.govt.nz/Environment/Environmental-information/Environmental-indicators/Coasts/Coastal-water-quality/Estuarine-water-quality-techinfo/). Dissolved oxygen was "Excellent" on over 75% of occasions (i.e. more than 90%), and ammonia levels were classed as "Excellent" on almost all occasions (less than 0.1gm^{-3}). However, turbidity readings exceeded the guideline level on 30% of occasions (more than 10 NTU), and nitrate and total phosphorous levels were unsatisfactory (more than 0.015 g/m^3 and more than 0.03 g/m^3, respectively) in nearly 50% and 75% of samples, respectively. Although this monitoring indicated elevated nutrients and high turbidity, water quality may well have improved since the survey following efforts of a local harbour care group to promote and facilitate improved farming practices such as riparian planting and fencing off waterways (http://www.harbourcare.co.nz/about).

In Porirua, estuarine water sampling commenced in 2011. Initial results indicated that median concentrations of nutrients, suspended sediments and chlorophyll *a* were all higher at the Onepoto Arm sites than those in the Pauatahanui Arm (Oliver 2013). Other indicators relating to general estuary health, such as levels of *Enterococci, E. coli* and faecal coliforms, and intertidal macroalgal cover, such as *Ulva* and *Gracilaria* have been monitored over a longer time period and provide an indicator of elevated nutrient levels. Localised nuisance conditions were often present in both arms with 10% of the estuary exceeding 50% cover, 6.6% in the Pauatahanui Arm, and 22.2% in the Onepoto Arm (Stevens & Robertson 2011). Levels of nutrients and total organic carbon in the intertidal sediment also indicate low-moderate eutrophication in parts of the harbour near to urban settlements, whilst other areas are not affected (Robertson & Stevens 2009, 2010).

Figure 5: Ranking of coastal water quality for 26 sites across the Auckland region (Scarsbrook 2008).

An analysis of long term water quality data in the Auckland region harbours indicated poorer water quality inside harbours and estuaries, which was linked to water quality in connected freshwater sources (Scarsbrook 2008). Open coastal sites had the best average ranking whilst sites closest to the sources of freshwater input in the Upper Waitemata Harbour, inner Manukau (Mangere Inlet) and upper Tamaki were worst (see Figure 5). In many cases, water quality has improved during the period monitored due to improved management of point source discharge and sediment controls. In the Manukau, parameters relating to suspended solids (Total Suspended Solids, turbidity and TP) showed decreases, and sites close to the Mangere waste water treatment plant showed significant decreases in faecal coliforms and ammoniacal nitrogen concentrations, reflecting the major upgrades carried out to this facility since 2000. Similar significant declines in total suspended solids were also observed in the inner Waitemata, although levels of nitrogen and phosphorous were still relatively high compared to other sites. Monitoring since this long term review has noted that there has been an increase in the number of sites having “Poor” water quality. In the Waitemata 4 – 6 sites out of the 11 monitored were classed as “Poor” in 2010 and 2011, and for the Manukau and Tamaki, all sites monitored were classed as either “Poor” or “Fair” in 2011 (Walker & Vaughan 2013a, 2013b).

Both freshwater and saline water quality indices indicate similar patterns in the harbours assessed, with poorer water quality found in inner parts of the harbours closer to freshwater sources, including increased turbidity and nutrient levels. Raglan probably has the best water quality compared to the other harbours, along with the Pauatahanui Arm of the Porirua Harbour, although these, and the Kaipara Harbour also had high turbidity levels and elevated nutrients on some occasions in some areas. Water quality was variable within the Waitemata depending on the nature of the local catchment, and poorest overall in Manukau and Tamaki harbours.

Table 8: Summary of information available on estuarine water quality for the six harbours. Italics denote information from different sources for the same harbour.

	Kaipara	Raglan	Manukau	Porirua	Waitemata	Tamaki
Information availability and source	Median value from Shelley Beach 1993–2007 (Scarsbrook 2008). +2011 data*[2] for 6 sites (Walker & Vaughan 2013b) *NRC results from 9 sites (2009/2011)*	Monitored 2002–2003. % compliance and range of medians and data range from 4 stations (Waikato Council website)*[1]	Range of median values from 6 sites Scarsbrook (2008) +2011 data for 7 sites (Walker & Vaughan 2013b)	Range of Medians (raw data range) from 6 sites over 2010 / 2011 (Oliver & Milne 2012)	Range of median values from 10 sites (Scarsbrook 2008) +2011 data*[2] for 11 sites (Walker & Vaughan 2013b)	Range of median values from 2 sites (Scarsbrook 2008) +2011 data*[2] for 2 sites (Walker & Vaughan 2013b)
Turbidity	1993–2007: n/r 2011: 2.3 – 7.8 NTU (0.6 – 45.7) *<5 NTU 75% of occasions*	<10 NTU on 60% occasions 5.2 – 15.8 (0.1–23.8)	1993–2007: n/r 2011: 2.3–7.7 NTU (0.7–33)	2.4 – 11.7 NTU (1.2 – 210)	1993–2007: n/r 2011:2.9–6.6 (0.7–43.8)	1993–2007: n/r 2011:3.8–6.6 (2.2–28.5)
Nitrate nitrogen ($N0_3N$) or Nitrite–nitrate nitrogen (NNN)	1993–2007: $N0_3N$: 0.02 mg/L 2011: $N0_3N$: 0.002–0.005 (0.001–0.072) mg/L *NNN: < 0.444mg/L 45% occasions*	$N0_3N$: < 0.015(g/m^3) 55% of occasions NNN: 0.015 – 0.035 (0.003–0.411) (g/m^3)	1993–2007 $N0_3N$: 0.029–0.282 mg/L 2011 $N0_3N$: 0.001–0.014 (0.001–0.024) mg/L	$N0_3N$: 0.002–0.084 (0.001–0.660) mg/L	1993–2007 $N0_3N$: 0.01–0.071 2011 $N0_3N$: 0.001–0.003 (0.001–0.008) mg/L	1993–2007 $N0_3N$: 0.014–0.052 2011 $N0_3N$: 0.0015 (0.001–0.01) mg/L
Ammoniacal nitrogen (Raglan: Total Ammonia)	1993–2007: 0.032 mg/L 2011: 0.0025–0.0115 mg/L (0.0025–0.089) *<0.021mg/L 56% of occasions*	<0.1(g N/m^3) 95% of occasions 0.02 – 0.04 (0.01 – 0.11)	0.02–0.305 mg/L 2011: 0.0025–0.0115 (0.0025–0.089) mg/L	0.005–0.0165 mg/L (0.005–0.110)	1993–2007: 0.01–0.03 mg/L 2011:0.0025–0.0275 (0.0025–0.454)	1993–2007: 0.017–0.031 mg/L 2011: 0.0015 (0.001–0.01)
Total phosphorous	1993–2007: 0.076 mg/L 2011: 0.018–0.04 mg/L (0.003–0.094) *< 0.03 g/m^3 45% occasions*	<0.03 (g/m^3) 20% of occasions 0.031 – 0.062 (0.021– 0.118)	1993–2007: 0.05–0.30 mg/L 2011: 0.03–0.144 (0.009–0.202)	0.016–0.041 mg/L (0.012–0.25)	1993–2007: 0.04–0.06 mg/L 2011: 0.026 – 0.039 (0.013–0.591)	1993–2007: 0.041–0.06 mg/L 2011: 0.033–0.037 (0.019–0.084)
Faecal coliforms	1993–2007: 2 MPN/100 ml *<150 MPN/100 ml 80% of occasions*	8–16 cfu/100 mL (max = 1700)	1998–2007: 2.7–14.3 MPN/100 ml 2011: n/r	Median values : 32–80 cfu/100 mL (max: 1000)	1998–2007: 4–140 MPN/100 ml 2011: n/r	1998–2007: 7.5–16.5 MPN/100 ml 2011: n/r

	Kaipara	Raglan	Manukau	Porirua	Waitemata	Tamaki
Enterococci	2011: 1–2 (0.9–58) MPN/100 ml *97% < 140 cfu./100 ml*	4 – 16 (max = 410) cfu/100 mL	2011: 5–7.5 (5–63) MPN /100 ml	4–80 cfu/100 mL	2011: 5–30.5 (5–1900)	2011: 7.5–30.5 (5–5172)
Total Suspended Solids (mgL^{-1})	1993–2007: 59.7 2011: 8.5–33 (2.1–93)	Not measured	1993–2007: 14.5–27 2011:7.5–19 (2.3–86)	7.5–21.5 (2–460)	1993–2007: 11.9 – 18 2011:5.8–12 (2.5–60)	1993–2007: 11–17.5 2011:8.9–15.5 (1.2–61)
Rating	1993–2007: Fair 2011: Poor – Good	Average score was 75% Satisfactory= ~ Fair–Good	1993–2007: Poor – Fair 2011; Poor – Fair	~Fair–Good	1993–2007: Poor – Good 2011:Poor–Excellent	1993–2007: Poor/Good 2011: Poor

*[1] Compliance data for Raglan harbour quoted from Waikato Council website. Raw data provided by Waikato Council. *[2] Data reported as range of median values calculated for sites over the year with maximum and minimum single recordings. cfu = colony forming unit (ie viable cells). MPN= Most Probable Number (estimate of number of viable cells)[*]

3.3.1 Sedimentation

In the Kaipara Harbour, Swales et al. (2013) found that sedimentation rates were variable; major fine-sediment accumulation zones included the inner part of the southern arm, the Kakaraia Flats near the Hoteo River mouth and the Arapaoa River in the north-east, with the Otamatea and Oruawharo rivers also likely to be mud sink environments. Within the Arapaoa River, where high catches of rig were recorded, ^{210}Pb and ^{137}Cs sedimentation rates from individual cores ranged from 1.6–3.4 mm yr^{-1}. This area contains numerous infilled embayments and extensive intertidal flats. In other parts of the harbour, such as the Omokoiti, Kaipara and Wairoa River flats, waves and tidal currents rework sediment deposits and accumulation is much less. Using stable-isotope signatures to track sediment sources, the Wairoa River was identified as the major source of mud in the northern Kaipara and north-eastern arms including the Arapaoa, and even reaching as far south as Shelley Beach in the southern Kaipara (Gibbs et al. 2012). A harbour-wide average ^{210}Pb SAR for the Kaipara was 6.7 mm yr^{-1} (SE = 1.9 mm) (Swales et al. 2013). This value included two outlier estimates of 21 mm at the Hoteo River site and 30 mm at a site in the southern arm of the harbour. Excluding these outlier measurements as not representative of the whole harbour, reduced the rate to 4 mm (s.e. 0.6 mm yr-^{1}). This is not significantly different from ^{210}Pb estimates of Auckland east coast estuaries (5.1 mm SE = 0.8), which include the much smaller Mahurangi, Puhoi, Okura and Te Matuka estuaries. It is still however significantly higher than some other North Island estuaries such as Pauatahanui and the Bay of Islands (1.9 – 3.4 mm yr^{-1}).

Raglan Harbour is much smaller than Kaipara, the CER is double that of the Kaipara, and the intertidal area is nearly 70% of the high-tide surface area. In the Waingaro Arm, re-suspension from waves driven by the prevailing southwest wind have resulted in no long-term sedimentation (Swales et al. 2005b). However, in the southern Waitetuna Arm, the pre-human SAR of 0.35 mm yr^{-1} has increased three-fold after deforestation, averaging 1.1 mm yr^{-1} since 1890, with a further increase suggested from pine pollen presence, to 2.5 mm yr^{-1} since the early 1990s (maximum of 8 mm yr^{-1} at a site in Okete Bay) (Swales et al. 2005b).

Porirua Harbour is a comparable in size to Raglan, but differs in that it is largely subtidal and has the largest CER (28.2) of all of the estuaries (Table 4). A study of sedimentation based on a comparison of historic and more recent hydrographic surveys (Gibb & Cox 2009), estimated that from 1974–2009, net average deposition rates increased to 5.7 mm yr^{-1} in the Onepoto Arm and 9.1 mm yr^{-1} in Pauatahanui Inlet, with the tidal prism reduced by 1.7% in the Onepoto Arm and by 8.7% in the Pauatahanui Inlet since 1974. Based on reconstruction from radioisotope and pollen dating, Swales et al. (2005a) estimated average ^{210}Pb SAR at 2.4 mm yr^{-1} over the last 150 years, ^{137}Cs SAR at 3.4 mm yr^{-1} since 1950, increasing in the mid-1990s to 4.6 mm yr^{-1}. They predicted future SAR to be almost certainly over 2.4 mm and most likely over 4 mm, pointing out that planned development of sub-catchments (e.g. Duck Creek) and harvesting of large areas of exotic forest in the Horokiri sub-catchment had potential to increase sediment loads in the immediate future (5–10 years). Hicks et al. (2009) estimated that forest harvesting increased sediment yield by 40% and exposed earth during urban development also significantly increases erosion (Hicks 1994). However, recent monitoring carried out for the Greater Wellington Regional Council using sedimentation plates deployed at key sites has recorded variable, but relatively low sediment deposition with mean values ranging from -1.7 to 3.2 mm/yr over the four-year monitoring period (Oliver & Milne 2012).

Manukau Harbour has a much smaller CER (2.8) compared to the other sites. Reed et al. (2008) estimated ^{210}Pb SAR for the south-eastern Manukau and Pahurehure Inlet; average SAR from cores in the estuary ranged from 2.2 – 12.6 mm yr^{-1} with one core from the wave-exposed sand flats at the western end of the sampling area close to zero. No comparative studies of sedimentation have been undertaken in the northern part of the Manukau where the rig survey was carried out. The tidal creeks of the upper Waitemata are largely infilled already; Hume & McGlone (1986) found that since 1854 the main channel areas of Lucas creek had experienced deposition rates of less than 2 mm per year and predicted that with future urbanization, this SAR would double. Henderson Creek has infilled and the intertidal area of its upper reaches are entirely colonized by mangroves (Swales et al. 2002a). Following deforestation, agriculture and urbanization, its catchment land use includes nearly 50% regenerating native forest, 20% urban and 20% pasture. The ^{210}Pb derived SAR in this creek range from 2.6 – 5 mm yr^{-1} since the 1950s, with a suggested increase to around 6 mm since the 1980s (Swales et al. 2002a). The largely subtidal central Waitemata Harbour has extensive subtidal flats east of Te Atatu Peninsula. Whilst the southern shore has been extensively urbanized for some time, the northern shore catchments have remained predominantly rural. Net sedimentation rates since the 1950s have averaged 3 mm yr^{-1}, with an increase in the last 20 years. Swales et al. (2002a) concluded that the intertidal flats of Waitemata and other east coast estuaries had shoaled by an average of 0.5 m over the last 50 years and would continue to be in filled at a rate of several millimetres a year. In the Tamaki Estuary, Abrahim (2005) estimated that SAR increased from 2.4 mm yr^{-1} following Maori settlement to 6.25 mm yr^{-1} since European settlement in the area from 1840 onwards, with a maximum of 17 mm yr^{-1}. Sedimentation rates for the inner Pakuranga Estuary, a tributary of Tamaki estuary, have been estimated at 1.7 – 3.8 mm yr^{-1} since rapid urbanization starting in the 1960s, with a maximum annual average SAR of 32.6 mm at the head of the creek since that time (Swales et al. 2002b). The estuary has a large CER (30.1) and is 90% intertidal. This study indicates that urbanization has resulted in a 3-fold increase in soil erosion over that estimated for pasture.

Sedimentation rates across the harbours were generally within the same range of around 2 – 6 mm a year, with some harbours recording much higher values at the heads of their tidal creek / tributary arms (Tamaki, Kaipara) and Raglan at the lower end of the scale (see Table 9). In all harbours, these rates were higher than at any other time in the history of the estuary. In the case of mature urban settlements, such as the Tamaki, sedimentation is not likely to increase further. However, in areas where there is potential for future development of agricultural land to urban settlement, such as Kaipara, Raglan and Porirua, there is potential for increased sedimentation rates which could negatively impact the harbours.

Table 9: Summary information on annual sedimentation rates and sediment contaminants from the six harbours assessed. Where italics are used, this denotes information from a second source for same harbour.

	Kaipara	Raglan	Manukau	Porirua	Waitemata	Tamaki
Information Sources	Swales et al. (2013)	Swales et al. (2005b)	Reed et al. (2008) *Swales et al. (2002a)*	Swales et al. (2005a) *Gibb & Cox (2009)*	Swales et al. (2002a) *Hume & McGlone (1986)*	Abrahim (2005) *Swales et al. (2002b)*
Sedimentation Rate (SAR)	Harbour average: 6.7 mm yr^{-1} (SE =1.9) or 4 mm yr^{-1} (S.E. = 0.3) with selected outliers removed (Range: 1 – 29.7)	Waitetuna Inlet: 2.5 mm yr^{-1} (since 1990), up to 8 mm yr^{-1} Waingaro Inlet: no sedimentation	SE Manukau / Pahurehure Inlet: 2.2 – 12.6 mm yr^{-1}	Pauatahanui Inlet: 4.6 mm yr^{-1} since 1980s *Onepoto Arm: 5.7 mm* yr^{-1} *between 1974 – 2009* *Pauatahanui Inlet: 9.1 mm* yr^{-1}	Henderson Creek: 6 mm yr^{-1} since 1980 Central Waitemata: 2.3 – 3.6 mm yr^{-1} since 1950s *Lucas Creek: 2 mm* yr^{-1} *(present day)*	Harbour average: 6.25 mm (1840 onwards) *Pakuranga: 1.7–3.8 mm* yr^{-1} *(average annual rate since 1960)* *Head of estuary: 32.6 mm* yr^{-1}
Information sources for Sediment contaminants	N. Kaipara: Online Annual Monitoring Report (2010/2011) *S. Kaipara: Mean concentrations of total metals (2 sediment fractions) and PAHs* (<500 µm) *from 6 intertidal sites (2009 and 2010) Hailes et al. (2010).*	Median and range of total metals and PAH levels (<2 mm fraction) from 5 intertidal sites sampled in 2008 (Rumsby 2009).	Same sources as Waitemata; 18 sites sampled	Median and range of levels of total metals, PAHs and DDT (<2 mm sediment fraction) from 17 sites sampled in a 2009 pollution hot spot survey (Sorensen & Milne 2009). *Range of mean values for total metals (<2 mm fraction.) from 4 sites in an intertidal monitoring survey (Robertson & Stevens 2010).*	Range of median values for total metals (2 sediment fractions) and PAH (<500 µm fraction) from 45 sites sampled between 1998 and 2010 (Mills et al. 2012). DDT (<500µm fraction) concentrations from the sediment monitoring programme, (Reed & Gadd 2009)	Same source as Waitemata; 10 sites sampled.
Zinc mg/ kg dry wt	Below ANZECC guidelines *<63 µm: 19–36* *<500 µm: 13–34*	48 (33–56)	<63 µm: 37–144 <500 µm: 23–154 3 sites > ERC Amber	150 (44–410) *23–62*	<63 µm: 6.1–249 <500 µm: 13.8–270 6 sites > ERC Red 4 sites > ERC Amber	<63 µm: 77–214 <500 µm: 30–199 6 sites >ERC Red 1 site >ERC Amber

	Kaipara	Raglan	Manukau	Porirua	Waitemata	Tamaki
Lead mg/ kg dry wt	Below ANZECC guidelines *<63 µm: 3.2–5.9* *<500 µm: 1.3–3.5*	5.2 (4–9.1)	<63 µm: 4.9–27.7 <500 µm: 2–29.1 1 site >ERC Amber	21 (8.2–34) *3.6–9.1*	<63 µm: 7–90 <500 µm: 4.5–65.6 3 sites > ERC Red 21 sites > ERC Amber	<63 µm: 22 – 50 <500 µm: 5–34 5 sites >ERC Amber
Copper mg/ kg dry wt	Below ANZECC guidelines *<63 µm: 8.8 – 22* *<500 µm: 1.8–5.4*	7.3 (3.9 – 9.5)	<63 µm: 7.7–35 <500 µm: 3.2–31.5 All sites< ERC Amber	11 (4.1 – 30) *1.8–5.1*	<63 µm: 12–43.8 <500 µm: 2 – 213 2 sites > ERC Red 25 sites > ERC Amber	<63 µm: 12–34.8 <500 µm: 2.8–28.8 7 sites > ERC Amber
DDT mg/kg dry wt	No information	Not detected	Max Total DDT <0.004 mg/kg (<500 µm)	0.00001 – 0.032 *Not detected*	Max Total DDT <0.004	Max Total DDT <0.0015
PAHs mg/kg dry wt	*From S. Kaipara Total PAH*[1]: 0 – 0.136*	Detected at one site: Total PAH*[2]:0.0498 LMW PAH*[3]: 0.0121 HMW PAH*[4]:0.0108	HMW PAH: 0.023 – 0.156 mg/kg	LMW*[5]PAH: 0.032–0.402 HMW*[6]PAH: 0.036–4.273 *Total PAH: 0.091 – 5.945*	HMW PAH : 0.059–0.359	HMW PAH: 0.28 –1.1

*[1] The sum of all individual PAH values given, normalized to 1% total organic carbon (TOC)

*[2] Low molecular weight PAHs are the sum of concentrations of acenaphthene, acenaphthalene, anthracene, fluorene, naphthalene and phenanthrene.

*[3] High molecular weight PAHs are the sum of concentrations of benzo(a)anthracene, benzo(a)pyrene, chrysene, dibenzo(a,h)anthracene, fluoranthane and pyrene.

*[4] Total PAHs calculated by summing the data, where a concentration was below the detection limit half the detection limit was used as a value. Where all values were below the detection limit a total value could not be calculated.

*[5] –Total Low Molecular Weight PAH – Sum of the concentrations of naphthalene, 2-methyl-naphthalene, acenaphthalene, acenaphthene, fluorene, phenanthrene and anthacene.

*[6] Total High Molecular Weight PAH – Sum of the concentrations of chrysene, fluoranthene, pyrene, benz[a]anthracene, benzo[a]pyrene and dibenz[a,h]anthracene.

3.3.2 Pollution

Human activities result in a variety of pollutants entering the marine environment via runoff from the land. These include heavy metals such as zinc from roofs and car tyres, copper from car brake pads and building materials, organic compounds such as organochlorine pesticide residues (e.g. DDT) and polycyclic aromatic hydrocarbons (PAHs) from motor vehicle emissions and discharge of petroleum products. Urban stormwater runoff is a significant source of heavy metals including lead, copper and zinc, but agricultural practices are also a source. Trace elements may precipitate out and accumulate onto sediments in areas where there is a sudden change of redox conditions, salinity or pH, such as where freshwater enters estuaries. They can also be associated with sediment which settles as water velocity slows.

A summary of recent monitoring data for levels of heavy metals, PAHs and DDT is given in Table 9. In the Kaipara, two sites have been monitored by Northland Regional Council for sediment contaminants and biological communities since 2009. The 2010/2011 Annual Monitoring Report does not give raw or summary data but does state that levels of heavy metals were within the ANZECC guideline values at these sites, and levels of copper, lead and zinc are all lower in 2010 than the first year of sampling. In the Southern Kaipara, Auckland Council monitors six stations and reported that levels of heavy metals and PAHs are also well below guideline levels (Hailes et al. 2010). No information was found on levels of DDT in Kaipara Harbour sediments, but it is likely that it would at least be detected in certain areas, given its widespread use (Reeve et al. 2009)

In Raglan Harbour, as expected with such a low level of urbanization, concentrations of heavy metals in intertidal sediments did not exceed guideline trigger values, and were at the lower end of the expected range (Rumsby 2009). There was a slight elevation of levels in the southern part of the harbour and trace quantities of PAHs (fluoranthrene, phenathrene and pyrene) were found in the vicinity of Raglan township, but no organochlorine pesticides were detected.

In Porirua, a broad scale intertidal monitoring study assessed levels of a range of heavy metals concentrations in the sediment and found that in all cases, concentrations were low to very low, and all below ANZECC guidelines (Robertson & Stevens 2010). Total DDT concentrations in all samples were below the detection limits (less than 0.00003 mg/kg dry weight). However, a one-off survey targeting “hotspots” close to known sources of potential pollution, recorded much higher concentrations (Sorensen & Milne 2009). At the southern end of the Onepoto Arm (near the outlet of Porirua Stream and multiple stormwater outflows), levels of copper and lead exceeded ARC ERC amber thresholds at some sites, but were below the ANZECC ISQG-Low trigger values, whilst zinc concentrations exceeded the ARC ERC amber threshold at all sites and the ISQG-Low trigger level of 200 mg at multiple sites. Concentrations at sites in the Pauatahanui Arm where urban streams discharge into the harbour were lower and did not exceed trigger levels. Total PAH concentrations were detected and measured in all samples, and were highest adjacent to the stormwater outfalls at the Porirua Stream mouth, and at the Onepoto Stream mouth, where they exceeded the ANZECC ISQG-Low trigger value. At all sites where DDT was detected, levels exceeded the ANZECC ISQG-Low trigger value and the ARC ERC red threshold level. Similar patterns were found in subtidal sediments; levels of copper and lead in the two Onepoto Arm sites exceeded ARC ERC amber thresholds, but not their respective ANZECC ISQG-Low trigger values in all four surveys (2004 – 2010), whilst zinc levels exceeded ARC ERC red levels and the ANZECC ISQG-Low trigger value at one site in three out of four surveys (Milne et al. 2009, Oliver & Milne 2012) Summarising the results of the targeted survey and previous broadscale monitoring, Sorensen & Milne (2009) concluded that although stormwater derived contamination was evident in intertidal and subtidal sediments within the harbour, in most cases, concentrations only exceeded “alert” or “early warning” levels and management intervention was still possible. However, zinc and DDT were of particular concern, given the widespread occurrence of levels above their respective ISQG-Low trigger levels and their known persistence in the environment.

Within the Auckland region, recent assessments of the status and trends of sediment contaminants have shown increasing trends in copper and zinc at many sites since 1998, whilst lead shows mainly a declining trend (Mills et al. 2012, Reed & Gadd 2009). Highest concentrations of contaminants were found in the sheltered upper reaches and side arms of catchments with the longest history of urbanization and or industrialization, particularly in the Tamaki and central Waitemata Harbour. Those with catchments that are predominantly rural, have lower concentrations. Within the Manukau Harbour levels of metals and PAHs are generally low in most areas, apart from Mangere Inlet in the northeast, where levels of both zinc and copper reach ARC ERC Amber thresholds at some sites and have exceeded the ARC ERC Red threshold for zinc historically (equivalent to the ANZECC ISQR – Low trigger value). Historically there are more sampling sites within the Waitemata harbour, where levels of copper and lead exceeded the ARC ERC Amber thresholds at around than half of the sites and nearly 10% of sites exceeding ERC Red / ANZECC ISQR-Low trigger value for zinc. The central Waitemata is most heavily contaminated, and concentrations in the upper harbour are higher than would be expected for the more rural catchments. High levels of heavy metal pollution were also detected in the older, densely urbanized, headwater zones of the Tamaki estuary, with more than half the sites exceeding the ARC ERC Amber thresholds for copper and lead and 60% of sites exceeding the ARC ERC Red threshold / ANZECC ISQR – Low trigger value for zinc.

At a screening level of approximately 0.01 mg kg^{-1}, DDT, and its metabolites were detected in only a few samples to a maximum of 0.012 mg kg^{-1} (Reed & Gadd 2009). A subsample of nine sites were further analysed using a lower detection limit, and DDT (along with up to 14 other organochlorine pesticides) were found in six samples, with the highest concentrations in the northeastern Manukau (Anns and Mangere Inlet) and the upper Whau, in the central Waitemata (Reed & Gadd 2009). None of these samples exceeded the ARC ERC red guideline values, and all were lower than in previous monitoring (McHugh & Reed 2006).

Although not monitored as frequently as heavy metals, samples have been analysed for PAHs on a number of occasions in Auckland harbours. These contaminants are present in samples above background levels in all three harbours, but in the majority of cases, are well below ARC's environmental response criteria of 1.7 mg/kg (for high molecular weight PAHs) (Depree & Ahrens 2007, Mills et al. 2012). A small number of sites in the central Waitemata and the upper Tamaki River have recorded PAH concentrations close to, or exceeding ARC's ERC red criterion at some point during the monitoring period, with some sites (5 out of 37 monitored) showing significant increases. Depree & Ahrens concluded that, apart from the minor PAH accumulation found in sentinel benthic organisms there was little evidence for toxicity even where levels were elevated, and the environmental risk to benthic estuarine biota was deemed negligible. However, in their more recent assessment, Mills et al. (2012) noted that PAHs may contribute to "multiple stressor" effects that might cumulatively cause toxicity, and a recent study (Williamson & Mills 2009) has highlighted that some PAHs can be more toxic in the presence of ultra violet light, termed "phototoxicity". Organisms affected by phototoxicity are only those that are exposed to sunlight and it is not yet understood whether this effect is important for benthic fauna in New Zealand estuaries, but Williamson & Mills (2009) suggested that 70% of sites in Auckland had levels of PAHs that could be potentially phototoxic. This report also points out that over 50% of the sites monitored had PAH concentrations that exceeded the threshold for potential onset of liver lesions in benthic fishes, assuming that New Zealand species respond in a similar way to species studied in the Northern Hemisphere. Reed et al. (2011) applied selected biological effects tools (gene expression tools for metal-specific effects and other general stressor effects and the micronuclei assay tool for metal-related and general stress effects) to assess the adverse effects of metal exposure in cockles (*Austrovenus stutchburyi)* and yellow-belly flounder (*Rhombosolea leporina*) from a number of sites in the Auckland region. Their results showed induction of micronuclei in tissues at all sites sampled, suggesting that biochemical and cellular damage is occurring in some individuals in response to the elevated levels of heavy metal contaminants.

Concentrations of Cu, Zn and PAHs have been predicted to increase in Auckland estuarine sediments, along with a decline in Pb (Williamson & Mills 2009), however, an analysis of trends in data from 1998 to 2010 concluded that contaminant levels in most areas had not changed much (Mills et al. 2012).

Decreases in lead have been recorded in most sites, probably reflecting its removal from petrol, whilst zinc and copper trends are more variable. Where significant changes in zinc did occur, they were mainly increases. Management of stormwater is a priority with the Auckland Council and a range of legislation and measures have been put in place to reduce the impacts. However, the high cost of retro-fitting better stormwater treatment facilities means that in many already established areas, there are no quality controls in place (e.g. Pakuranga Estuary) and sediment and associated contaminants will continue to build in the receiving environment.

In a review of organic contaminants, such as plastics, plastic additives, resins, petroleum products, pesticides and biocides Ahrens (2008) ranked halogenated flame retardants, surfactants (and metabolites) and certain pharmaceuticals and personal care products (notably oestrogens) of greatest potential environmental concern. This was mostly as a result of their high persistence and bioaccumulation, as well as their elevated potential to cause endocrine disruption (Ahrens 2008). The most likely source of these contaminants is from landfill leachate (especially from decommissioned landfill sites), agricultural runoff, and sewage. Nearshore settling zones, marinas and water bodies being fed from catchments containing decommissioned landfill sites are likely areas of accumulation. Currently, no guidelines regulate discharges of these contaminants into the environment and no monitoring is carried out to assess concentrations. There is the possibility that additive or synergistic effects, such as endocrine disruption and long term effects on behaviour, growth and reproduction, may become apparent.

3.3.3 Habitats and Biological Communities

Over 40% of the total area of the Kaipara comprises intertidal habitats. A recent study of changes in vegetated intertidal habitats using GIS analysis of historical aerial photographs found that mangrove habitat (*Avicennia marina*) was substantially reduced through large-scale reclamation work in the southern Kaipara, whilst in the northern area, a substantial increase (41%) has occurred from 2101 ha in 1966/1977 to 2954 ha in 2002/2007 (Swales et al. 2013). The harbour-wide change in mangrove habitat was from 6845 ha in 1966/1977 to 7615 ha in 2002/2007; an 11% increase to approximately 19% of the intertidal area of the harbour, equates to approximately 10% of overall area at high tide. The remaining intertidal area is classed as sand or mud in the Estuary Classification database, making up around 32% of the total estuary area at high tide (Table 10). Seagrass habitat (intertidal and subtidal) is not distinguished in this database, but recent targeted aerial photography in the Southern Kaipara estimated a total of 20.4 km^2 in the southern part of the harbour, equating to around 2.8% of the total high water area (Morrison et al. 2014).

Table 10: Percentage of high water total area of each harbour classed as intertidal mud and sand (combined) and mangrove habitat, from the Estuary Classification database.*original value of 8% updated to reflect recent changes estimated by Swales et al. (2013).

	Kaipara	Raglan	Manukau	Porirua	Waitemata	Tamaki
% Mud/Sand	32	68	60	11	24	32
% Mangrove	10*	<1	2	0	12	8

Hewitt & Funnell (2005) completed an extensive study of the marine habitats and communities in the southern Kaipara as part of the State of Environment Monitoring Programme for the former Auckland Regional Council. Within the intertidal zone, mangroves were observed to fringe large areas, and much of the intertidal area between Helensville and Sandy Beach comprised mudflats. *Zostera* beds were recorded in the middle of the main southern harbour (e.g Kaikaraia and Omokoiti Flats) and near the mouth of the harbour. Along the more exposed coastal areas closer to the harbour mouth, substrate was sandy with rocky outcrops and intertidal reefs. Subtidally, mud and sand flats and high-flow channels were the main habitat (Figure 6). Fifteen different community types were identified in intertidal soft sediment habitats, six of which were dominated by bivalves such as *Macomona liliana* and *Austrovenus hartvigiana*, and *Musculista.* Seagrass meadows were found to have similar communities to bare sand habitats (with respect to macro-invertebrates of at least 1 mm), whilst mangroves were found to have distinct communities with lower diversity, dominated by mud crabs (e.g. *Helice crassa*) and infaunal species such as nereid polychaetes and the bivalave *Arthritica*. The subtidal community was dominated by variable densities of sand dollars (*Fellaster*), or a sand dollar/gastropod mix. Many areas displayed high taxonomic diversity at both species and order level, with a number of large, long-lived taxa identified. Species associated with pristine environments such as sponges, ascidians, bryozoans, and hydroids, were also found, occurring mainly in the central moderate-depth subtidal area, along the channel banks, and in the main channel near South Head. Outside the high diversity areas, similar to other New Zealand harbours and estuaries, polychaete-dominated communities were most common, including infaunal deposit-feeding, predatory, scavenging and tube-building polychaetes. Whilst many of the taxa and habitats recorded in the southern Kaipara are ubiquitous throughout the Auckland region, Hewitt & Funnell (2005) considered some fauna unique, such as the high numbers of the tube-building worms *Owenia, Macroclymenella, Euchone* and *Phoronids* found in the shallow subtidal area of the main southern harbour. Other rarer habitats included *Atrina* beds and subtidal *Zostera* meadows.

The inner estuary arms (Oruawharo, Otamatea and Arapaoa Rivers) are characterized by muddy, mangrove lined embayments and intertidal mudflats, with benthic communities more characteristic of degraded environments (Haggitt 2008). Muddy habitats are dominated by deposit-feeding bivalves such as *Nucula hartvigiana*, and predatory / scavenging polychaetes, whilst *Austrovenus stutchburyi* and *Macomona liliana* are found in sandy areas. Patches of oysters occur along the upper shore, giving way to clumps of the tube-building worm *Pomatoceros caerulus* lower down. Common gastropods include *Zeacumantus lutulentus*, *Diloma* sp, *Cominella glandiformis*, *Zediloma subrostrata*, *Micrelenchus huttoni*, and *Xymene plebeius*. Patches of horse mussels (*Atrina zelandica*) and *Hormosira banksii* were found in the Oruawharo, whilst Asian date mussels (*Musculista senhousia*) were spread throughout the rivers. The northern Wairoa arm has a similar broad-scale pattern of sediment distribution, but with a lower proportion of intertidal flats and muddy embayments and coarser sediments found further into the harbour, particularly along the inner eastern coast (Brockbank 1983, Hewitt et al. 2006, Hume et al. 2003). Benthic communities are poorly studied in this area, but are presumed to be similar to the other parts of the harbour (Haggitt 2008).

Overall, the Kaipara Harbour has been identified as comprising many areas of high biodiversity and abundance of habitats of high ecological value, but also with evidence of degraded communities in the muddier upper reaches (Brockbank 1983, Hailes & Hewitt 2012, Hewitt et al. 2012, Hewitt et al. 2006, Hume, et al. 2003). Since 2009, the Auckland Council has carried out bimonthly ecological monitoring programme at six sites distributed throughout the southern harbour (Hailes & Hewitt 2012) Sites were positioned near mud/sand transition zones on various banks, flats and at the mouths of selected creeks. Benthic communities at different sites were distinct, mainly dominated by polychaetes, or a combination of polychaete and bivalves. Mean species counts per sample ranged from 7 – 19, with Shannon-Weiner diversity indices remaining constant (range: 1.5 – 2.5), or increasing over the monitoring period. Benthic Health Model CAP scores relating to the gradient of mud content showed increases over the period of 2009 – 2011, with sites previously ranked either 1 or 2 (“Very Healthy” and “Good Health”) changing to all being ranked 2. The CAP scores from the BHM for metals also showed increases, resulting in a change from all sites being ranked 1 to a combination of 1s and 2s. The overall health index (BHM CAP scores and TBI score combined) for 2010/2011 ranked Kaipara sites as “Good Health” to “Moderate / Fair” (3) (Hewitt et al. 2012) (see Figure 9).

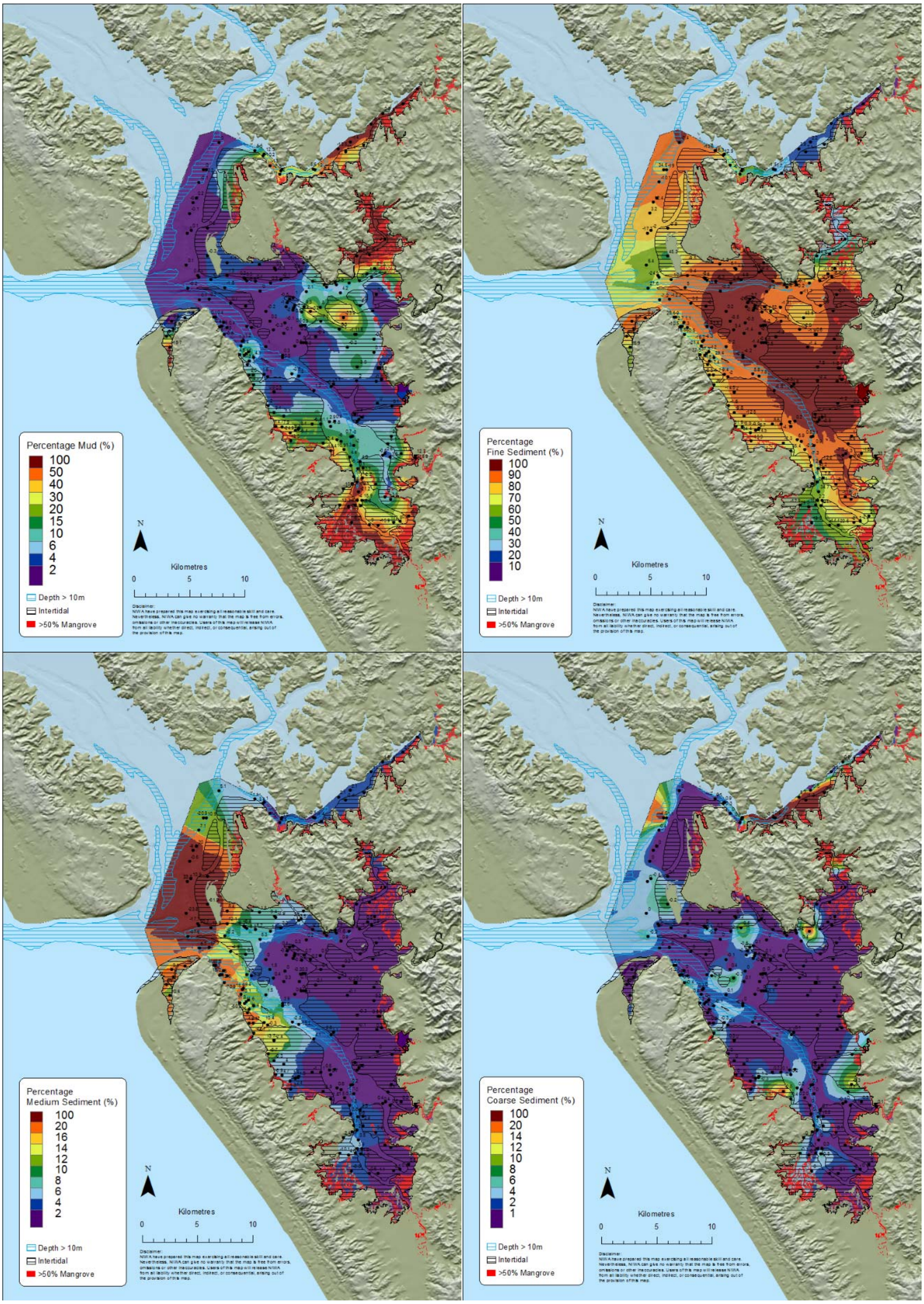

Figure 6: Percentage Mud of surface sediments (top left), fine (top right), medium (lower left) and coarse (lower right) sediment in the southern Kaipara. (source: Hewitt & Funnell 2005)

Raglan Harbour had the largest proportion of intertidal area, at 69% of the total high water area (Table 4). Vegetated cover represents approximately 4% of the estuary area, the rest being intertidal mudflats and channels (source: http://www.waikatoregion.govt.nz/Environment/Environmental-information/Environmental-indicators/Coasts/Natural-character-and-biodiversity/co2-keypoints/). An estuarine survey carried out in 2004 mapped vegetation in the coastal area including intertidal seagrass, mangrove and saltmarsh (Graeme 2005). Scattered young mangrove stands were found in the south-western bays and larger, denser mangroves in the north-northeast parts of the harbour with the Waingaro River characterized by thick stands lining the narrow arms, reaching 3–4 m high. A total of 0.274 km^2 of mangroves were mapped and 0.1385 km^2 of seagrass (Singleton 2009), making up less than 1% each of the total harbour area (Table 10). An estuary monitoring programme, including benthic community sampling of the soft sediment communities has been carried out since 2001 (Singleton 2009, 2010a, 2010b). Five sites characteristic of the intertidal sand / mudflats are monitored four times a year. Polychaetes (e.g. *Aquilaspio aucklandica, Cossura* sp. and capitellids) and bivalves (e.g. *Austrovenus stutchburyi*, *Nucula hartvigiana, Macomona liliana* and *Arthritica bifurca*) are the most common taxa with crabs, gastropods and amphipods found consistently around the harbour. Around 20 – 30 species were identified in each core, with mean abundance of organisms ranging from around 40 – 180. An increase in the proportion of mud content in surface sediment samples from around 7% to more than 10% was observed between 2001 – 2006, with an accompanying decline in abundance of infauna at muddier sites, but no evidence of a decline in known sensitive species (Singleton 2009). More recent results reported on the website indicate that communities have remained relatively stable during the sampling period, with changes in abundance a reflection of natural variation (http://www.waikatoregion.govt.nz/Environment/Natural-resources/coast/Regional-Estuary-Monitoring-Programme/Results/). Variation in community composition and lower abundance was observed at the muddier sites. No overall ecological health index was available for this harbour.

In Porirua, muddy subtidal basins dominate (64% of overall estuary area) with only 11% intertidal. A total of 0.585 km^2 of seagrass beds (where cover was greater than 1%) were mapped in the harbour, located in the seaward, well flushed tidal flats of each arm, making up nearly 8% of the total harbour high water area (Stevens & Robertson, 2008). Analysis of aerial photographs of past and present abundance indicate that these beds were previously more extensive, with a 40% loss since 1960 (Matheson & Wadhwa 2012). Significant macroalgal cover, mainly *Gracilaria* and *Ulva,* was found over 68% of intertidal areas (0.194 km^2), but no mangrove habitats (Stevens & Robertson 2008). Compared to other New Zealand estuaries, the survey indicated that intertidal areas had relatively little soft mud (1.5%). This study also noted the presence of artificial structures, such as sea walls, rail, roads and boat houses along a significant proportion of the estuary edge (2.3%). Monitoring data is available for both intertidal and subtidal benthic communities from surveys conducted between 2004 and 2010. Subtidal fauna is predominantly polychaetes, crustaceans, bivalves and gastropods, with 26 – 54 species per site, and a total of 51 – 64 species identified per survey (Milne 2010, Oliver & Milne 2012). Diversity is lower at the two Onepoto sites, where higher sediment and metal contaminant concentrations are also recorded, and a relationship was found between overall community health, represented by scores from a CAP based on species counts, and sediment pollution, represented by scores from a PCA (Principal Component Analysis) of environmental variables (Oliver & Milne 2012). Compared to many other New Zealand estuaries, a relatively high biodiversity and abundance (33 – 42 species per core, in 2008, 27 – 46 species per core in 2009) were recorded in the unvegetated tidal flats that were the dominant intertidal habitat (Robertson & Stevens 2010). The AMBI scores calculated for the four sites were generally less than 3.0, and the overall ranking was "Good", or "Moderate' (slightly polluted), reflecting a diverse macrofaunal community with a large number of species sensitive to organic enrichment, but also an increasing abundance of species moderately tolerant of organic enrichment, such as deposit-feeding polychaete worms (e.g. *Heteromastus*) (Robertson & Stevens 2010).

Manukau Harbour has extensive intertidal habitats (62%) with sand and mud flats accounting for 60% of these and limited localized areas of mangroves in sheltered areas (2% overall, Table 10**Error! Reference source not found.**). The once extensive seagrass beds on Te Tau Banks and along the northern tidal flats, described by Morton & Miller (1968) as "*splendid Zostera fields of the Manukau Harbour are in some places up to a mile across*.", had all but disappeared by the 1980s (Inglis 2003). Studies of the soft sediment benthic fauna have described intertidal communities on Karore bank off Auckland Airport as dominated by *A. stutchburyi*, *Macomona liliana* in fine sediments and

Halicarcinus cooki and *Owenia fusiformis* in coarser sediments. Subtidal communities east of Cornwallis are dominated by *Maoricolpus roseus* and *Nucula hartvigiana* and in the outer harbour, iron sand substrates are associated with *Arachnoides placenta*-dominated communities (Henriques 1980). Grange (1979) characterised four subtidal macro benthic species groups in the harbour: a *Microcosmus / Notomithrax* community, a *Halicarcinus / Bugula* community, an *Amalda / Myadora* community, and a *Fellaster / Pagurus* community. Henriques (1980) surveyed a range of habitats including bare mud and sand, seagrass and mangroves and the number of species per station sampled ranged from nine species on bare mud habitat to 21 in dense *Zostera* beds with values for Pielou's Evenness metric ranging from 0.45 at muddy sites to 0.75 at sites with dense mangroves. Ecological monitoring of soft sediment macrofauna on the intertidal sand flats has been carried out at selected sites in the Manukau since 1987. Using the Benthic Health Model approach, these central harbour sites have generally ranked as having "Fair" (3) to "Very Good" (1) ecological health (see Figure 9), with no evidence of responses consistent with heavy metal contamination or sedimentation (Hailes & Hewitt 2009). The most significant changes (declines in BHM CAP scores for levels of mud and contaminants) were observed at the Cape Horn site (northern channel) between 2000 and 2005, and were related to a strong El Niño Southern Oscillation (ENSO) as well as the decommissioning of the Mangere wastewater treatment plant. As part of the general descriptions of the sites, the presence of ray pits have been noted in many places during summer months as well as dense patches of nuisance algae such as diatom mats, *Gracilaria* sp. and *Ulva lactuca*. This monitoring programme suggests that current management initiatives being implemented by Auckland Council are maintaining the health of these extensive intertidal sand flats, despite on-going urbanization and industrialization. However, monitoring of selected tidal creeks and inlets indicate that some inner areas of the harbour are not so healthy (Greenfield et al. 2013). For example, Mangere Inlet in the northeast of the harbour represents an area with a long history of coastal modification and pollution. Muddy sediments dominate, and mangroves cover 0.1 km^2. Species counts from core samples at six sites ranged from 13 – 26 per core, and Pielou's metric of 0.15–0.75 (Kelly 2008). The communities at lower diversity sites were dominated by pollution-tolerant species such as the deposit feeding polychaete worm, *Heteromastus filiformis*. Ecological condition was described as degraded at all sites, getting worse to the east of Mangere Bridge, with BHM scores ranging from "Fair" (3) to "Very degraded" (5) (Kelly 2008, Hewitt et al. 2012, Greenfield et al. 2013). Other inlets (Pahurehure and Waiuku Inlet, and Waimahia Creek) were also found to be generally in poor health with reduced or low functionality, and BHM scores of 4 or 5 for all except one site (Greenfield et al 2013).

A benthic habitat survey of the Upper Waitemata found that intertidal sediments are comprised predominantly of mud (i.e., silt + clay), or of a combination of mud and fine-medium sand (Cummings et al. 2002). These intertidal areas represent around 36% of the total harbour area, with mangroves covering 12% overall (Table 10), forming extensive stands in sheltered creeks such as Lucas Creek (Morrisey et al. 2010b). Seagrass beds were once found in bays in the outer harbour, such as Stanley and Hobson Bay, but had disappeared by the 1930s (Inglis 2003). The mean number of taxa at intertidal stations ranged from 3.3 – 12.7 per core, with a mean abundance ranging from 10 – 138 individuals. Similar numbers were found at subtidal sites; mean number of taxa ranged from 3.4 – 22.5, and mean abundance from 6.2 – 167.8 per core. SIMPER analysis defined seven location groupings (inner and outer main body and five different creeks), with oligochaete and nereid polychaetes amongst the most common species at many intertidal sites, along with *Arthritica bifurca*, *Macrophthalmus hirtipes, Nucula hartvigiana* and *Heteromastus filiformis*. The polychaetes *Aricidea* sp., *Cossura* sp. and *Heteromastus filiformis* were found in most of the subtidal areas sampled, along with *Musculista senhousia* at one site.

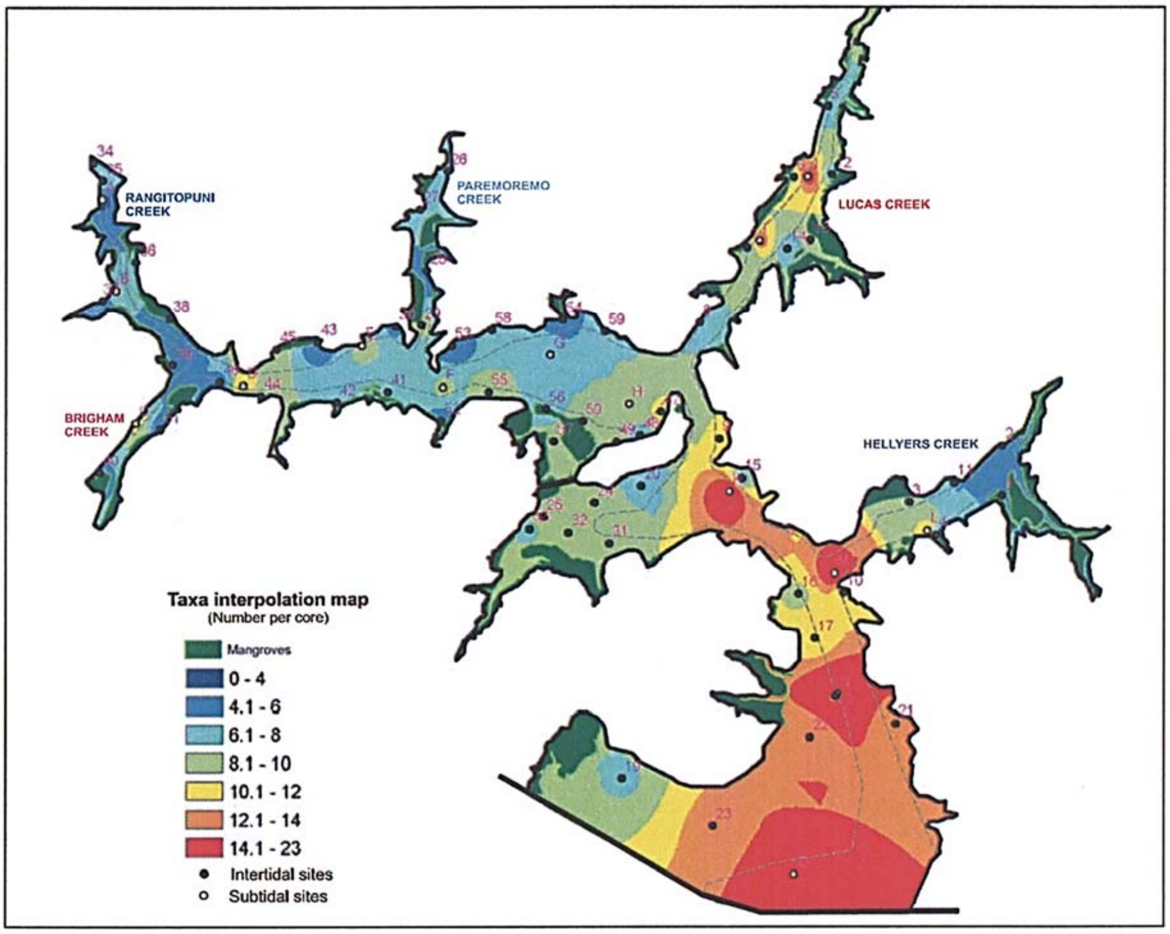

Figure 7: Interpolated map of number of taxa (per core) in the Upper Waitemata Harbour. Red numbers indicate station numbers (source: Cummings et al. 2002).

Monitoring in the upper Waitemata between 2005 and 2008 found higher mud content and lower species diversity in the upper reaches of the harbour, and ecological communities dominated by burrowing corophid amphipods, oligochaetes and polychaetes, whilst sandier sites closer to the entrance had high diversity bivalve-dominated communities (10 – 30 species per site) (Miller et al. 2008). Monitoring in the central Waitemata has taken place since 2000 (Halliday et al. 2012, Hewitt et al. 2012, Townsend et al. 2008). A number of trends in selected species abundance were noted over time, such as a decline in the bivalves *Nucula hartvigiana, Paphies australis* and *Macomona liliana* at certain sites, and increasing abundance of silt-tolerant polychaetes such as the capitellid worm**,** *Heteromastus filiformis, Aricidea* sp. and *Prionospio* (*Aquilaspio*) *aucklandica* (Townsend et al. 2008, Halliday et al. 2012). At Meola reef, one of the few hard substrate habitat features in the harbour, monitoring between 2001 and 2008 has noted a generally stable community dominated by *Crassostrea gigas* in the intertidal zone, as well as the anemone *Anthopleura aureoradiata*, the small mussel *Xenostrobus pulex*, along with grazing gastropods and chitons (Ford & Pawley 2008, Hewitt et al. 2012). At subtidal depths, canopy forming brown algae (e.g. *Carpophyllum* sp.) cover mainly unconsolidated substrate, crustose and coralline turfing algae, along with sponges and solitary ascidians. The dominant mobile organism on the reef was *Turbo smaragdus.* Although no changes in the community were detected, an increase in the cover of sediment was correlated with declines in abundance of many species and it was suggested that that the rates of sediment deposition is likely to result in declines in abundance of most species and overall diversity (Ford & Pawley 2008). Multivariate analysis of the soft sediment sites also found a strong correlation between community composition and sediment mud content (Halliday et al. 2012). The most recent Benthic Health Model results (see Figure 9), using all three indices combined (CAPmetals, CAPmud and TBI), found that more than 60% of sites in the central and upper Waitemata, were "Poor"

(4) or “Unhealthy” (5), with stations in more exposed and / or central areas being classed as “Moderate” (3) to “Good” (2) (Hewitt et al. 2012).

The Tamaki estuary is dominated by low relief intertidal sand / mud flats (40% of estuary area is intertidal) with extensive mangrove forest in localized upper reaches (e.g. Pakuranga, Otahuhu and Otara creek and Middlemore). A recent review estimated 186 ha total coverage of mangrove forest from 2006 aerial photographs, equating to less than 1% of the total estuary area (Kelly 2008), although the Estuarine Environment Classification database estimates that 8% of the overall estuary area is covered by mangroves**Error! Reference source not found.**. Similar to the other two Auckland estuaries, previous extensive seagrass meadows present up until the 1960s, are no longer found in the Tamaki (Inglis 2003). Kelly (2008) also assessed benthic biodiversity, total abundance and distribution patterns in the soft sediment habitats; benthic biodiversity was generally low throughout the estuary, and declined from the outer (30–34 species) to the inner Tamaki (13 – 17 species), with the exception of the mid-Pakuranga site where relatively high abundances were found (n=29). Values for Pielou’s Evenness ranged from 0.77 in the outer estuary to 0.44 in the Panmure Basin (Figure 8**Error! Reference source not found.**). Sheltered muddy sites were dominated by high numbers of pollution-tolerant species such as predatory (Neriedae), deposit-feeding (*Cossura consimilis*) and sedentary (polydorid) polychaetes, and had lower values of Pielou’s evenness index. A previous characterization of benthic macrofauna and an intertidal habitat survey carried out in 2005 (Hayward & Morley 2005) both demonstrated distinct changes in benthic communities reflecting changes in water quality and substrate. Species diversity was highest in the outer estuary where there was also a high degree of habitat diversity including hard rocky substrate; sponges, ascidians, barnacles, gastropods and chitons. Hayward and Morley recorded 12 species of sea slug from around the entrance of the harbour, large colonies of flea mussel (*Xenostrobus securis*) and encrusting coral *Culicia rubeola*. Further up the estuary, as muddy substrate increased and water quality declined, species associations changed. In the mid part of the estuary abundant species included epifaunal snails, bivalves such as *Austrovenus stutchburyi* and the Asian date mussel and mud crabs *Helice crassa*, *Hemigrapsus crenulatus* and *Macrophthalmus hirtipes* as well as snapping shrimp and tube worm. The inner estuary region was dominated by mangroves and epiphytic acorn barnacles, mud snails (*Amphibola crenata*), cockles (*A. Stutchburyi)* and mud crabs. Benthic Health Model scores calculated for the Tamaki Estuary (see Figure 9) rank sites in the upper reaches, such as Middlemore and Otahuhu as “Unhealthy” (5) , with benthic communities improving down the estuary, with outer estuary sites such as Benghazi and Glendowie ranked at “Moderate” (3) (Kelly 2008, Hewitt et al. 2012).

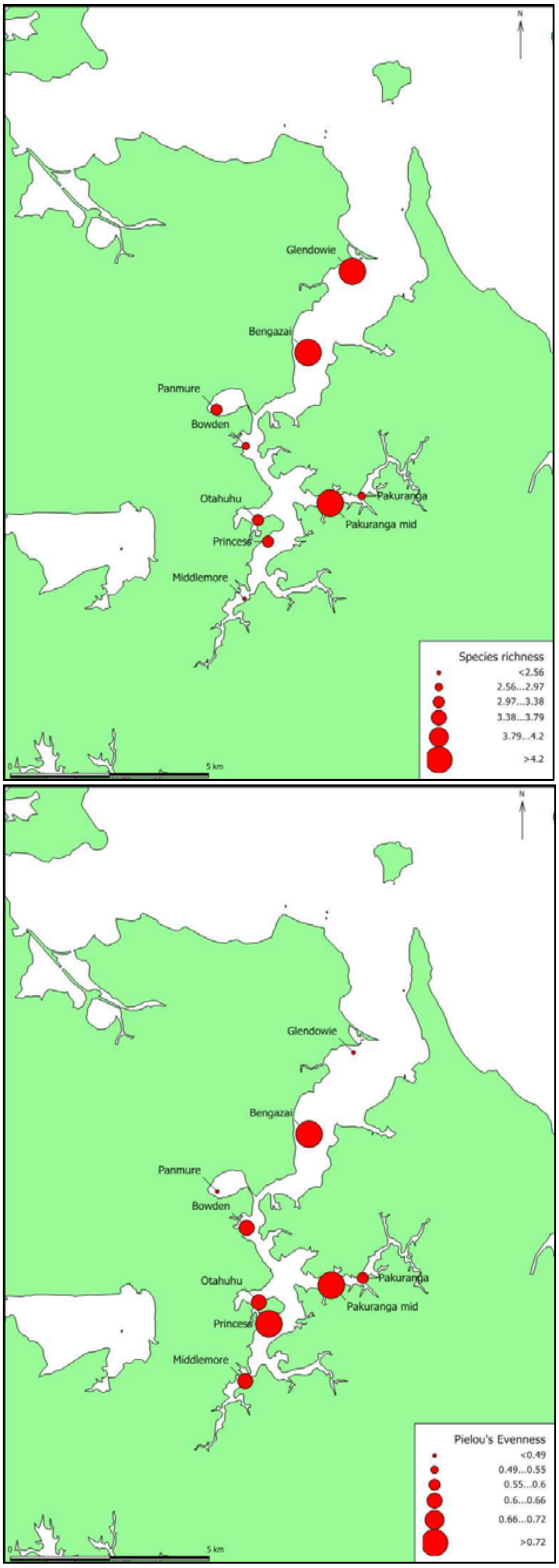

Figure 8: Species Richness (top) and Pielou's Evenness index (bottom) of benthic dwelling macroinvertebrates in Tamaki Estuary (source: Kelly 2008).

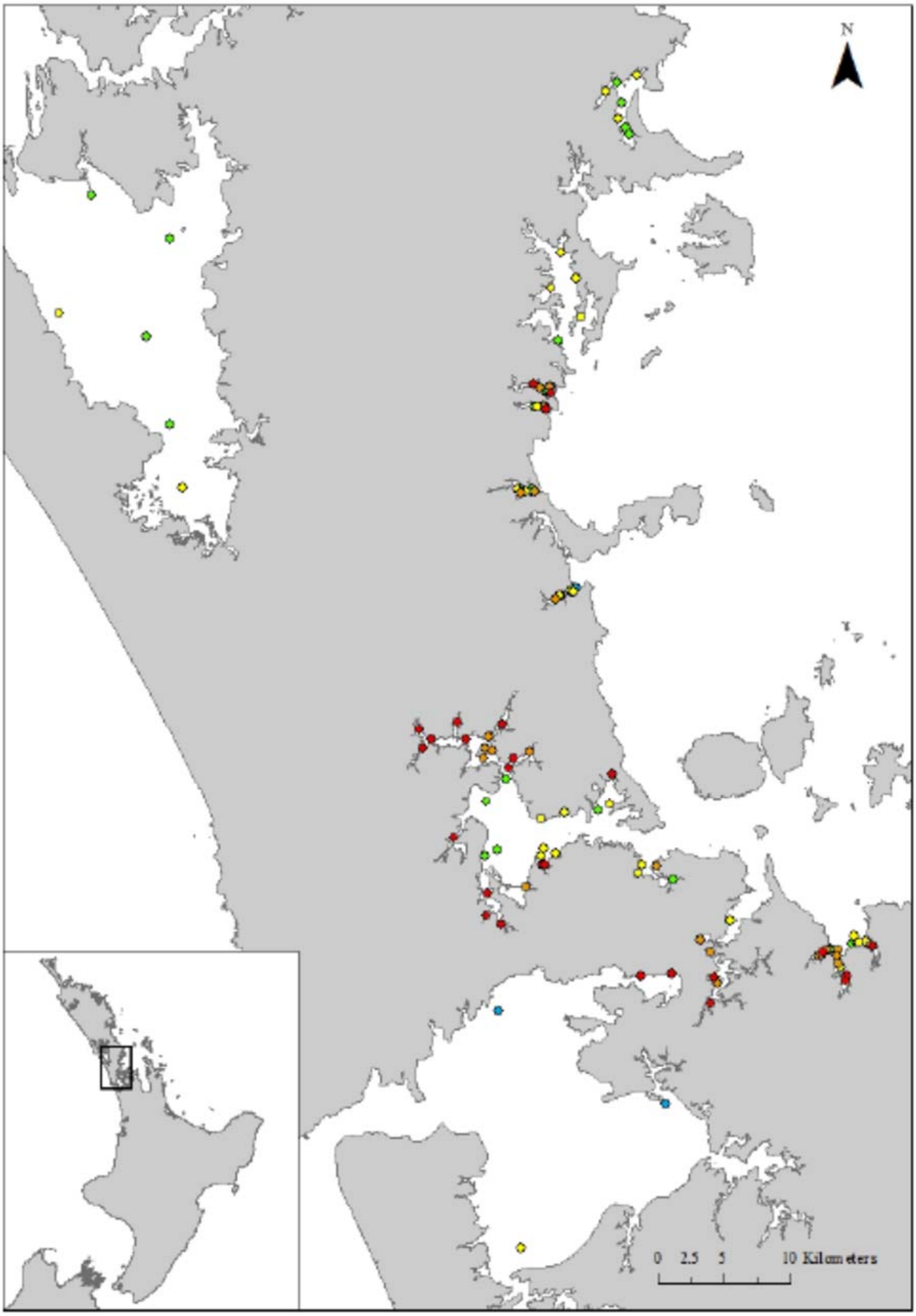

Figure 9: Ecological health scores of benthic communities reflecting the CAP mud, CAP metals and TBI indices. Health scores indicated by colour; rated from Blue = "Extremely Good", Green = "Good", yellow = "Moderate", orange = "Poor", red = "Unhealthy" (source: Hewitt et al. 2012)

3.4 Water-Based Threats

3.4.1 Fishing

The final groomed dataset for the three fishing years, six statistical areas and four fishing methods contained 11 816 fishing events. Of these, 54.5% were made by set net, 44.2% by ring net, 1.1% by drag net, and 0.2% by beach seine. The four different methods are fundamentally different, and measures of effort cannot be directly compared among them. Set nets are fixed in position (passive) whereas ring nets are set around schools of fish and drag nets and beach seines are dragged through the water (active). The amount of net set for each of the methods is shown in Figure 10. For ring nets, the amount of net reported on CELR forms is the length of the actual net, but the net may be set more than once (usually 1–3 times) during the same day.

Fishing effort was greatest in Kaipara and Manukau Harbours, intermediate in the inner Hauraki Gulf, and low in the other harbours and adjacent coasts. Latitudes and longitudes were supplied for only four fishing events inside the harbours of interest, so spatial analyses below were restricted to the level of a statistical area.

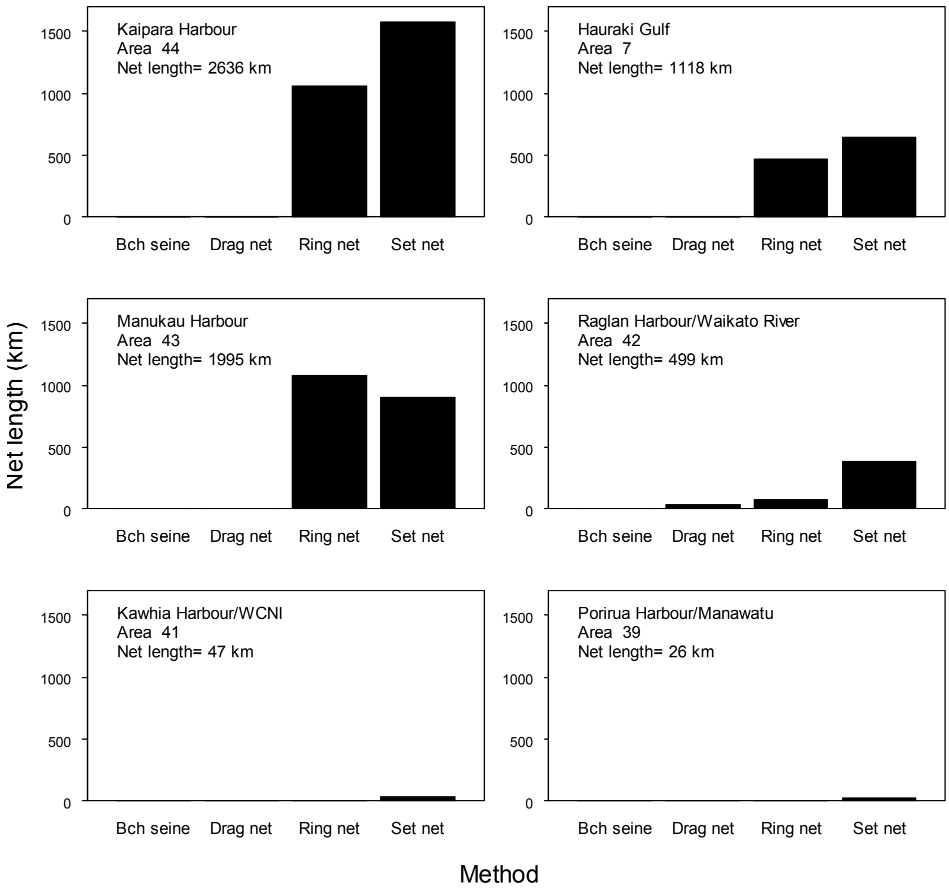

Figure 10: Total length of net set (Net length) in six statistical areas classified by fishing method for three fishing years (2007–08 to 2009–10). For set net and drag net, only mesh sizes up to 100 mm are included. Comparisons among areas are valid, but comparisons among methods within areas are not.

Set net

Most set net fishing events in all harbours used mesh sizes of 81–100 mm (Figure 11). Inspection of the data at finer resolution showed that mesh sizes of 90–92 mm were favoured, comprising 77% of the net (of 100 mm mesh or less) set in Kaipara Harbour, 55% in inner Hauraki Gulf, 79% in Manukau Harbour, 83% in Raglan Harbour/Waikato River, 60% in Kawhia Harbour/ West coast North Island (WCNI), and 43% in Porirua Harbour/Manawatu.

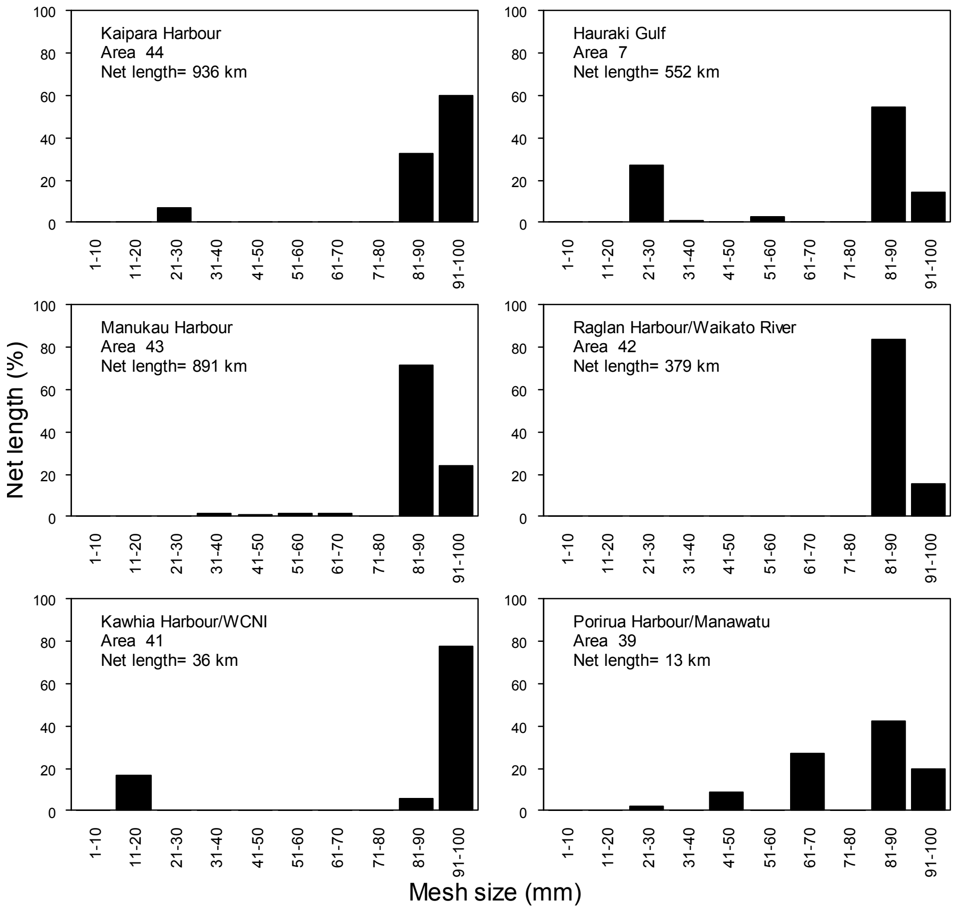

Figure 11: Percentage of set net length classified by statistical area and mesh size for three fishing years (2007–08 to 2009–10). Only mesh sizes up to 100 mm are included.

The main target species in all areas except Porirua Harbour/Manawatu was grey mullet (GMU) (Figure 12). Yellow-eyed mullet (YEM) was the main target in Porirua Harbour/Manawatu and flatfish (FLA) and kahawai (KAH) were also important in the inner Hauraki Gulf. Fishing effort was seasonally variable with peak effort occuring at different times in different harbours; June – September in the Kaipara Harbour, Dec – March in Manukau Harbour and Raglan Harbour/Waikato River and peaks in February, May and September in Porirua Harbour/Manawatu) (Figure 13). Overall, in all six areas, significant percentages of effort were expended in late spring-autumn, (December – April) when 0+ rig are likely to be present.

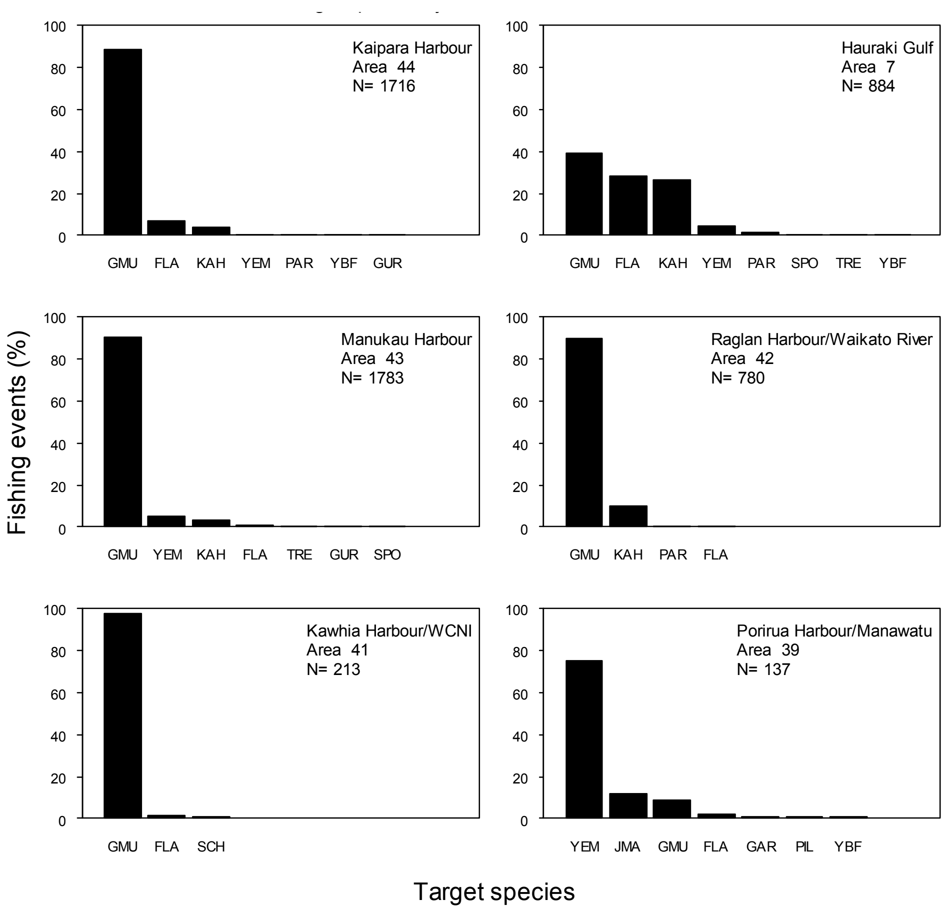

Figure 12: Percentage of set net fishing events classified by statistical area and target species for three fishing years (2007-08 to 2009-10). Only mesh sizes up to 100 mm are included.

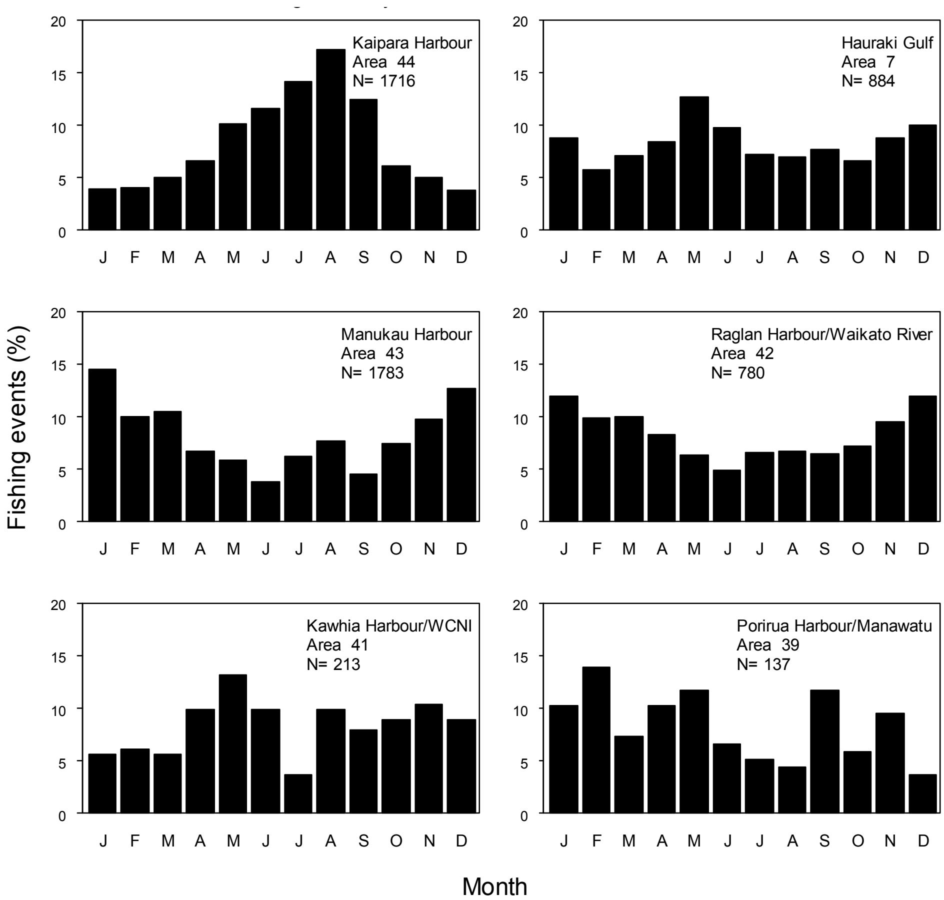

Figure 13: Percentage of set net fishing events classified by statistical area and month for three fishing years (2007–08 to 2009–10). Only mesh sizes up to 100 mm are included.

Ring nets

No mesh size data were available for ring nets. This method is used mainly to target grey mullet in all harbours where it is used (**Figure 14**). Kahawai is occasionally targeted in the inner Hauraki Gulf. In the main areas where it is used (Kaipara and Manukau Harbours, inner Hauraki Gulf), ring nets are used year-round (Figure 15).

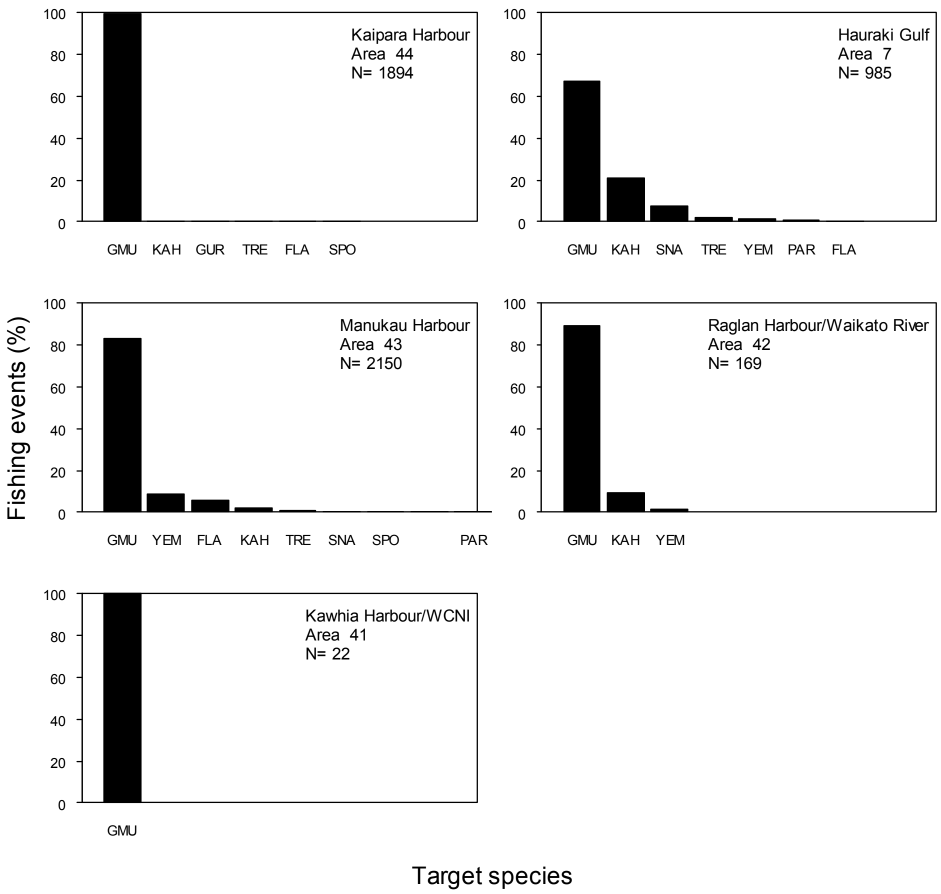

Figure 14: Percentage of ring net fishing events classified by statistical area and target species for three fishing years (2007-08 to 2009-10).

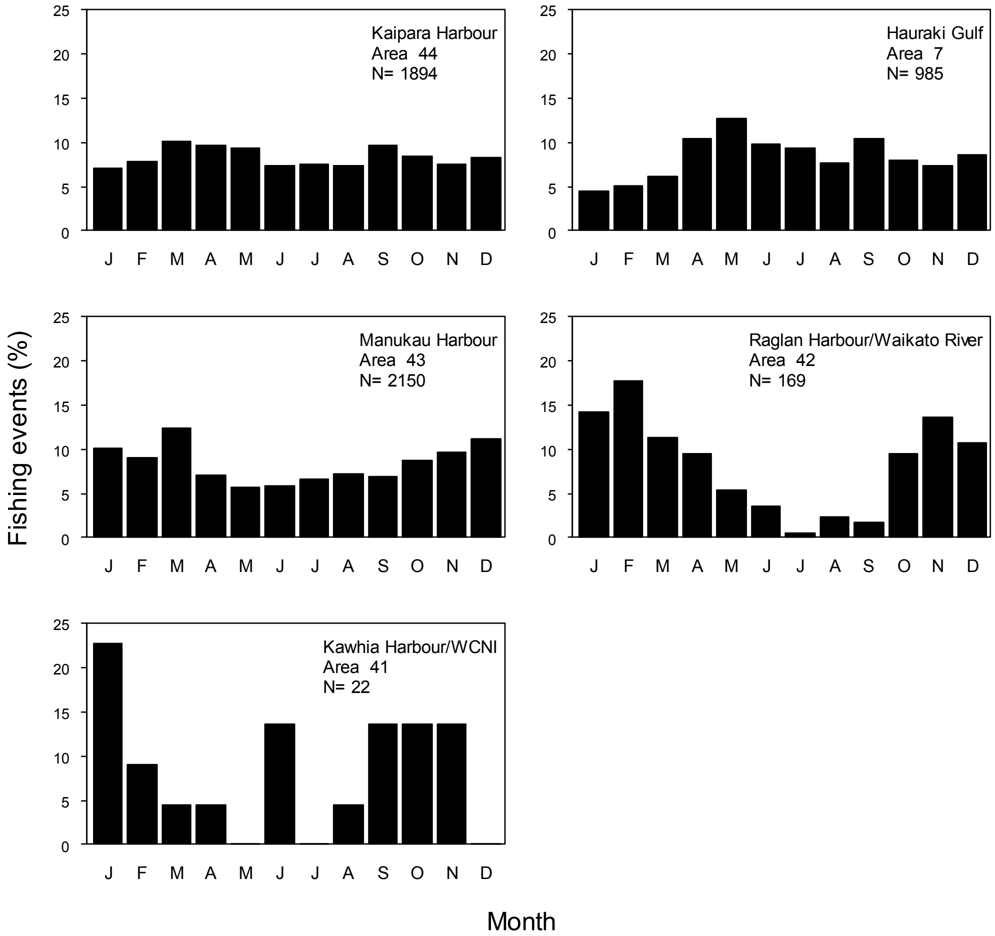

Figure 15: Percentage of ring net fishing events classified by statistical area and month for three fishing years (2007-08 to 2009-10).

Drag nets

Drag nets were rarely used, and then only in two of the six statistical areas – Manukau Harbour and Raglan Harbour/Waikato River. They mainly used mesh sizes of 81–90 mm to target grey mullet, and occasionally yellow-eyed mullet and kahawai, between September and May (spring – autumn) (Figure 16 to Figure 18).

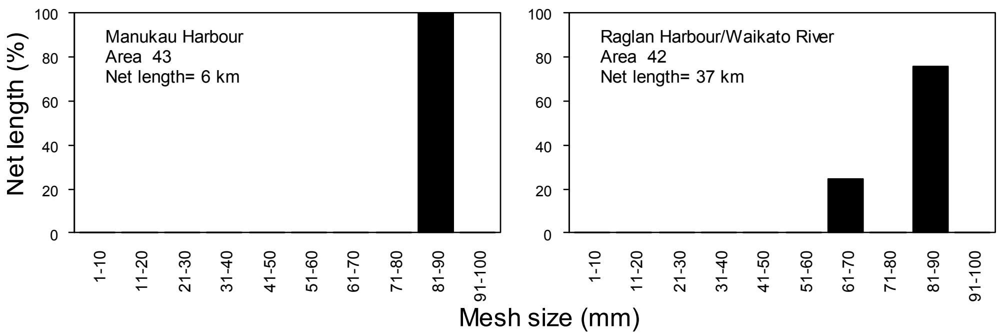

Figure 16: Percentage of drag net length classified by statistical area and mesh size for three fishing years (2007–08 to 2009–10). Only mesh sizes up to 100 mm are included.

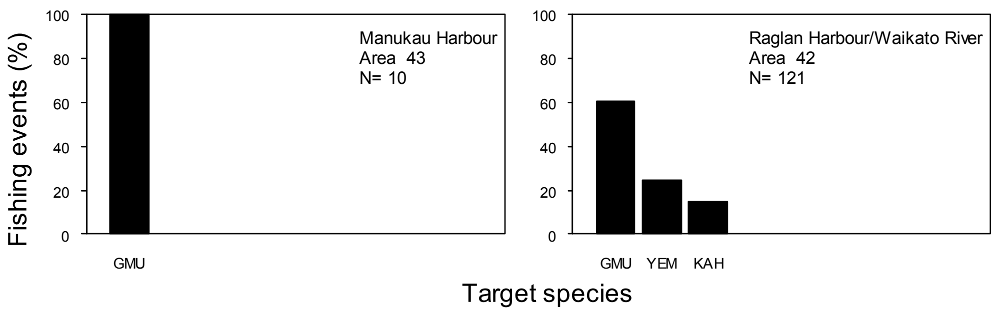

Figure 17: Percentage of drag net fishing events classified by statistical area and target species for three fishing years (2007–08 to 2009–10). Only mesh sizes up to 100 mm are included.

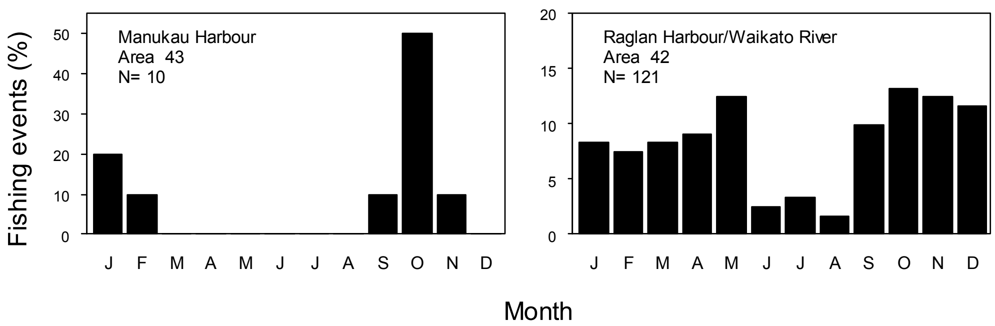

Figure 18: Percentage of drag net fishing events classified by statistical area and month for three fishing years (2007–08 to 2009–10). Only mesh sizes up to 100 mm are included. Note the different Y-axis scales.

In summary, the only fishing methods likely to pose a significant risk to 0+ rig in estuaries and harbours are those using small mesh nets. Of these, only set nets and ring nets are used in quantities large enough to be a potential threat. Total fishing effort using mesh sizes of 100 mm or less was greatest in Kaipara and Manukau Harbours, inner Hauraki Gulf, and Raglan Harbour/Waikato River. Fishing effort was relatively low in Kawhia Harbour/WCNI and Porirua Harbour/Manawatu, but the harbours in these statistical areas are small so even a small amount of effort may impact on rig.

The main fishery in each statistical area, regardless of method, was a target grey mullet or yellow-eyed mullet fishery. These fisheries operate mainly or exclusively in the harbours (i.e. not on the adjacent open coast) because of the behaviour and habitat of the target species, and the operating requirements of ring nets and small mesh set nets. There is no information on where these fisheries operate within harbours, so it is not known whether they overlap spatially with rig nursery areas within the harbours. However juvenile rig range widely within these harbours so spatial overlap is likely. Temporal overlap occurs in all harbours.

3.4.2 Aquaculture

Aquaculture has occurred in the Kaipara Harbour since the early 1900s, with commercial farming of the native rock oyster (*Saccostrea glomerata*) expanding in the 1960s, the introduction of the Pacific oyster (*Crassostrea gigas*) in the 1970s (Haggit 2008) and cultivation of greenlip mussels occurring once wild stocks were exhausted (Morrison et al. 2014). There were 31 licences / permits as of 2008 covering an area of 190 hectares, including sites in the Pahi, Otamatea and Arapaoa rivers, Paparoa Creek, in Hargreaves Basin (more than 100 hectares), but many of these have been abandoned following the effects of the OsHB micro variant virus in 2010, with only three farms thought to be currently operating (J. Dollimore, Biomarine, pers. comm.). One of these is the recently established and organically certified 75 hectare farm near Kakaraia flats in the mouth of the harbour, predicted to become New Zealand's largest oyster farm producing more than 24 million oysters a year.

Impacts of oyster farming include introduction of novel habitat (with potential shading effects), pests (e.g. fouling organisms, toxic algae and disease), and changes to water clarity, nutrient cycling and benthos (from bio deposition and enrichment) (Forrest et al. 2009). In their assessment of Aquaculture Management Areas within the north east arms of the Kaipara (including the Arapaoa and Otamatea Rivers), Haggitt & Mead (2005) noted that the areas were dominated by polychaete worms such as *Glycera americana* and *Orbinia papillosa*, the mud crab *Helica crassa*, *Alpheus* sp. and *Nucula hartvigiana*, indicating that these areas were already degraded and flagged potential problems in the capacity for these sites to cope with increased enrichment. Recent studies of the BioMarine open water oyster farm (hanging baskets rather than the traditional stick and rack system), found that shading of the underlying seagrass habitat was limited to shading directly under the basket lines and had minimal environmental impact on this habitat (Bulmer et al. 2012).

It is unlikely that aquaculture farms pose a direct threat to rig as they are able to avoid localized adverse environmental conditions, and in fact feed on species which thrive in these environments such as mud crabs and polychaetes. However, depending on the intensity and spatial extent of farming, if the areas beneath become degraded beyond their capacity to support such benthic communities, this could represent a loss of foraging habits, in addition to the threat of parasites and invasive species further compromising communities within the harbour on a broader scale.

There are currently no aquaculture farms in any of the other harbours.

3.4.3 Vessel Traffic

In the Kaipara harbour, information provided by Auckland and Northland Regional Council listed 106 coastal permits (including boat ramps, jetties, seawalls and other activities such as marine farming) and 46 mooring permits. Small marinas, jetties and mooring areas exist at Whakapirau, Port Albert and Tinopai, Helensville, Dargaville, Ruawai and Kelly's Bay. Relative to other harbours these structures are limited and in terms of shore hardening, pollution from vessels and noise disturbance, potential for adverse effects are currently relatively low. In Raglan Harbour only 14 mooring permits are registered with Environment Waikato and there are very few areas of the coast modified in terms of jetties and boat ramps etc. The projected increases in local and visiting population attracted to the area for recreation are likely to increase pressure on these limited facilities and there are proposals by the local council to increase ease of boat access.

Porirua Harbour has seven areas where boats can be moored including Mana Marina (which now contains upwards of 300 berths and which removed 0.4% of the harbour's intertidal area,), Onepoto, Shearer's Point and Browns Bay. Mana cruising club has about 800 members and there is a variety of other popular recreational water sports.

Within the Waitemata Harbour as a whole there are over 3700 moorings, 1900 in Westhaven, the largest marina in the southern hemisphere, 415 in Bayswater Marina on the North Shore, and 860 in the upper harbour, including 592 berths in Westpark Marina near Hobsonville (Auckland Council). Upwards of 1400 large vessels visit Auckland port a year (averaging 3–4 a day), along with around 100 cruise liner visits. A number of fishing vessels also land into the port and, an extensive ferry network operates around the harbour (http://www.poal.co.nz/about_us/). In the Tamaki Estuary there are five mooring management areas with 1685 berths including Half Moon Bay Marina and ferry terminal and Bucklands Beach yacht club. Haul-out sites and wharfs are also situated around Panmure Bridge, along Mount Wellington industrial foreshore and the Otahuhu Power station. There are no designated mooring areas in the Manukau, but fishing vessels and a daily ferry service operate out of Onehunga port. This smaller facility has less traffic than the Waitemata port (fewer than 100 vessel visits), being used mainly for coastal reshipment within New Zealand.

The overlap of vessel traffic in the harbours and juvenile rig habitat is unknown, but is likely to be small / non-existent for the larger vessels at least. Whether vessel traffic has an impact on movement out of the harbour is also unknown, but the presence of juveniles indicates that adults are entering these areas and successfully pupping. However the high level of vessel traffic in the three Auckland harbours, and to a lesser extent, Porirua Harbour, means a higher risk of pollution from discharged ballast water, anti-fouling paint, oil spills and other hazardous substances, as well as an increased risk of unwanted marine organisms. Although juvenile rig may not be present in the immediate vicinity of the busy port areas, a large pollution incident would impact other parts of those harbours and could damage important habitats and prey populations.

3.4.4 Non-Indigenous Species

Within the Hauraki Gulf, a series of baseline and targeted surveys by Biosecurity New Zealand have recorded 139 non-indigenous species (Morrisey et al. 2010a), 66 having become established in the Waitemata Harbour (Haggitt 2008). These include now dominant bivalves such as *Theora lubrica, Limaria orientalis* and *Crassostrea gigas,* as well as unwanted species such as the Mediterranean fan worm *Sabella spallanzanii,* the clubbed sea squirt *Styela clava*, Asian kelp *Undaria pinnatifida* and the Japanese mud crab *Charybdis japonica.* Other non-indigenous species include bryozoans *Bugula flabellata, Bugula neritina, and Celleporaria sp 1*, the tube dwelling polychaete, *Hydroides elegans*, the hydroid *Pennaria disticha* and the Asian date mussel*, Arcuatula senhousia*,. Many of these species may well be established in the nearby Tamaki Estuary, but there were no data available for this estuary. The other harbours have had only single baseline, or no surveys carried out. A baseline survey carried out in 2006 at Onehunga port in the Manukau found 16 introduced species, but none on the unwanted list (Campbell et al. in draft). The species recorded included the red algae *Solieria* sp., three ascidians (*Molgula manhattensis*, *Styela plicata*, and *Diplosoma listerianum*), four bryozoans (*Amathia distans, Cryptosula pallasiana, Conopeum seurati,* and *Bugula neritina*), one mollusc (*Crassostrea gigas*), and four polychaetes (*Polydora cornuta, Barantolla lepte*, *Polydora hoplura,* and *Neanthes* aff. *Succinea).* Data from the MITS (Marine Invasive Taxonomy Service) database listed 13 species from the Manukau (9 noted in the baseline survey and 4 additional ones), including the brown algae *Rosenvingea sanctae-crucis* and ascidian *Eudistoma elongatum*, (a secondary target species), and the spider crab, *Pyromaia tuberculata (*Anjali Pande, MPI, unpublished data).

At least 20 non-indigenous species have been recorded from the Kaipara, such as the bryozoans, *Membraniporopsis tubigera*, and *Zoobotryon verticulatum*, bivalves; *Crassostrea gigas*, *Tiostrea chilensis (*Chilean oyster), *Arcuatula senhousia* and *Theora lubrica*, red algae; *Graciliaria chilensis* and *Polysiphonia sertularoides* and the Japanese mantis shrimp *Oratosquilla oratoria* (Haggit 2008, Inglis et al. 2010). *A. senhousia* has spread throughout the harbour and is thought to be linked to a decline in polychaete tubeworm abundance (Hewitt & Funnell 2005), and *M. tubigera* became very prolific in 2001, clogging the nets of local fishers (Gordon et al. 2006). The closest site to Raglan harbour that has been surveyed is the Taharoa Terminal, an ironsand loading facility approximately 20 km south of Kawhia harbour. Only six non-indigenous species were detected in a baseline survey here; three algae (*Polysiphonia subtilissima, Polysiphonia brodiei* and *Polysiphonia* aff. *Sertularioides)*, a freshwater plant, a barnacle (*Austromegabalanus nigrescens*) and a bryozoan (*Electra angulata*) (Inglis et al. 2008). A further two algal species and the ascidian *Diplosoma listerianum* have also been detected there (Anjali Pande, MPI, unpublished data). There have been no surveys targeting non-indigenous species in Porirua harbour, but *Undaria pinnatifida* has been recorded since 1992, although not in high densities (Stevens & Robertson 2008), as well as *Chondria harveyana* (Blaschke et al. 2010), although this red algae is not considered invasive. The clubbed sea squirt *Styela clava* has also been reported in the harbour (Anjali Pande, MPI, unpublished data), and other species are likely to occur. Smooth cord-grass *Spartina alterniflora* was introduced to North Island estuaries in the 1950s to promote reclamation of tidal flats (Swales et al. 2005a) and *Spartina* marshes are found in all six harbours.

The number of non-indigenous species, (including unwanted species) recorded in the different harbours is included here as indicative of the level of anthropogenic impact and increased risk of threat to the native eco-system (Molnar et al. 2008), however the difference in sampling effort between these harbours makes it difficult to compare directly. The impact of individual, or combinations of invasive species on the functioning of harbours as nursery grounds for rig will depend on whether that species enhances or threatens essential habitats and / or prey populations. For example, *Charybdis japonica* is a highly aggressive predator of native bivalves such as cockles and pipi, but juvenile rig have been found to prey on this, as well as the Australian prawn, *Metapenaeus bennettae* (Getzlaff 2012). It is not known if this change in diet could have any effect on growth and subsequent survival.

3.4.5 Sand extraction and dredging

There has been a history of sand extraction from the Pouto shoreline and Tapora and Fitzgerald Banks in the Kaipara harbour (Haggitt 2008). Following an assessment of the sustainable volumes of sand that could be extracted from different areas of the harbour (Hume et al. 2003),two permits were granted in 2006 to remove a total of 400 000 m^3 of sand per year for five years, with increasing quantities permitted once further conditions have been met (Auckland Council website). Current extraction rates using suction pumps and barges are 219 000 m^3 per year from Tapora Bank and an additional site is being scoped adjacent to Kaipara Heads. In his review of environmental information for the Kaipara harbour, Haggitt (2008) noted that the area is fairly exposed, with fine-to-medium grain sediment and relatively low biological diversity. Localized impacts associated with extraction are thought to be comparatively small in terms of benthic diversity, although concerns have been raised about declines in populations of tuatua both within the extraction area and in a nearby control site (Grace 2004, Haggit 2008). There are also gaps in information concerning sediment transport processes operating in this highly dynamic environment in relation to the long term impact on the flood shield around the Taipora region and water flows inside the harbour. Potential physical changes in water flow may have impacts on more vulnerable habitats inside the harbour. It is also not known whether these activities have any impact on fish movements into and out of the harbour.

Maintenance dredging of shipping channels to the ports and marinas occurs in the three Auckland harbours (Cole et al. 1997, Flaim 2008, Gowing et al. 1997), and has been proposed for Pauatahanui Inlet in Porirua (Tuckey 2011). Similar to sand extraction, the impacts of such dredging include direct removal of benthic organisms, the potential release of contaminants, nutrients and anoxic sediments, along with smothering from plumes of turbid water and possible alteration of the hydrodynamic regimes (James et al. 2009). Sediment accumulation rates of 10 – 50 000 m^3 per year have been recorded around the Auckland ports in the past (Parliamentary Commissioner for the Environment 1995), and routine maintenance dredging continues. Historically, dredged material was disposed of at a deep offshore site, but more recently dredged material from both the Waitemata and Onehunga port in the Manukau has been utilized in the reclamation area at the Fergusson container terminal by mixing with cement to make mudcrete
(http://www.poal.co.nz/community_environment/dredging.htm). This strategy keeps the dredged material, and any negative impacts, in a very localized region, and monitoring programmes have indicated that water quality and contamination impacts are minimal (Rosie Mercer, Ports of Auckland, unpublished data). It is unlikely that the areas dredged overlap with important juvenile rig foraging or resting habitats, being in the deeper channels of the central Waitemata, but it is not known if activities could have an effect on migration into or out of the harbour by adults or sub-adults.

3.4.6 Energy

The large size, lack of commercial shipping and strong tidal flows make Kaipara Harbour an attractive site for marine tidal power generation. In March 2011 Crest Energy was granted consent to establish, on a staged basis, 200 turbines in the harbour connected by cables to a substation at Pouto Point. The site is in the mouth of the harbour along the North Head coast to coincide with highest tidal flows that can exceed 5 knots. Currently turbines being built and deployed are 10 – 17 m diameter, although the consent applied for is for a maximum size of 25 m, to be situated in water at least 31 m depth with 7 m of clear water above. During the consent process, the potential impacts of collision, electromagnetic fields, noise and habitat loss were considered for marine fish and mammals (Francis 2009, Francis 2010). The design features of the proposed current-cables were believed to be sufficient to result in little impact on elasmobranch behaviour, and it was thought that collision was not likely to present a problem (Francis 2009). However, there is currently no detailed information on the movement patterns of adult rig into and out of the harbour or of juvenile movements when they finally leave, and no actual data on the noise levels generated by the turbines *in situ*. Thus the impact of the array on the Kaipara as a significant nursery habitat for rig is unknown. Measurements made near a much smaller 6 m diameter turbine in Orkney indicated that the turbine produced broad spectrum noise above background levels out to 200 m (Parvin & Brooker 2008), which was believed to be well within the hearing range of elasmobranchs such as rig (Casper & Mann 2006). It was acknowledged that impacts may be mitigated by high ambient noise, non-continuous operation and the nature of the noise patterns; steady rise and fall rather than pulsed or sudden loud noises and eventual habituation. However, given the lack of species- and site-specific information, baseline monitoring for three years was recommended to ensure sufficient data on movement patterns and use of the area before installation begins. There are no similar current activities or proposals relevant to the other five harbours that the authors are aware of.

The water-based human impacts on the six estuaries are summarised in Table 11. A crude comparison of fishing effort was given by dividing the total length of set nets reported by the area of the harbour. For Raglan, the area value used included that of the Waikato River (18.2 km^2) and for Tamaki and Waitemata, the length of set nets was given as a combined value for the Inner Hauraki Gulf (including Firth of Thames and inner Gulf islands), so the value is potentially much lower depending on how much of the effort occurred outside the harbours. For most other threats insufficient information was obtained other than presence / absence of occurrence.

Table 11: Summary of water based human activities, by harbour. Where activities are known to occur but no readily available data was found to compare, presence only (•) is indicated.

	Kaipara	Raglan	Manukau	Porirua	Waitemata	Tamaki
Fishing Effort (km of net/set km^2)	3.5	10	5.5	3.4	2–10	2–10
Vessel Activity:						
Moorings	46	14	None known	<500	3 700	1 685
Large Vessel port calls			84		1 461	
Aquaculture	•					
Dredging / sediment extraction (m^3 per year)	(>200 000)		(5 – 10 000)	•	(~50 000)	(<10 000)
Energy generation activities / structures	•					
Non-indigenous species	~20	Unknown (< 10)	~20	3 known	66	unknown

4. DISCUSSION

The previous sections have outlined the information available on human activities that are likely to impact on both the ecological integrity of the estuary systems, and the available monitoring data assessing that integrity. Table 12 summarises this information into a number of metrics with suggested relative rankings to reflect the level of threat for these stressors. These levels are based as much as possible on information contained in relevant literature. Synthesis and integration of such information into an overall Human Threat metrics is an approach which is being used to assess the extent and severity of human impacts on freshwater and coastal systems around the world (Burke et al. 2011, Halpern et al. 2008, Mattson & Angermeier 2007, Paukert et al. 2011, Sowa et al. 2007, Vorosmarty et al. 2010). A fully integrated assessment was outside the scope of this study, but Table 13 suggests the estimated severity of the identified metrics for each estuary. The human populations around the three Auckland harbours and Porirua, and the large increases in density predicted over the next 20 years (particularly Waitemata and Tamaki) represent the major stressor to these harbours through the impacts of expansion of urban settlements, impervious surfaces (houses, roads, etc.), sewage and stormwater with their associated sedimentation, nutrient and pollution levels. The Tamaki Estuary catchment already has very high population densities, the highest percentage of impervious cover, high levels of boating traffic (mainly small craft) and localized areas of high contamination due to its long history of industrial use. The poor water quality and degraded benthic communities reflect this, but the estuary still appears able to function as a nursery ground with juvenile rig caught along the length of the estuary (mean number of 2.9 0+ rig per set, Francis et al. 2012). It is not known whether larger populations were supported previously and if degraded water quality, pollution levels and less diverse benthic communities impact on the growth rates and survival of juveniles from this nursery. Similar catch rates were found in the Upper Waitemata Harbour, which has a similar suite of land-based stressors. Parts of the upper catchment remain less urbanized, but water quality and benthic community health ratings were highly variable. Commercial shipping activity and the associated risks of both chronic and acute pollution, and invasive species are highest in this harbour compared to the others. Fishing effort, in terms of kilometres of net set was considered intermediate although the extent of the statistical area from which data was taken (Inner Hauraki Gulf) could equate to a much lower impact, depending on the spatial distribution of the fishing activity.

The water quality and benthic health of the Manukau Harbour varied considerably from contaminated and degraded areas in the inner harbour, close to densely populated urban settlements and freshwater inputs with high levels of sedimentation, and healthy and biologically diverse areas in the outer harbour and where the adjacent catchment was less urbanized. Large increases in population density are predicted for parts of Manukau City and future subdivision and urbanization of less developed parts of the catchment will potentially present significant impacts through increasing sedimentation and pollution etc. However, in contrast to the smaller Waitemata and Tamaki estuaries, the Manukau Harbour has a very small CER (Table 4) and river discharge (relative to its size) and this potentially mitigates the impact of these land-based threats. Fishing is likely to be a significant threat, with higher effort in Dec-March when juvenile rig are present. Despite the low proportion of mangrove and muddy intertidal habitats that characterize other rig nursery habitats, Porirua Harbour has been shown to reliably support juvenile rig (mean catch of 4 0+ rig per set, Francis et al. 2012). This small harbour faces similar threats to the Auckland harbours, in terms of relatively dense populations in parts of the catchment, which are impacting on the water quality and health of benthic communities in these localized areas. The amount of shore hardening is significant; sea wall, road and rail corridors directly border about two thirds of each arm and have been identified as having a significant impact on the estuary function (Stevens & Robertson 2008). Total fishing effort was low but potentially represented a similar level of pressure to other harbours in relation to the harbour size.

Agricultural activities rather than urban settlements represent the most significant human stressor to both Raglan and Kaipara harbours, the main impacts being high levels of sedimentation and nutrient levels. In Raglan, a very active local harbour care group appears to have made significant improvements in water and estuarine habitat quality through a programme of education and riparian fencing and planting, although up-to-date monitoring data are required to confirm this. Catches of 0+ rig were amongst the highest of the entire set net survey and, relative to its size, the harbour is clearly a productive nursery ground (Francis et al. 2012). As such it should be recognized that urban development, even at a relatively low scale, could have detrimental impacts and should be carefully managed. Raglan is a popular holiday destination and there are likely to be requirements to develop and expand the marina facilities. Fishing effort appears to be relatively high in relation to the size of the harbour, assuming that the recorded fishing effort occurs only within Raglan and Waikato River estuaries. Commercial fishing targeted at adult rig entering the harbour is also known to occur and has the potential to have highly detrimental impacts on the productivity of this nursery.

The Kaipara Harbour is the largest harbour assessed, and given the high catches recorded during the set net survey, this estuary is potentially the most important known rig nursery ground in New Zealand, although more extensive sampling across the wider harbour system would be required to confirm this. The impacts of agricultural land use resulting in high sedimentation rates and elevated nutrient levels have had significant impacts on water quality and benthic community health in the northern and north-eastern arms of the harbour in particular. The predicted expansion of the wider Auckland population is likely to put increasing pressure on the southern arms of the harbour. Fishing pressure also appears to be a potentially significant threat, with some historically high effort and evidence of declining abundance of adults in recent years (Morrison et al. 2014). This harbour is also the only one of the six assessed where other marine-based activities are either currently occurring (aquaculture and sand mining) or planned for the future (tidal power generation). Of these activities, only aquaculture potentially overlaps directly with juvenile rig nursery habitat, but the impact of all of these activities in terms of both adult and sub-adult rig movements into and out of the harbour are unknown. The Kaipara scored at a similar level to Raglan in the Human Threat Ratings, being lower than the four more urbanized and densely populated harbours (Table 13). However, based on the size of the harbour, the potential extent of suitable juvenile rig habitat at risk, and the evidence of a significant contribution to the rig population, this could be the most vulnerable harbour, particularly given the broad range of potential stressors.

In the absence of direct impact studies, the true vulnerability of juvenile rig to the stressors identified in this study is not fully known. The set net survey targeting juvenile rig found that catches were greatest at stations with muddy sediments, medium to high turbidity, and with significant freshwater input (Francis et al. 2012). It is likely that juvenile rig forage over sand and mud flats and also in mangrove covered areas during flood tides. They are non-visual predators, and the diet studies carried out during the survey indicated that mud crabs (*Hemiplax hirtipes*) and snapping shrimp (*Alpheus richardsoni*) made up a significant proportion of their diet as well opportunistic predation on invasive species such as the Japanese mantis (*Oratosquilla oratoria*) and Greentail prawn *(Metapenaeus bennettae)* (Getzlaff 2012). Therefore juvenile rig appear to be tolerant of the degraded status of some of the harbours and may in fact benefit from the increase in mud and mangrove habitats that result from anthropogenic impacts, as long as environments do not become too degraded to support even impacted communities and / or become completely infilled with mangrove stands, thereby reducing access to suitable foraging grounds. It should also be considered that recent studies indicate that predators may select food based on nutritional value, ultimately to achieve optimum reproductive success (Jensen et al. 2012). Availability of a range of prey to provide the correct nutritional balance may therefore be important and changing benthic communities and invasive species could have significant implications in this respect.

Small mesh nets targeting grey mullet or yellow-eyed mullet inside the harbours are thought to be the only fisheries that are likely to catch juvenile rig as a bycatch. Such fisheries certainly exist to some extent in all the harbours with highest effort in the Kaipara and Manukau. Ring nets and set nets appear to be set for relatively short durations, although this variable could not be analyzed because of data errors and uncertain interpretation of the data. Rig caught during short duration sets of either method could be released alive, but the mortality rate would increase with increasing set duration. At-sea observation of catches in these harbour net fisheries would be necessary to determine whether the potential fishing threat identified here is in fact real, and to estimate the mortality rate of captured 0+ rig under actual operating conditions.

This review highlights that the harbours identified as important rig nursery habitats are all impacted by anthropogenic activities occurring in the coastal fringe as well as the wider catchment area. These pressures have degraded the water quality, habitat and benthic communities to varying extents. Juvenile rig appear to be relatively tolerant to these impacts, being found in large numbers in estuaries clearly impacted by agricultural activities in the wider catchment as well as heavily urbanized estuaries such as the Tamaki. The relatively high survey catches and large size of the Kaipara Harbour makes this potentially the most important rig nursery area in the country. The harbour is already significantly impacted by agricultural activities and the southern area in particular may be especially vulnerable to the effects of future urbanization. Although smaller in size, Raglan and possibly Kawhia Harbour may also represent significant nursery areas that have not been impacted by urbanization.

A full understanding of how resilient juvenile rig are to anthropogenic impacts requires more detailed knowledge of how specific habitats are utilized and the mechanisms by which stressors such as degraded water quality, pollution levels, prey availability and noise disturbance affect growth and survival. In the absence of this information it is recommended that rig nurseries with significant levels of either marine and/or land-based anthropogenic stressors are considered potentially vulnerable. It is recommended that MPI works with Regional Councils, public forums and community groups to raise awareness and prioritize agricultural and urban management practices that improve freshwater and ultimately estuarine and coastal water quality and reduce sedimentation rates. Identifying on a finer spatial scale the areas and / or habitats used by juvenile rig in highly vulnerable areas, such as Kaipara Harbour would assist the spatial planning process where multiple uses and values are likely. The impact of fishing effort on juvenile mortality should be assessed by MPI directly by gathering information on the frequency of juvenile catches and combined with field assessment of damage or tank-based survival experiments.

Table 12: Human Threat and Ecological Indicator Metrics and the criteria used to define four relative ranks for each

Stressor Metrics	Relative Rank				Classification method or literature used to weight ranks
	1	**2**	**3**	**4**	
% Urban Land cover	0–5	6–10	11–20	>20	Sowa et al. 2007 Wheeler et al. 2005
% Agricultural Land cover	0–30	30–50	51–75	>75	Allan 2004
% Impervious Cover	0–5	6–10	10–30	>30	Arnold & Gibbons (1996) / Schueler et al. 2009
Population Density (no./km^2)	<10	<100	<1000	<10000	Logarithmic interval scale (Small 2004)
Future Population Change, 2006 – 2031) (no./km^2)	0 or decrease	0.04–5	6–20	>20	Based on Sowa et al. 2007
Density of permitted discharges (no./km^2)	0	0.1–2	2.1–8	>8	Sowa et al. 2007
Road density (km / km^2)	<0.5	0.6–1.4	1.5–2.5	>2.5	Forman & Alexander 1998
Bridge density (no/ km^2)	0–0.09	0.1–0.19	0.2–0.4	>0.4	Sowa et al. 2007
Sedimentation Rates (mm/year)	<1	1–2	2–10	>10	Morrison et al. 2009
No of Invasive species	1	2	3	4+	Sowa et al. 2007
Fishing Effort (km of net set per km^2)	<1	1–5	6–10	>10	Unequal Interval
Ecological Indicator Metrics					
Pollution levels	<0.2 ISQG Low	< ISQG Low	<ISQG High > ISQG Low	> ISQG High	Robertson & Stevens 2009
Water Quality Index	Excellent	Good	Fair	Poor	Perrie & Cockeram 2010, Neale 2010b.
Benthic Health Rating	Excellent (5)	Good (4)	Fair (3)	Poor – Unhealthy (1–2)	Anderson et al. 2006, van Houte-Howes & Lohrer 2010, Borja et al. 2000

Table 13: Threat Ratings for the six harbours

	Relative Rank					
Human Stressor Metrics	Kaipara	Raglan	Manukau	Porirua	Waitemata	Tamaki
% Urban Land cover	1	1	3	3	4	4
% Agricultural Land cover	3	3	3	3	2	1
% Impervious Cover	1	1	2	2	2	3
Population Density (no./km^2)	1	1	3	3	3	4
Future Population Change	2	2	4	4	4	4
Density of permitted discharges (no./km^2)	2	1	2	2	3	2
Road density	2	1	3	2	4	3
Bridge density	2	2	3	2	4	3
Sedimentation Rates (mm/year)	3	3	3	3	3	3
No of Invasive species	4	4	4	3	4	4
Fishing Pressure (km of net set per km^2)	2	3	3	2	3	3
Total score	**23**	**22**	**33**	**29**	**36**	**34**
Estuary Health Metrics						
Water Quality (Freshwater)	Poor-Good	Good	Fair-Good	Poor- Fair	Fair– Excellent	Poor- Fair
Water Quality (Saline)	Poor-Good	Fair-Good	Poor-Fair	Fair-Good	Poor-Excellent	Poor
Benthic Health Rating	Moderate - Good	?	Unhealthy-Moderate	Moderate - Good	Unhealthy-Good	Unhealthy-Moderate
Pollution						
Zinc	1	2	2	2	3	3
Copper	2	1	2	2	2	2
Lead	1	1	2	2	3	3

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Appendix A Land use within harbour catchment

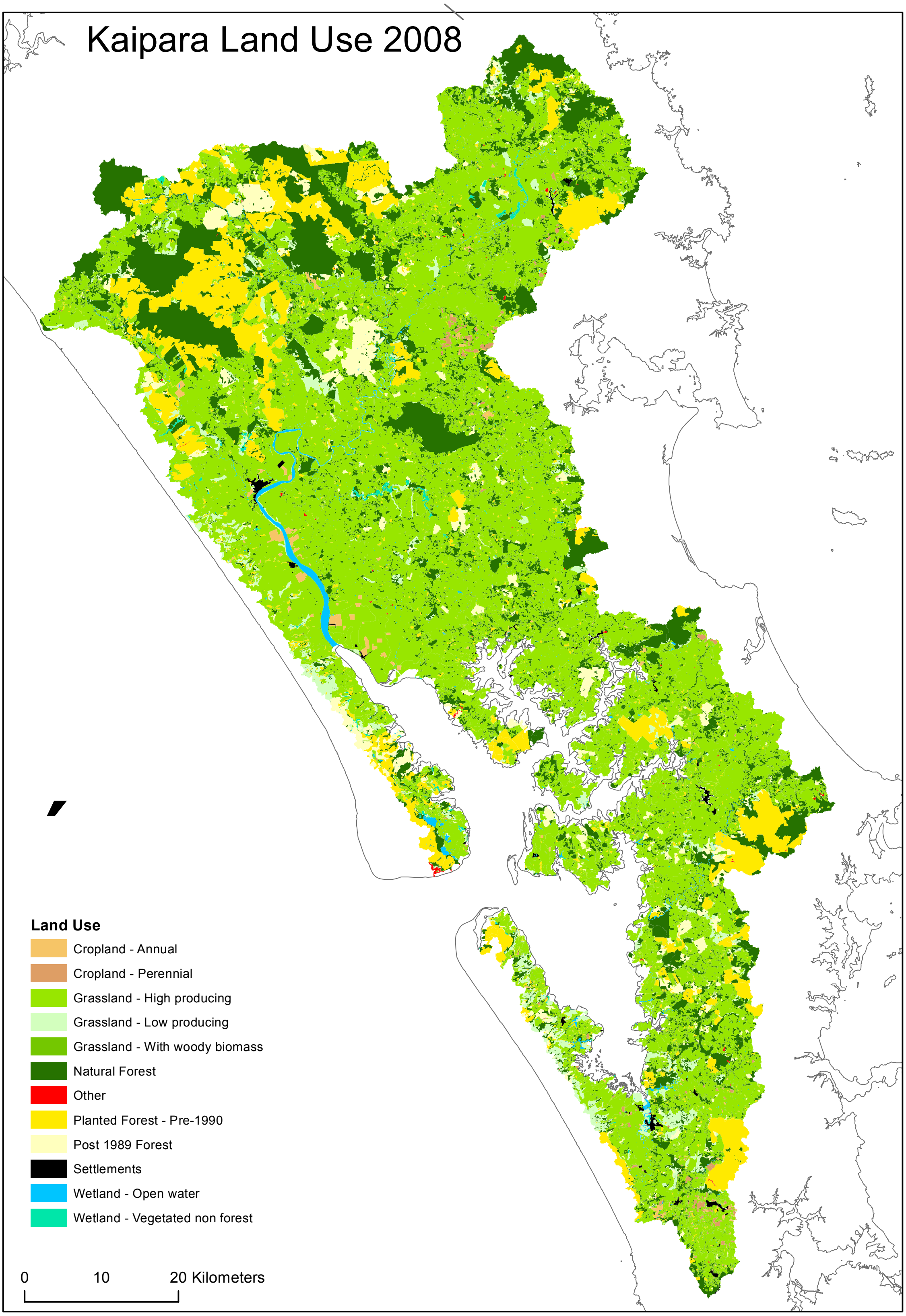

Figure A-1 Land use in the Kaipara Harbour catchment area. "Other" category refers to "montane rock/scree, largely bare ground (if not cropland), any other remaining land" (http://www.mfe.govt.nz/issues/climate/lucas/)

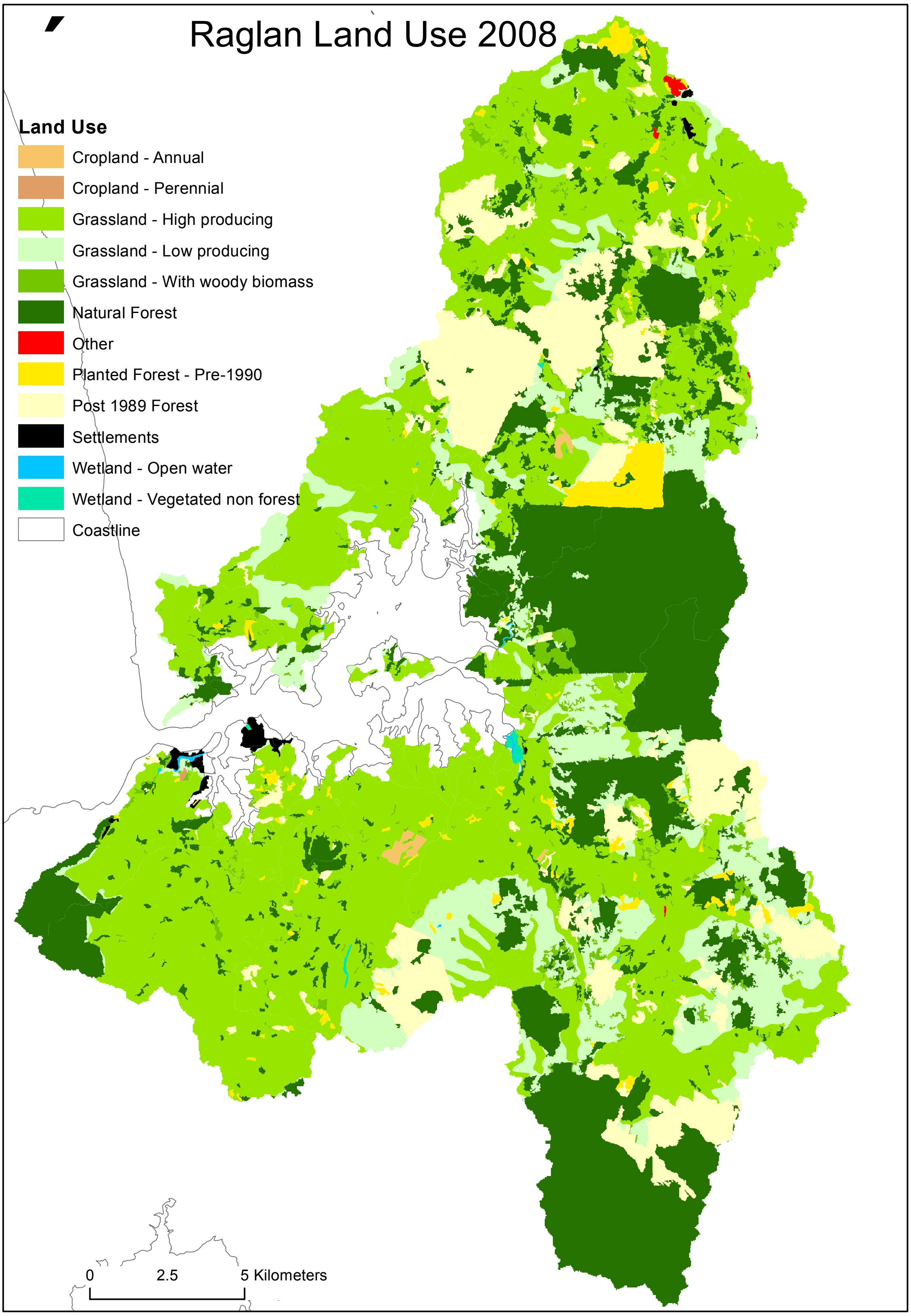

Figure A-2 Raglan Harbour.

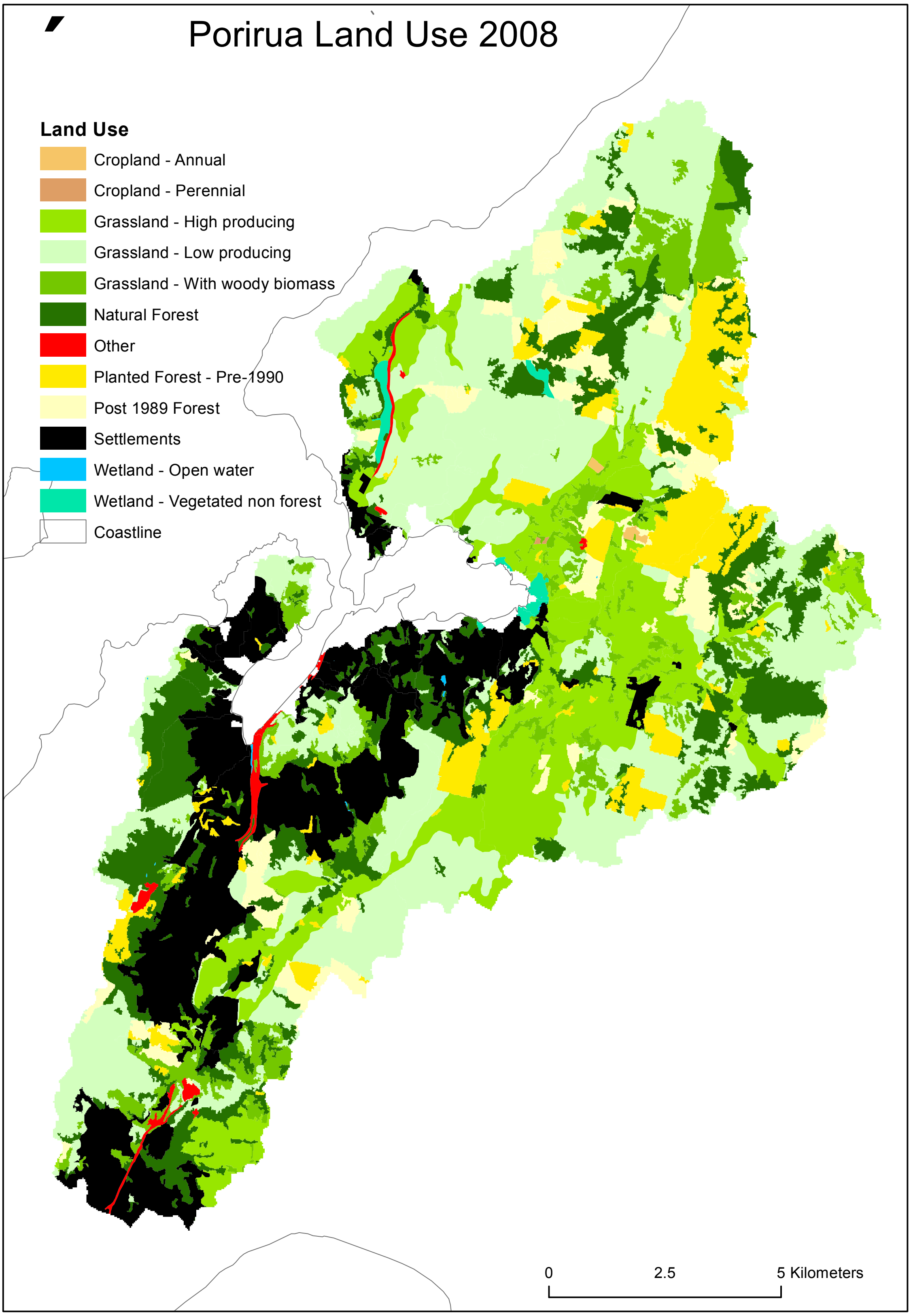

Figure A-3 Porirua Harbour.

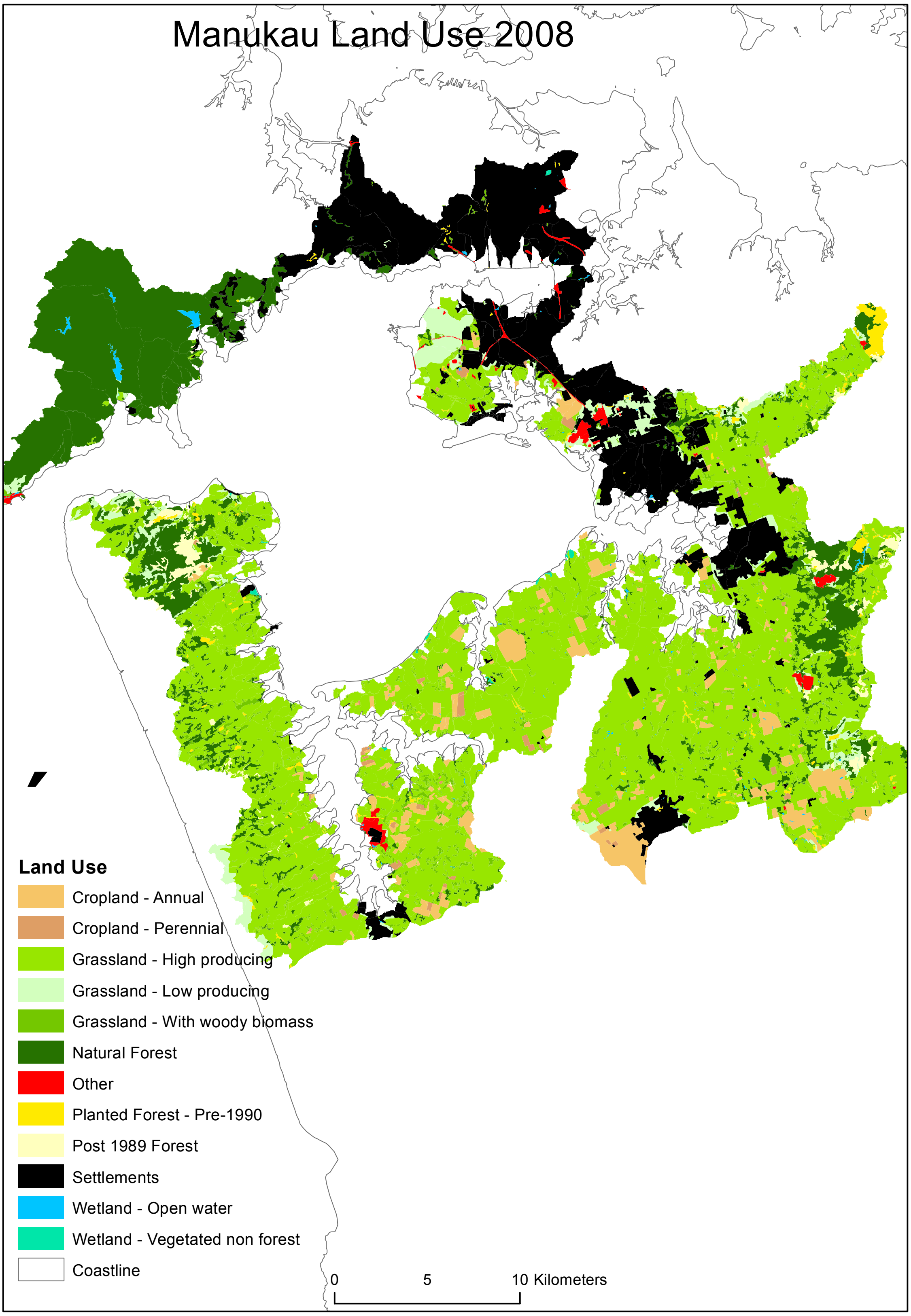

Figure A-4 Manukau Harbour.

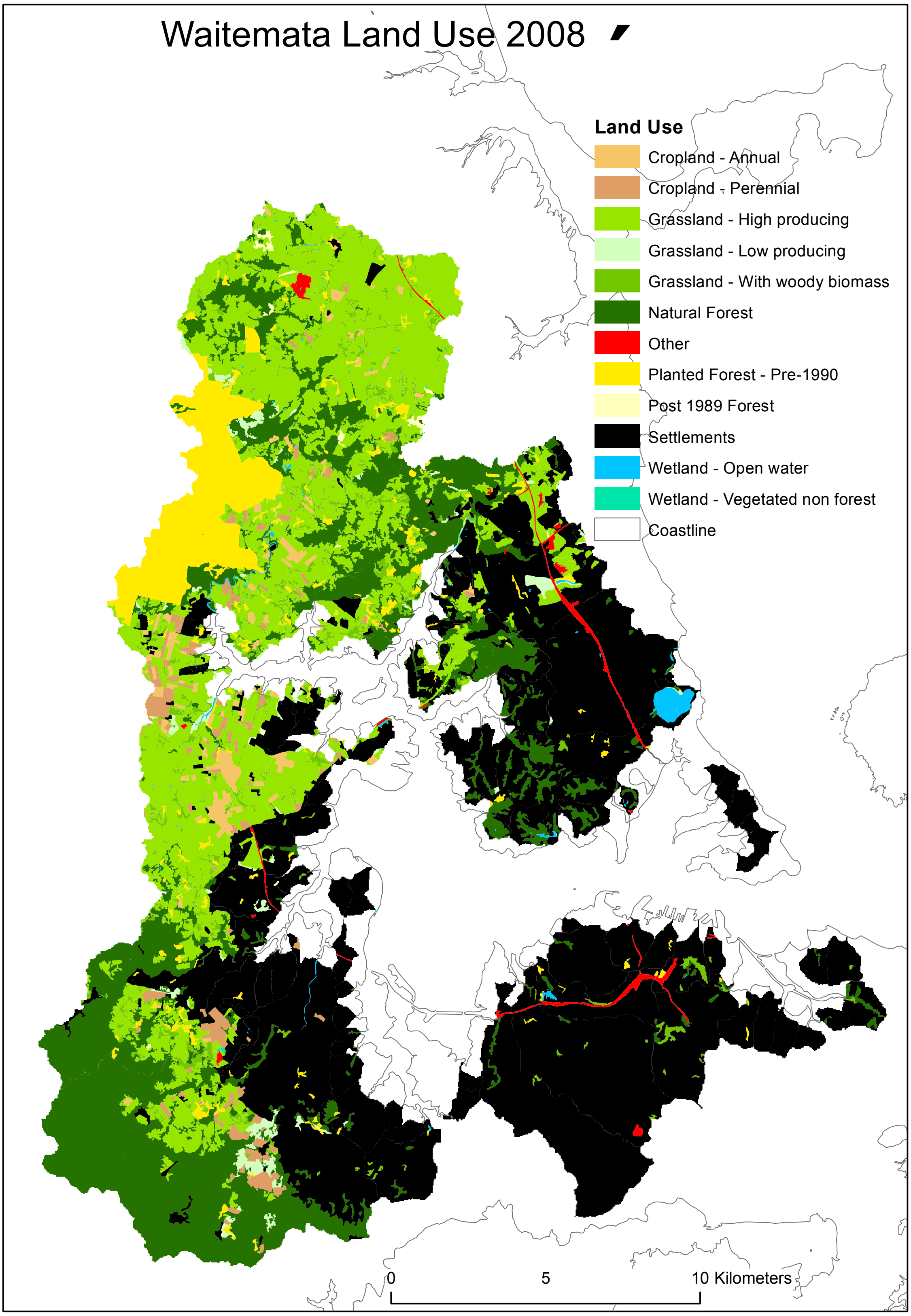

Figure A-5 Waitemata Harbour.

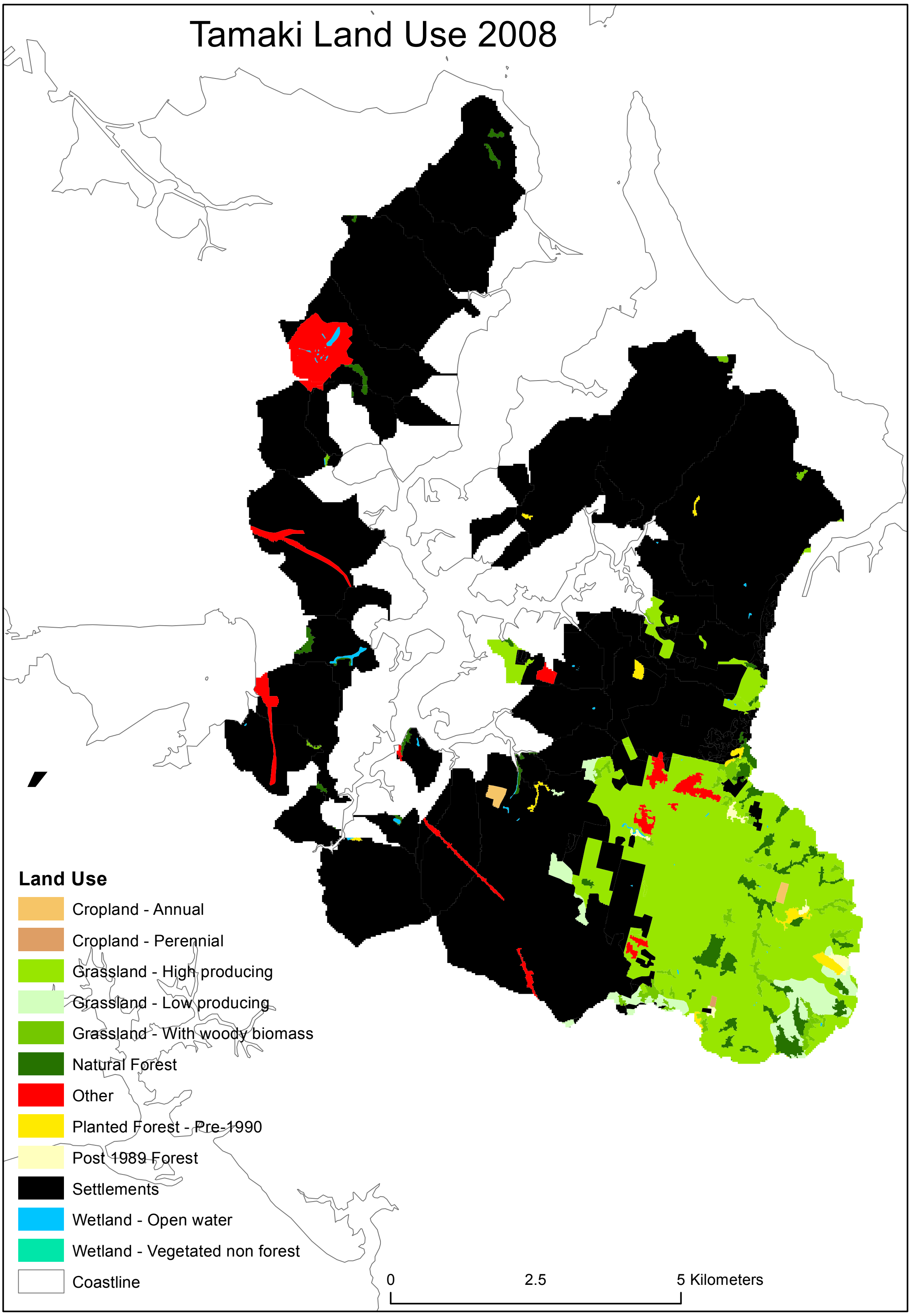

Figure A-6 Tamaki Estuary.