Predicting suitable shellfish restoration sites in Whangarei Harbour

Larval dispersal modelling and verification

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Executive summary

This investigation aimed to identify suitable habitats for shellfish restoration based on the likelihood of successful larval settlement derived from the Whangarei Harbour hydrodynamic (DHI) model and NIWA's newly developed larval tracking model (LTRACK). Larval dispersal was simulated under seven wind conditions (1) Calm; 2) NW 50%, 3) NW 90%, 4) SW 50%, 5) SW 90%, 6) E 50%, and 7) E 90%. Model inputs including maps of spawning habitat and suitable settlement habitat from a 42 site survey of Whangarei Harbour by NIWA in December 2008. Model predictions of larval settlement success were compared to field samples of larval concentration in plankton nets, collected at 8 sites in 2009 and 7 sites in 2012.

The model predicted high variability between sites for total settlement success, with high success in Snake Bank, McDonald Bank and Parua Bay for most wind scenarios. Settlement in the Upper Harbour was predicted to be low and variable. Connectivity between all regions of the harbour was predicted to be high, with sites near the mouth (e.g., Snake and McDonald Banks) predicted to provide large quantities of larvae for settlement throughout the harbour, but with all sites capable of providing larvae for settlement elsewhere and receiving larvae from all regions in the harbour. Settlement and larval connectivity varied most at Takahiwai, with some wind conditions resulting in higher self-recruitment, while other conditions resulted in higher settlement from neighbouring seaward regions. Highest retention rates (i.e., most recruits from local region) were predicted for Parua Bay and the Upper Harbour.

Surprisingly, model output did not match field data for all sites, with Parua Bay and the Upper Harbour being most different from predictions. It is likely that these differences are explained by uncertainty in the underlying datasets that drove the model. While we are reasonably confident in our predictions of species' preferences for suitable habitats, we admit high uncertainty in our estimates of spawning density as our total sampling effort was limited to 42 sampling sites across the entire harbour, with most of our sampling effort concentrated in the mid and lower harbour. We suggest that the mismatch in model and field validation is because our larval spawning maps over-estimate spawning rate significantly in Parua Bay, and under-estimate spawning rate and habitat suitability in the Upper Harbour. Additional simulations involving revised spawning and settlement maps would likely reconcile differences between the model and field validation presented here.

Regardless, the general patterns of settlement can be used to identify highly valued habitat for larvae and juveniles, and for adult spawning populations. The model emphasises that Snake Bank and other high density cockle beds near the mouth of the harbour are highly valued habitat for adult spawning populations of cockles and pipis, and provide the highest contribution to larval settlement throughout the harbour. Predicted and actual settlement at Takahiwai, a shellfish restoration site, was generally high, and the model predicted high connectivity with seaward sites (e.g., Snake Bank) which contribute high proportions of total settlement under most wind conditions. Parua Bay had high predicted settlement, with highest contribution from within the bay, suggesting that restoration efforts were likely to increase recruitment in the bay. While model predictions of total settlement in the Upper Harbour sites were low due to under-estimates of spawning rate, high larval abundance was observed at the field sampling sites (Portland and Otaika). As such, restoration efforts in the Upper Harbour could result in high quality adult populations serving as larval source populations, and restored habitat quality would be likely to result in settlement of juveniles.

1 Background

Community restoration initiatives such as reseeding cockles and seagrass habitats are a high priority goal of councils, communities and iwi groups. In Whangarei Harbour, Kaitiaki Roopu Whangarei have identified and contributed to shellfish restoration projects (e.g., Takahiwai and Parua Bay), with goals of restoring historically important shellfish gathering sites.

These shellfish restoration projects in Whangarei Harbour have determined best practice transplantation methods of adult and juvenile cockles to increase transplant success rate (Cummings et al. 2007). They have also investigated whether these transplants enhance recruitment of juvenile shellfish (Cummings et al. 2008).

This current project builds on previous work with a combined hydrodynamic and particle tracking model of larval bivalves to determine likelihood of success of shellfish restoration sites. Lundquist et al. (2009) used the MIKE 21 Particle analyser model to predict larval dispersal trajectories for seven sites in Whangarei Harbour, for 27 different hydrodynamic conditions. By examining transport of particles released from the seven sites, they were able to approximate how often the particles were transported to the different sub-regions of the harbour, thus estimating the likelihood of recolonisation of different locations by planktonic bivalve larvae (Lundquist et al. 2009).

Substantial increases in technology and available software now allow inclusion of larval life history, spawning and settlement habitat maps, and species maps in larval dispersal models. LTRACK, a new larval dispersal software package developed by NIWA, includes these larval behaviour aspects, allowing for more accurate predictions of the most suitable habitats for restoration of shellfish based on larval connectivity. This study also utilises a higher resolution DHI hydrodynamic model to drive the larval model. This higher resolution hydrodynamic input allows for more accurate modelling of dispersal of larvae, particularly in intertidal zones.

The project will:

1. Develop shellfish spawning maps and suitable settlement maps using benthic monitoring data collected by NIWA in December 2008 at 42 sites.
2. Use LTRACK model simulations in conjunction with hydrodynamic simulations of Whangarei Harbour to identify shellfish habitats (e.g., cockles *Austrovenus stutchburyi*, pipis *Paphies australis*, wedge shells *Macomona liliana*) that both contribute to larval supply in the harbour, and are likely to receive shellfish recruits.
3. Validate model output by collecting field samples of relative abundance of larval shellfish in plankton samples at different sampling location in Whangarei Harbour. A comparison of predicted vs. actual shellfish presence will identify potentially degraded habitats, as well as uncertainty in the spawning and settlement maps that lead to either over- or under-estimation of predicted shellfish settlement.

4. Based on all information, identify highly valued habitats (for larvae, juvenile and adult shellfish), and areas which are most suitable areas for habitat restoration.

2 Methods

2.1 Hydrodynamic model

A total of seven different hydrodynamic conditions were simulated using the Danish Hydrodynamics modelling system, based on a prior validated model for Whangarei Harbour (Reeve et al. 2009). The modelled region was composed of 16510 triangular cells, each containing six vertical water column layers (Figure 2-1). The size of each triangular cell was influenced by local water-column depth (smaller triangles in shallower regions) and proximity to the region of interest (larger triangles outside Whangarei Harbour). The thickness of each layer amounted to 1/6 of the local water-column depth. The model included freshwater inputs (mean annual flow rate) from Hatea River, Waiahorea Canal and Limeburners Creek. With the exception of the applied wind-stress, the seven hydrodynamic simulations used the same initial and boundary conditions. Table 2-1 lists the wind-forcing adopted for each hydrodynamic scenario.

Each hydrodynamic simulation spanned 31 simulated days. Instantaneous hydrodynamic conditions (sea surface height, horizontal and vertical velocities, salinity) were saved at five minute intervals, and used to drive the particle tracking model. All seven hydrodynamic conditions were simulated for cockles. As the computation time required for each scenario was approximately 8 weeks, only one hydrodynamic condition (‘Calm’) was simulated for pipi and *Macomona*.

Table 2-1: Wind characteristics for each hydrodynamic simulation. The wind-speed and direction were held constant throughout each simulation.

Scenario name	Assumed wind (m s^{-1}; direction (from); wind-speed percentile)		
	Wind speed (m s^{-1})	Wind-speed percentile (for winds from the given octant)	Wind direction (from)
Calm	0	0	-
EA50	4.6	50	East
EA90	8.2	90	East
SW50	4.1	50	South west
SW90	7.2	90	South west
NW50	1.5	50	North west
NW90	4.1	90	North west

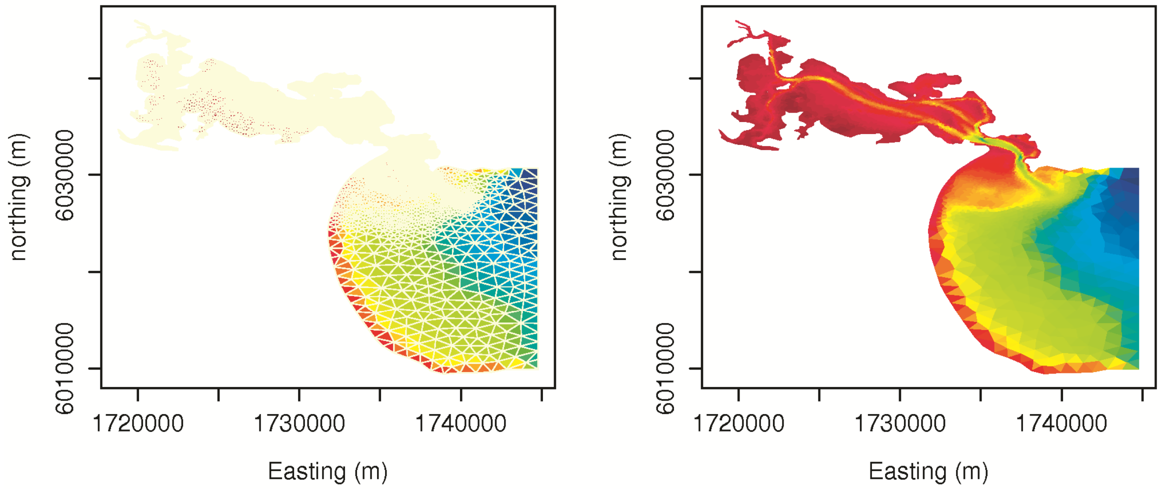

Figure 2-1: Model domain with colour indicative of the bathymetry. The two images show the same bathymetry. In the left hand one, the perimeter of each water-column is shown with a grey line. In shallow regions, the water-columns are narrow such that the grey-lines mask the bathymetry-colour. The grey lines are suppressed in the right-hand image.

2.2 Particle (Larval) Tracking Model

We used the particle tracking model LTRACK (Broekhuizen et al. 2011) to simulate the dispersal and settlement of larvae of cockles, pipi and *Macomona*. The LTRACK model uploads the hydrodynamic model output into a modelling package that incorporates larval behaviour (swimming behaviour, larval age/life history) and allows input of area-based spawning rates and habitat suitability maps that represent suitable settlement areas for larvae. LTRACK runs result in predictions of larval settlement based on hydrodynamic condition (wind strength and direction), spawning maps and habitat suitability maps.

Transport and particle-generation dynamics in LTRACK are discussed in Appendix A. In summary, particles (larvae) were released from each of several spawning polygons based on estimated adult shellfish densities (see *Derivation of spawning and habitat quality maps*). Particles were tracked until they settled, died, or were transported out of the model region (i.e., into Bream Bay). Particles were assumed to become able to settle from age 12 days, and die if they had not settled by age 21 days. A predicted map of suitable settlement habitat was created for each shellfish species (see *Derivation of spawning and habitat quality maps*), and used to allow preferential settlement of shellfish on suitable habitat, as well as relocation from unsuitable habitat.

2.3 Derivation of spawning and habitat quality maps

To develop broad scale maps of shellfish spawning habitat and suitable settlement maps based on habitat quality, we sampled 42 sites in Whangarei Harbour in December 2008 for macrofauna and for sediment characteristics (Figure 2-2). Sediments were analysed for grain size, chlorophyll *a* and percent organic content (Appendix B). The abundance and sizes of *Austrovenus stutchburyi*, *Paphies australis* and *Macomona liliana* were determined from 25 cm quadrats and 10 cm diameter, 15 cm deep macrofaunal cores (Appendix C). An intensive sampling was conducted on Snake Bank for higher resolution cockle abundance, grain size and chlorophyll *a* information (comprising an additional 69 sediment samples located on Snake Bank) (Appendix 2). The broad scale core sampling survey was also accompanied by a habitat mapping survey of the entire harbour, with highest resolution in the mid- and lower harbour based on locations of proposed shellfish restoration sites (Takahiwai, Parua Bay) and known sites of high shellfish density (e.g., the commercial shellfish banks at Snake Bank, McDonald Bank, and Mair Bank). The survey had poor resolution of the upper harbour, with only 7 total sampling locations in the upper harbour that did not include any high density shellfish habitats.

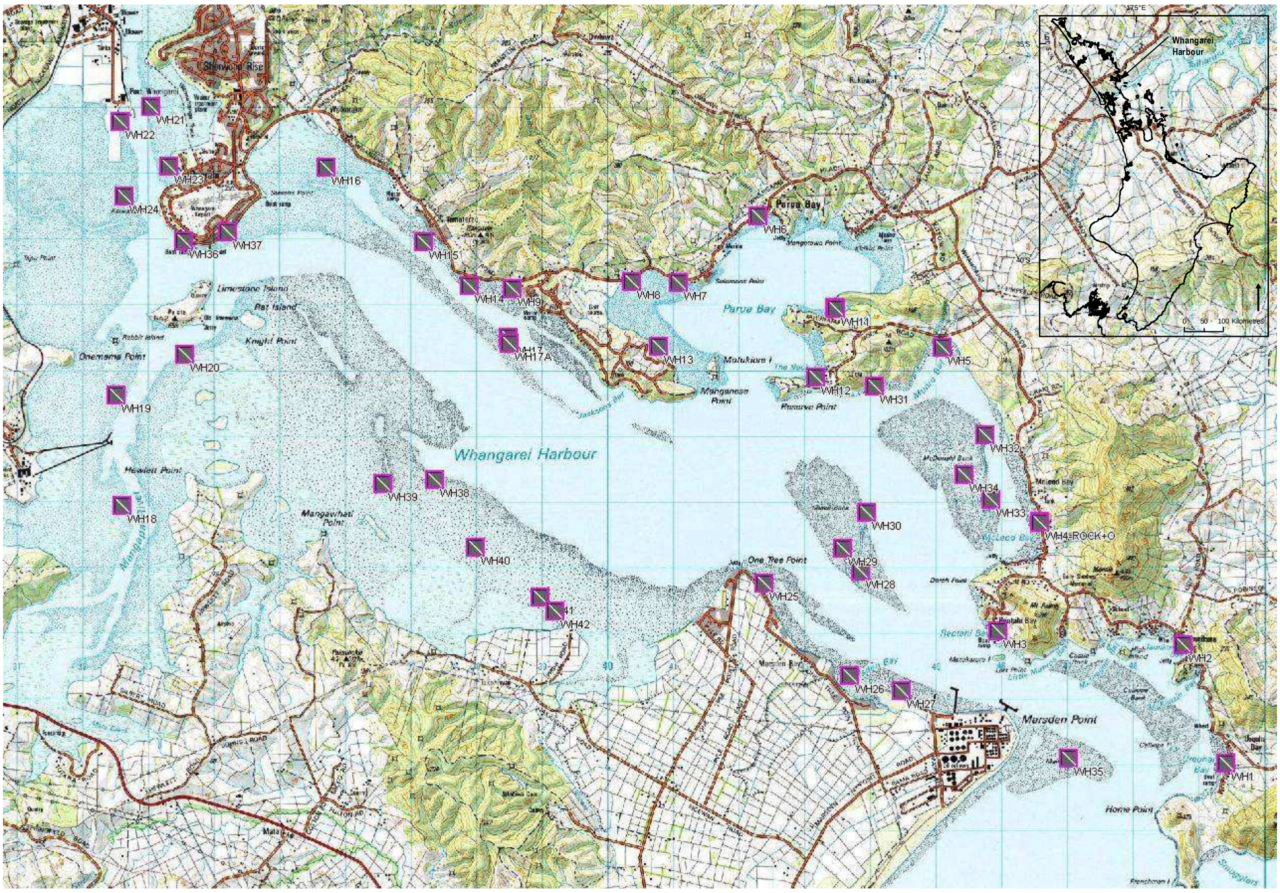

Figure 2-2: Map of Whangarei Harbour showing 42 study sites with map of the North Island of New Zealand in top right corner.

Habitat maps and sediment characteristics were used to identify 105 'polygons' within the harbour with similar sediment and vegetation characteristics (Figure 2-3). Spawning rates for each polygon were generated from mean counts of numbers of adult shellfish from three replicate benthic macrofaunal cores at each of the 42 survey sites. Mean adult abundance of three species of shellfish (cockle, pipi, *Macomona liliana*) were estimated for each polygon, and converted into species-specific numbers of particles spawned within each polygon based on the relative mean abundance of adult shellfish per m^2. A constant multiplicative factor was used to produce adequate numbers of larval production to analyse spatial and temporal patterns of larval transport. Spawning was determined for each polygon based on an average from benthic core samples that were located within the polygon. If no core samples were located within a polygon, we used information from the nearest neighbouring core sample from a similar physical habitat type. No core samples were taken within mangrove habitat (about 40 of these polygons); these polygons were determined to have spawning rate of 0, and to not be suitable settlement habitat for shellfish.

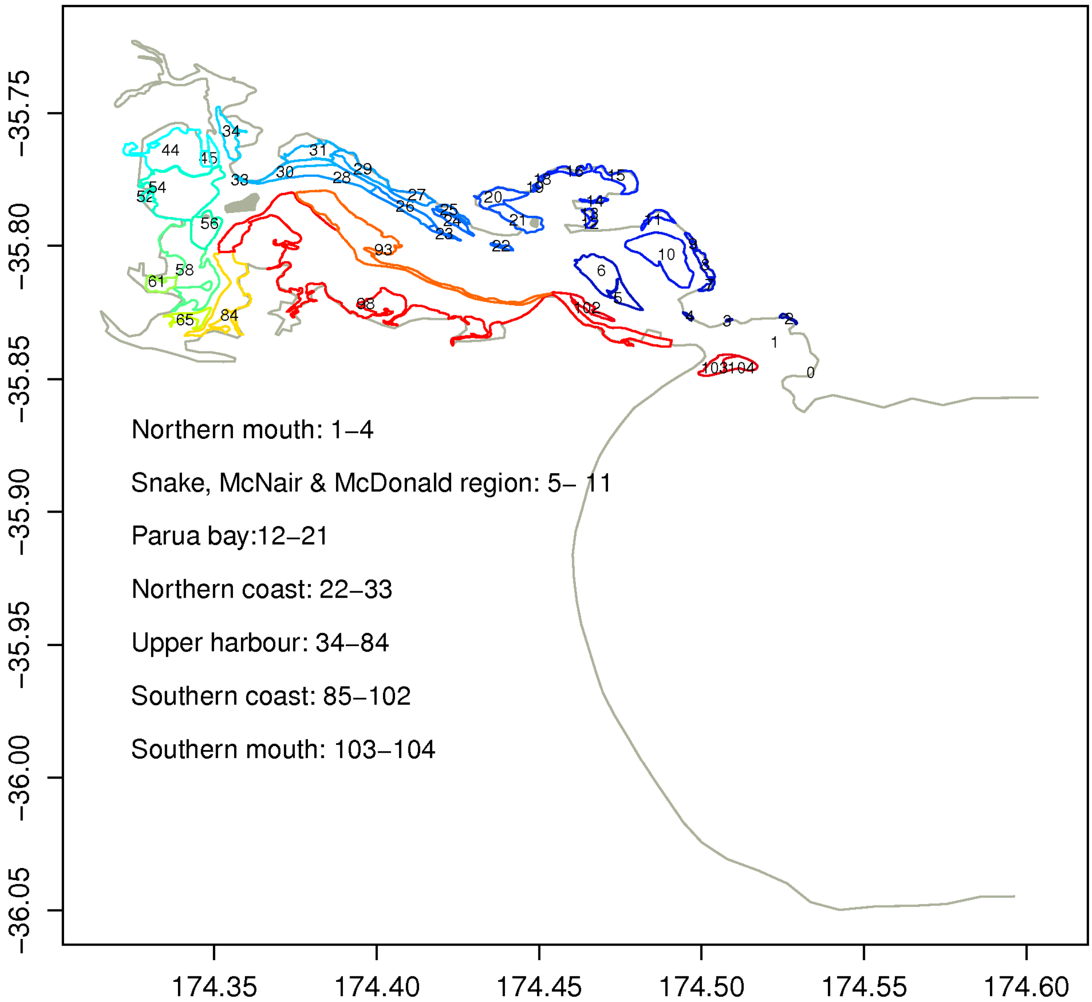

Figure 2-3: Polygons numbering and colour-coding systems. Polygons were colour-coded to assist in identification of locations of original of larvae particles in the model. Polygons are numbered in an (approximately) anticlockwise manner starting just outside the mouth of the estuary on the northern coastline. The inset text defines polygons located within the broad-scale sub-regions of the estuary. Polygons with zero habitat quality and zero spawning rates for all three species (i.e., all mangrove polygons) are not shown. The grey coastline provides an indication of the full extent of the hydrodynamic model's spatial extent.

Habitat suitability (settlement suitability) for each polygon was estimated based on sediment and vegetation type from the broad-scale habitat map of Whangarei Harbour, and whether adult cockles were present in that physical habitat identified for each polygon. In most cases, polygons were given scores of 1 (suitable) or 0 (non-suitable), but in some cases, polygons were given mid-weight for suitability for settlement (Table 2-2).

Polygons representing spawning and habitat suitability map were created in ArcGIS. Vertices of each polygon were input into LTRACK to spatially include spawning habitat and settlement suitability in the larval dispersal models.

Habitat type	Cockle habitat suitability index	Pipi habitat suitability index	*Macomona* habitat suitability index
Shell hash	1	1	0
Shell hash and pebbles	1	1	1
Mud (deep)	0.5	0	0.5
Mud (shallow)	1	0	0.5
Firm sand (usually high intertidal)	1	0	1
Firm sand and shell hash	1	1	1
Shallow subtidal	0	1	0
Coarse sand/ pebbles/cobbles	1	1	0.5

Table 2-2: Habitat suitability weighting based on descriptive physical habitat categories.

2.4 Fieldwork and sample processing

The water column in Whangarei Harbour was sampled for planktonic larvae in January 2012. Three types of plankton sampling were used:

1. plankton set nets at 8 intertidal sites (Snake Bank, Snake Bank 2, McDonald Bank, Parua Bay, Takahiwai, One Tree Point, Otaika, and Portland) (Figure 2-4). These nets were sampled 3 times for 24 hour intervals with paired set nets (~20 cm diameter, 125 micron mesh) located 63 cm above the sediment surface. At 2 sites (One Tree Point, Takahiwai), an additional set of paired nets was located 15 cm above the sediment surface. Additional sampling for a NIWA Aquatic Restoration project occurred in March 2009, using plankton set nets at 7 intertidal sites (Snake Bank, McDonald Bank, Parua Bay, Takahiwai, One Tree Point, Takahiwai 2, Parua Bay 2), with 5 of the sites overlapping the 2012 sites (Figure 2-4)

2. plankton net tows at each of 4 sites in the main harbour channel, sampled at incoming and outgoing tide (twice daily) for 3 days using a 125 micron mesh net with diameter of 50 cm [data not presented here], and

3. custom-built continuous water pumps sampling at three depths (1, 3 and 5 m from the surface) at one channel site (mouth of Parua Bay) at incoming and outgoing tide (twice daily) for 3 days.

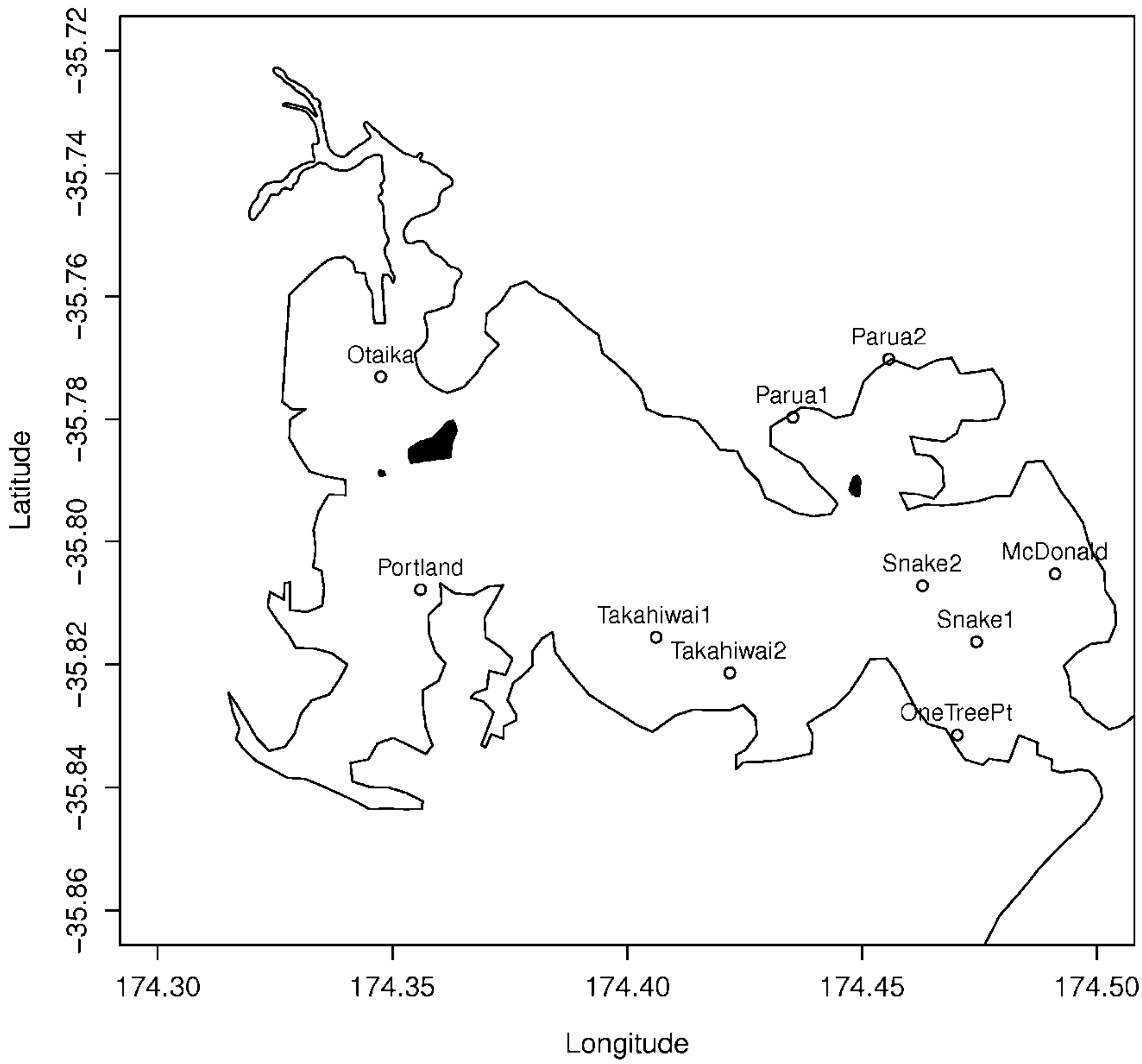

Figure 2-4: Net-trap sampling locations super-imposed upon the hydrodynamic model's coastline.

3 Results

3.1 Hydrodynamic circulation

In Bream Bay, the model predicts that time-averaged currents circulate in an approximately clockwise manner (see Reeve et al. (2009) for detailed discussion of Whangarei Harbour hydrodynamics). The circulation pattern changes in subtle manners under the differing winds, and eddy structure(s) immediately outside of the Whangarei Harbour entrance change location and complexity with differing wind conditions. Within the Harbour, the near surface currents tend to be larger than the near bed currents, particularly in the deeper channels. There is a small trend for deep-water layers to flow into the estuary whilst shallow water layers are more likely to have a net flow outward. Averaged over all depths, there is a net inward (westward) flow through the central, main channel of the estuary, which is balanced by net outward flows along one or both of the northern and southern shores of the estuary. Wind direction and strength influences the speed of the inflow in the main channel, and the balance between outflows along the northern and southern shorelines. Under the easterly wind, there is a weak clockwise flow (outflow is mainly along the northern shore). Under south-westerly winds, the model suggests a weak anticlockwise circulation (outflow mainly along the southern shore). Under north-westerly winds the model suggests a bifurcating flow (roughly equal outflows on both north and south shores).

3.2 Spawning and habitat quality maps

Relative spawning rates were calculated for each of 105 'habitat' polygons (Figure 3-1). These maps illustrate that: (a) spawn from each of the three species is being generated in different regions of the estuary, and (b) some polygons contribute vastly more spawn than others. Of polygons that contain adult shellfish, the least productive generated only around 10 particles, whilst the most productive generated 1000s of particles (Figure 3-2). These differences are driven by a combination of differences in the magnitudes of regional spawn production and the area of each polygon. For example, Snake Bank has the highest area-specific cockle spawn production and also a moderately large surface area, resulting in high spawn production. Cockle spawn production is also high in some parts of Parua Bay, which in total has a slightly larger intertidal area than Snake Bank, and also has some areas of high adult cockle density.

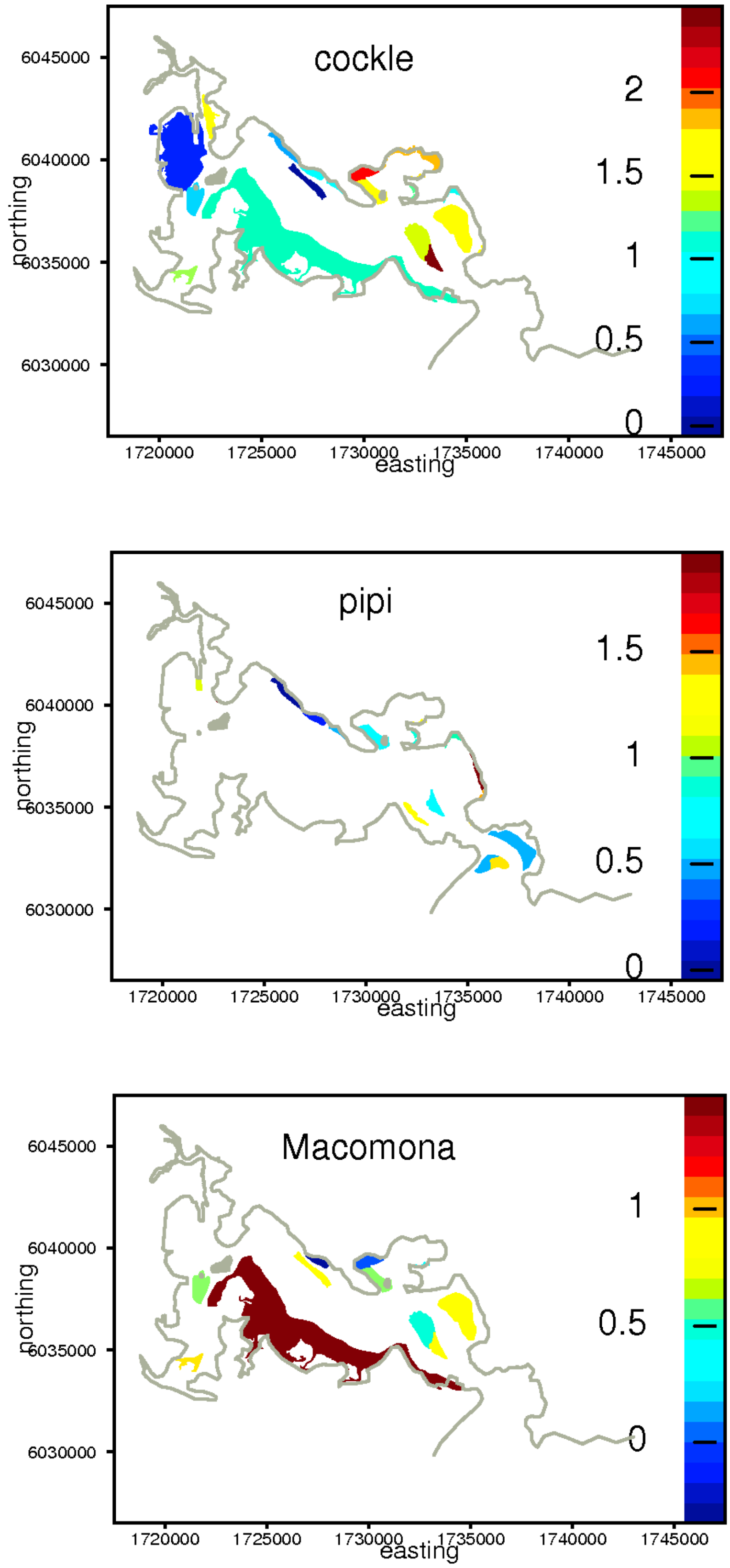

Figure 3-1: Spawning maps for each species shown on a log scale ($\log_{10}$(specific spawn production ($m^{-2}\ d^{-1}$)) for each species. Colour is indicative of habitat quality (white regions and deep blue regions have Spawn rate = 0 $m^{-2}\ d^{-1}$).

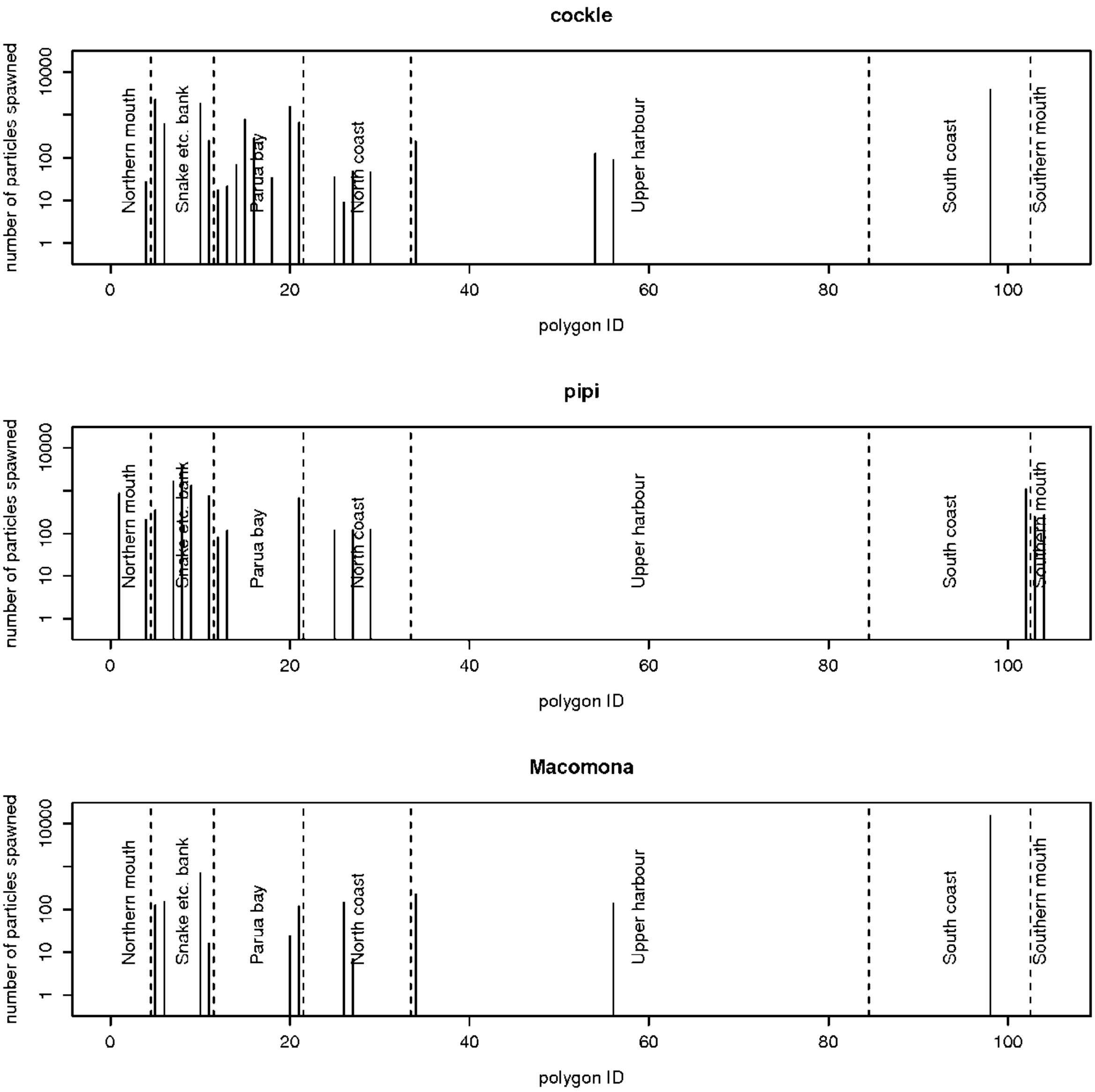

Figure 3-2: Histograms illustrating the numbers of particles spawned from each polygon within the domain (refer to Figure 2-3). The number of particles spawned by a polygon is proportional to the product of its surface area and its area-specific spawn production rate. Note that the y-axis is logarithmic. The broken vertical lines demarcate the boundaries between each sub-region of the estuary.

Habitat quality (settlement suitability) maps were generated from expert assessment of sediment and vegetation preferences for juveniles of each species for each polygon in Figure 2-3. Habitat quality maps reflect the broader distribution of cockles across a range of sandy and muddy habitats, the more restricted spatial distributions of *Macomona*, and the most restricted distributions of pipi (Table 2-2, Figure 3-3).

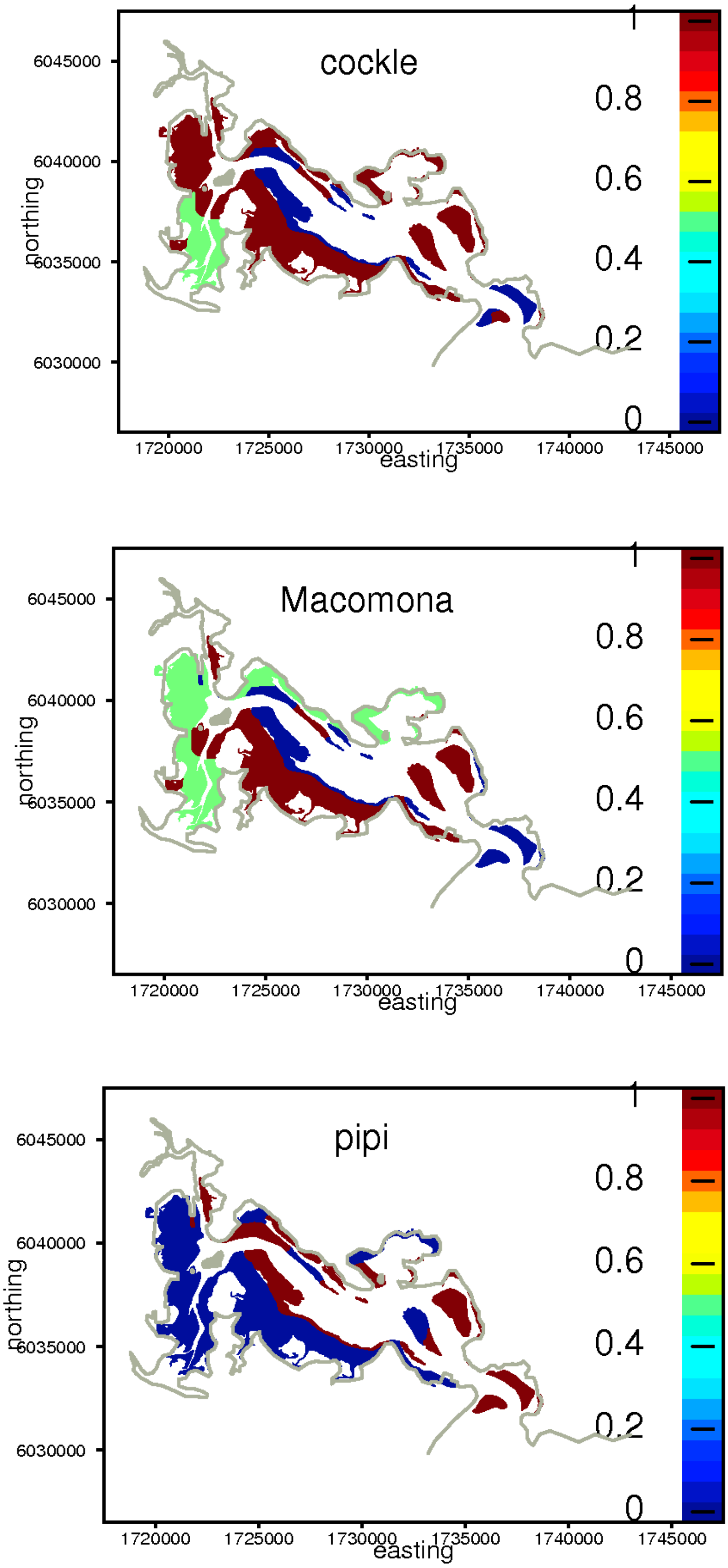

Figure 3-3: Habitat quality maps (settlement success) for each species. Colour is indicative of habitat quality (white regions and deep blue regions have quality=0).

3.3 Cockle larval dispersal

The model predicts strong differences between regions of the harbour in predicted larval settlement (Figure 3-4 to Figure 3-10), illustrated here by differences in number of dots each representing a location of successful settlement. These differences are driven by a combination of differences in the magnitudes of regional spawn production and regional flushing rates. For example, Snake Bank has the highest area-specific cockle spawn production and also a moderately large surface area, but much of the spawn production from Snake Bank is rapidly washed out to sea. Meanwhile, spawn production rates in parts of Parua Bay are also high, and, as Parua Bay is only slowly flushed, circulation promotes high retention rates leading to high settlement rates in the model.

The model predicts slight differences in settlement between regions of the harbour depending on wind conditions. The effect of wind is small, but there is some evidence for a weak, net anti-clockwise transport under the southwest winds scenario. During calm wind scenarios, settlement is predicted to be strongest on Snake and McDonald Banks, in the Northern Coast region of the harbour, and in Parua Bay, but much reduced in the Upper Harbour region compared to all other scenarios (Figure 3-4). Settlement in Parua Bay is slightly lower but similar during easterly and southwest wind scenarios, and lowest during northwest wind scenarios (Figure 3-5 to Figure 3-10). Settlement in the Upper Harbour is predicted to be generally low and variable. Settlement in the Northern Coast region is low during all wind scenarios except calm wind conditions. Settlement on the South Coast region (Takahiwai) is lowest during SW90 wind scenarios (Figure 3-4, Figure 3-9, Figure 3-10), and otherwise shows settlement rates between that of the Upper Harbour and Snake Bank and Parua Bay. Settlement at Snake Bank is lowest in the strong westerly wind scenarios (SW90 and NW90) (Figure 3-8 and Figure 3-10).

Plot colours represent locations of origin of settled particles, and as such show connectivity between different areas of the harbour. The settlement maps (Figure 3-4 to Figure 3-10) show only the birth polygon of the most recently settled particle, and are slightly biased toward local settlement. However, these plots illustrate that each birth polygon can contribute settlers to almost any part of the bay. Conversely, each recipient habitat polygon can receive colonists from almost any part of the estuary. Wind scenarios differ slightly in the relative proportion of exchange, with contributions of Snake Bank and the other northern mid- and outer harbour regions being highest during calm and easterly wind conditions, while contributions from spawning sites from the west to settlement sites to the east are higher during north- and south-westerly wind conditions. Contributions from the Upper Harbour region to elsewhere in the harbour are minimal, due to a combination of low spawning biomass estimated from the 42 site survey, and high retention in the upper harbour.

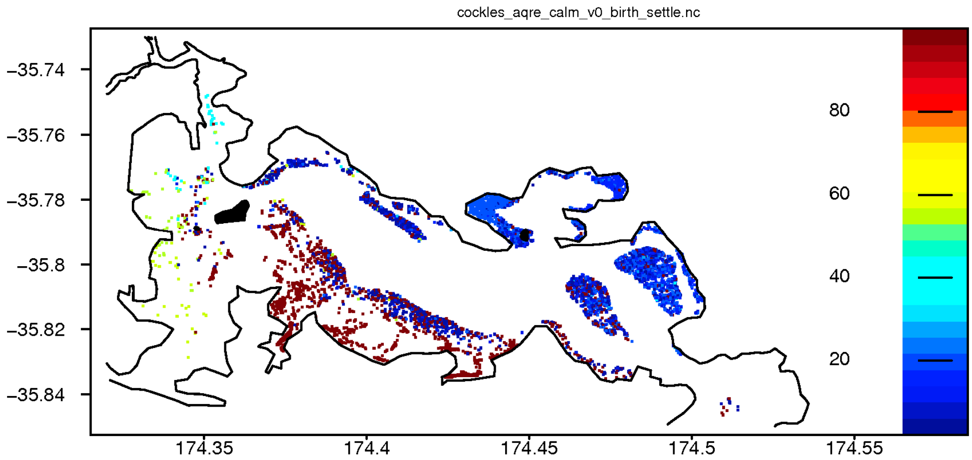

Figure 3-4: Simulated cockle settlement locations under the 'calm winds' scenario. Each location-point is coloured according to the ID number of the particle's birth-polygon. The colour-coding is the same as that used in Figure 4. Due to image resolution limitations, multiple dots may overlay one another. In such instances, only the dot-colour of the last-to-settle particle will show.

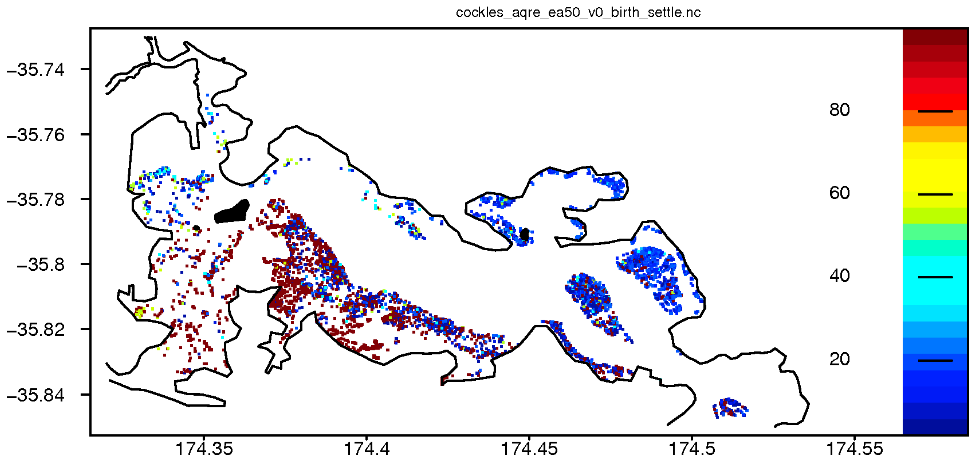

Figure 3-5: Simulated cockle settlement locations under the EA50 scenario. See legend to Figure 3-4 for further explanation.

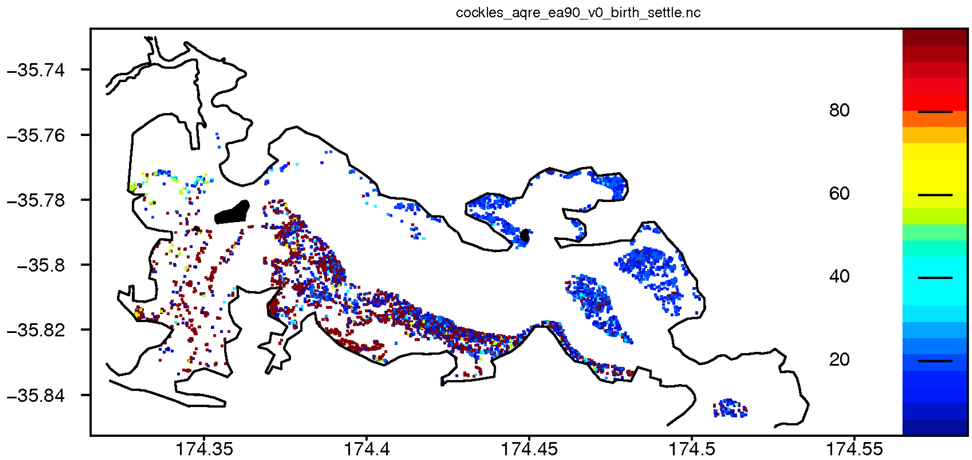

Figure 3-6: Simulated cockle settlement locations under the EA90 scenario. See legend to Figure 3-4 for further explanation.

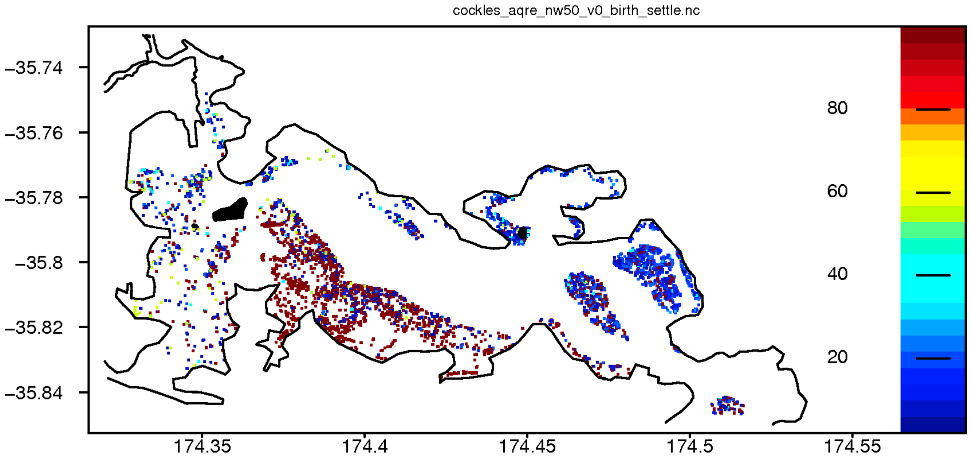

Figure 3-7: Simulated cockle settlement locations under the NW50 scenario. See legend to Figure 3-4 for further explanation.

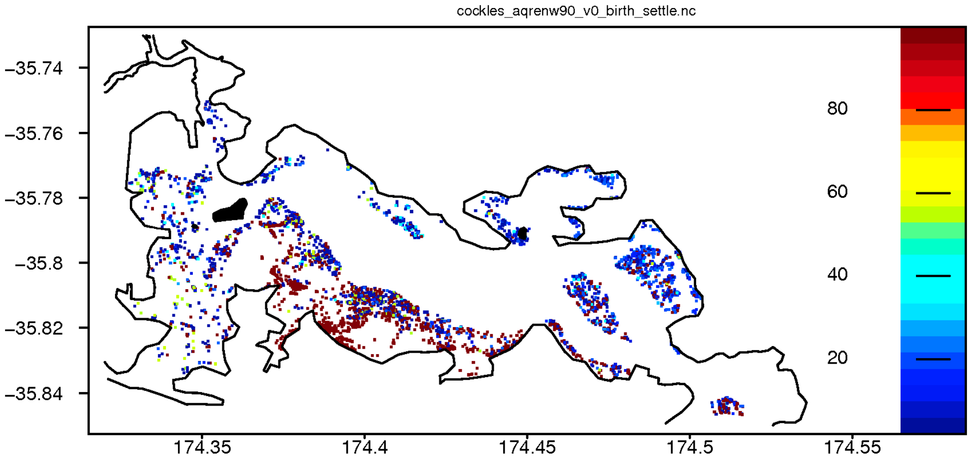

Figure 3-8: Simulated cockle settlement locations under the NW90 scenario. See legend to Figure 3-4 for further explanation.

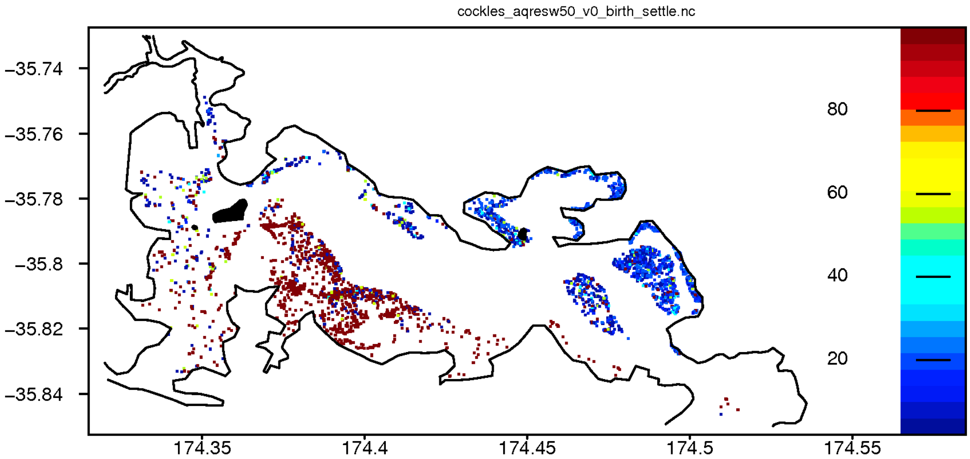

Figure 3-9: Simulated cockle settlement locations under the SW50 scenario. See legend to Figure 3-4 for further explanation.

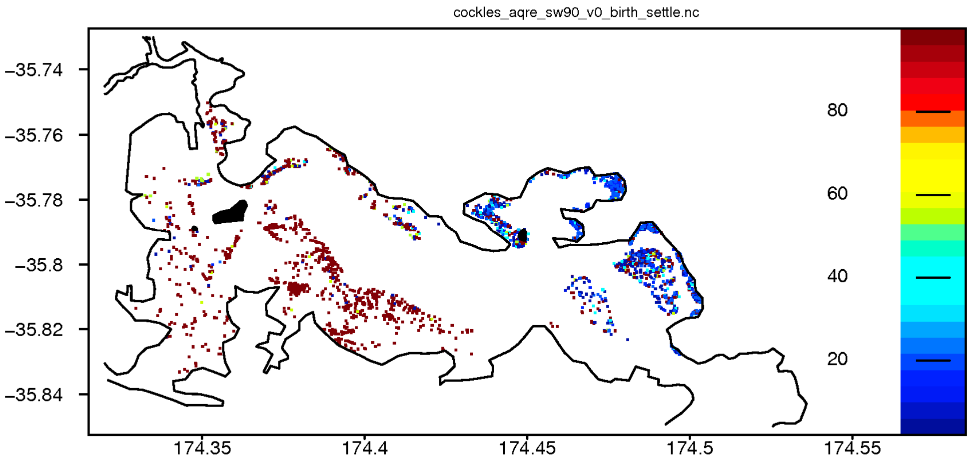

Figure 3-10: Simulated cockle settlement locations under the SW90 scenario. See legend to Figure 3-4 for further explanation.

Connectivity patterns are further illustrated in a plot of connectivity between habitat polygons, with results combined across all seven wind scenarios (giving each an equal weight). To maximise ease of comparing between sites, relative settlement between polygons was calculated as the fourth-root of the number of larvae originating at the pixel's birth polygon that subsequently successfully settled at the pixel's settlement polygon (assuming a per-capita mortality rate of 0.45 d^{-1} during the planktonic period). These plots again illustrate that each birth polygon can contribute settlers to almost any part of the harbour (i.e., coloured pixels form near complete columns). Conversely, each recipient habitat polygon can receive colonists from almost any part of the estuary (i.e., coloured pixels form near complete rows). Broadly speaking, the polygons corresponding to pixels which are below the 1:1 diagonal line (not shown) correspond to a net anticlockwise movement around the estuary from birth location to settlement location. Conversely, pixels above the line correspond to a net clockwise movement.

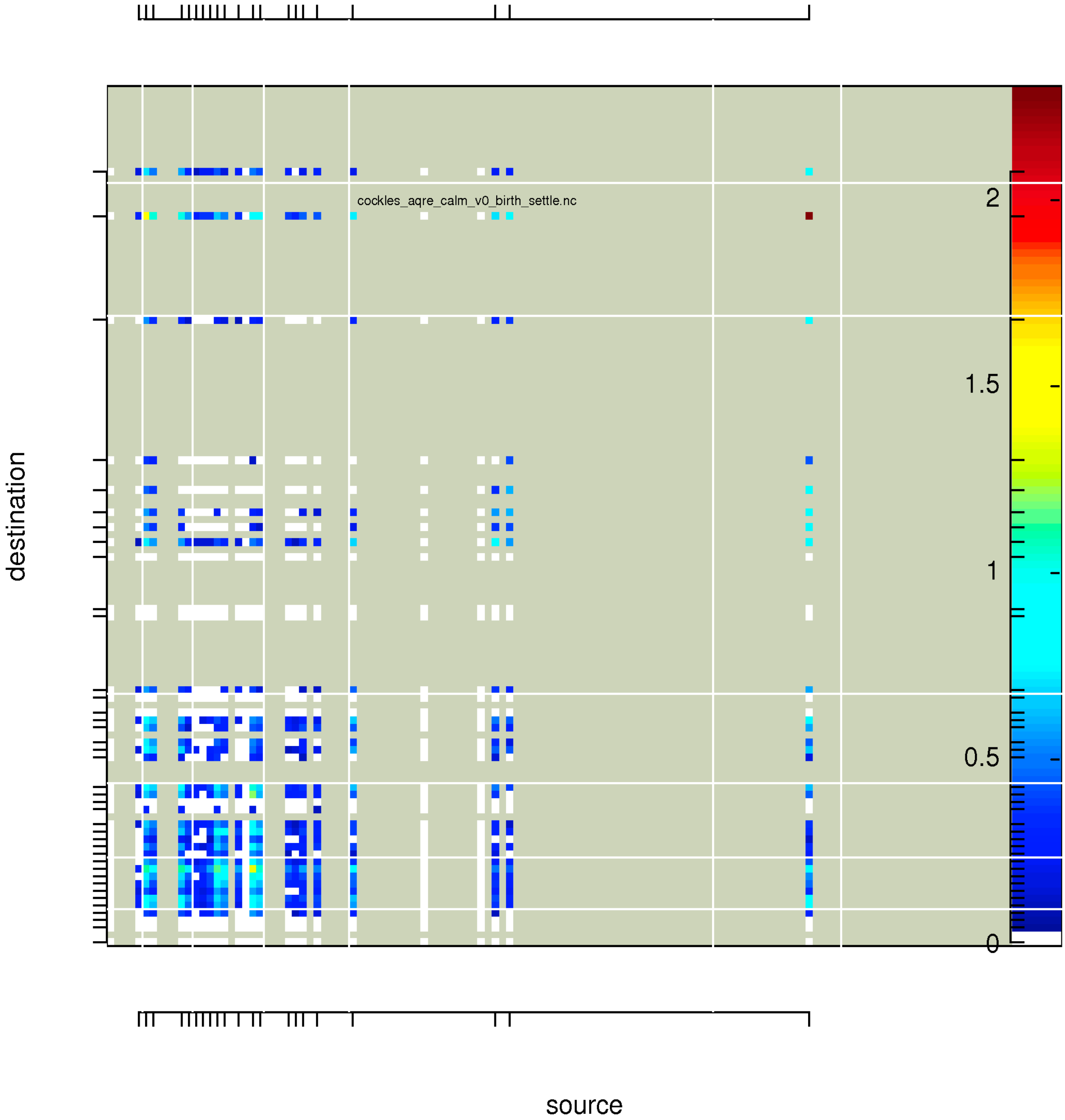

Figure 3-11: Connectivity matrix for cockles. The x-axis denotes the birth-polygon ID and the y-axis denotes the settlement polygon ID. Grey pixels correspond to polygon combinations which could receive no settlers (because one or both of birth-polygon spawn rate or settlement polygon habitat quality were zero). White pixels are polygon-combinations which, could, in theory have received settlers but, in reality did not. The tick-marks on the x-axis denote polygons which generated particles. Comparison of these ticks with the corresponding vertical 'bars' of (white+colour) reveal a few polygons which had non-zero spawning rates, but failed to generate any particles. The tick marks on the y-axis denote polygons having non-zero habitat quality (i.e., those onto which settlement is theoretically possible). The horizontal and vertical white lines denote the boundaries between adjacent coastal regions: 'Northern Mouth', 'Snake, McDonald & Mair Banks', 'Parua Bay', 'Northern Coast', 'Upper Harbour', 'Southern Coast' and 'Southern Mouth'.

3.4 Pipi and *Macomona* larval dispersal

Settlement scenarios were only performed for calm wind scenarios for pipi and *Macomona*. Pipi showed highest relative settlement on McDonald Bank, in the deeper mid channel and on the Northern Coast (Figure 3-12). Surprisingly, the model did not predict pipi dispersal into the Upper Harbour, whereas field surveys quantified reasonably high numbers of juvenile pipis in one location near the old port. As much of the adult biomass detected in the 42 site survey was near the harbour mouth, the model advects most of these spawned larvae into Bream Bay. All locations with successful pipi recruitment are dominated by pipis spawned on Snake and Mair Banks, and near the mouth of Parua Bay. The model predicts minimal contribution of spawning pipis from the southern and upper harbour to the remainder of the harbour.

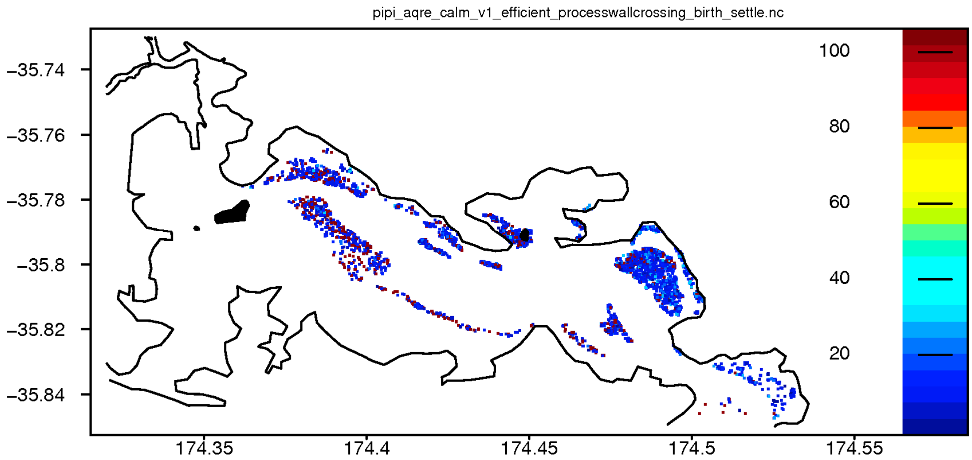

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Figure 3-12: Simulated pipi settlement locations under the calm scenario. See legend to Figure 3-4 for further explanation.

Macomona showed highest relative settlement on the Southern Coast (Takahiwai and One Tree Point), and on Snake and McDonald Banks (Figure 3-13). All locations with successful *Macomona* recruitment are dominated by shellfish spawned on the Southern Coast. The model predicts low and variable settlement in the upper harbour, with most larvae contributed from the upper harbour. Settlement of *Macomona* is predicted to be minimal in Parua Bay except nearest the mouth.

Connectivity patterns for pipi and *Macomona* are further illustrated in a plot of connectivity between habitat polygons for the calm wind scenarios (Figure 3-15, Figure 3-16). Similar to the cockle connectivity plots, these plots illustrate that each birth polygon can contribute settlers to suitable settlement habitat across the entire harbour (i.e., coloured pixels form near complete columns). Conversely, each recipient habitat polygon can receive colonists from almost any part of the estuary (i.e., coloured pixels form near complete rows). However, *Macomona* was less likely to exhibit westward transport, i.e., few polygons in the Southern Coast received larvae from Snake Bank or Parua Bay, while transport from the Southern Coast to Snake Bank and Parua Bay was common.

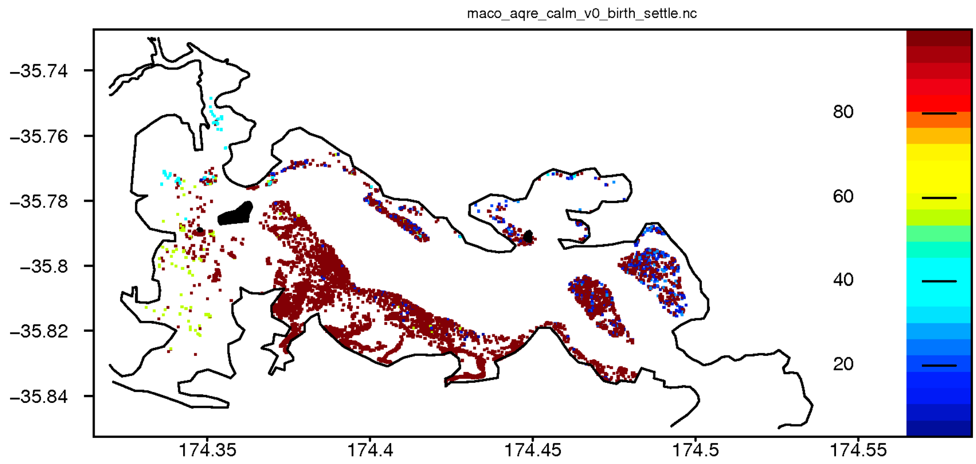

Figure 3-13: Simulated *Macomona* settlement locations under the calm scenario. See legend to Figure 3-4 for further explanation.

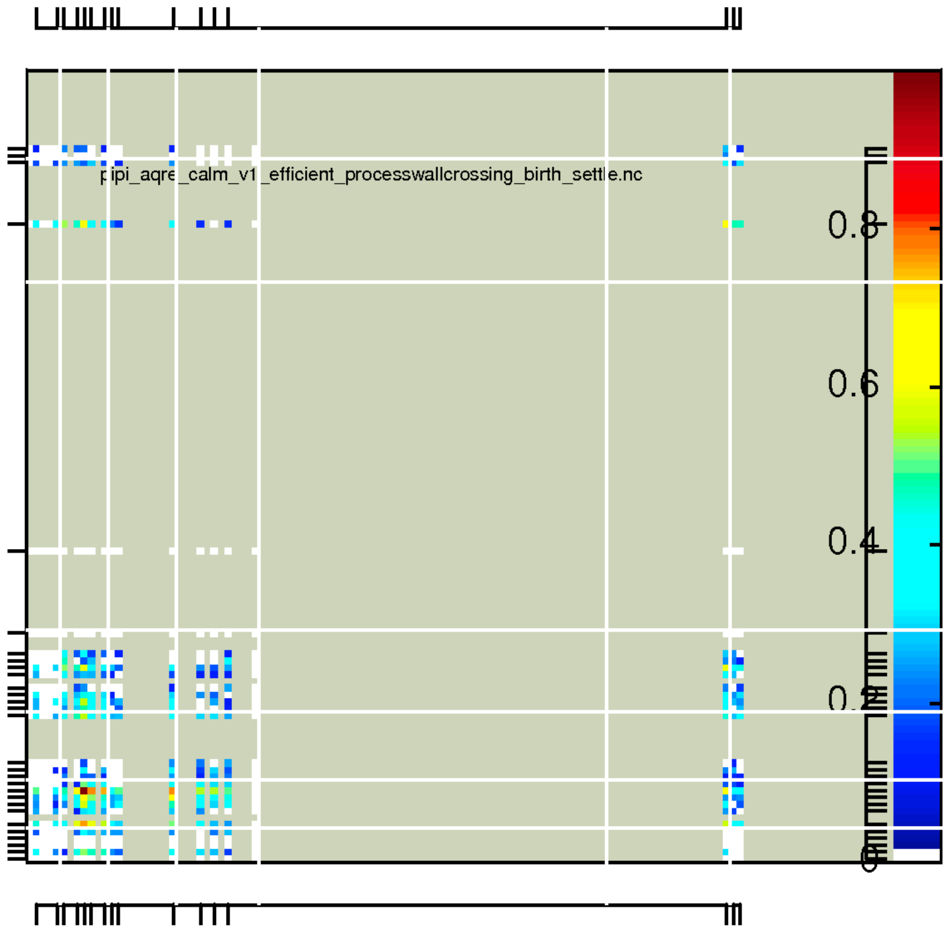

Figure 3-14:Connectivity matrices for pipi under the calm wind hydrodynamic scenario. The x-axis denotes the birth-polygon ID and the y-axis denotes the settlement polygon ID. See legend to Figure 3 11 for further details.

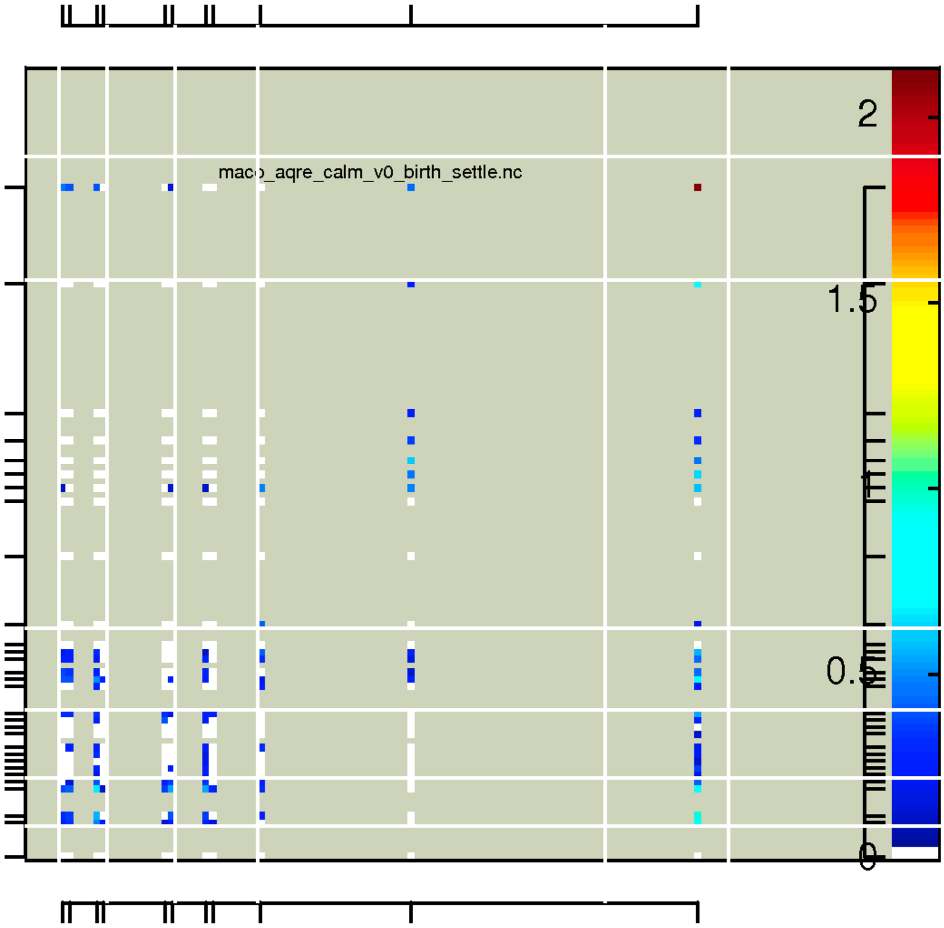

Figure 3-15: Connectivity matrices for *Macomona* under the calm wind hydrodynamic scenario. The x-axis denotes the birth-polygon ID and the y-axis denotes the settlement polygon ID. See legend to Figure 3-11 for further details.

Calculations of the likely settlement success of particles released from each region suggest that settlement success for cockles varied little between release sites, i.e., larvae are just as likely to survive and settlement if released from the Upper Harbour, Snake Bank, Takahiwai, Parua Bay or elsewhere in the harbour (Figure 3-16). The main difference in model predictions of relative settlement between locations is thus dominated by the relative spawning rate (adult abundance) in each region, in addition to hydrodynamics determining transport distance and direction.

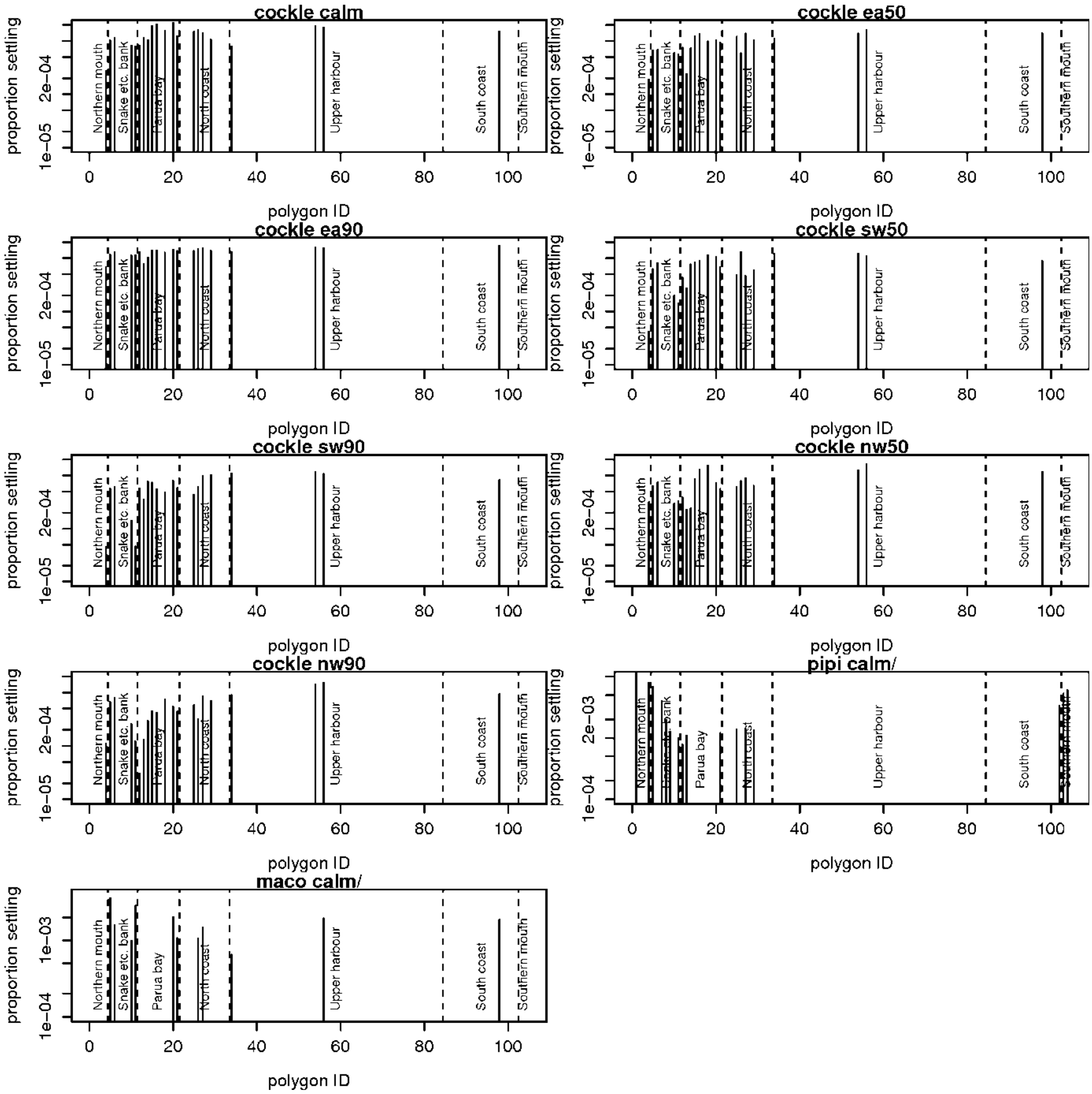

Figure 3-16: Proportion of larvae spawned from each polygon which subsequently successfully settled. The mortality rate was assumed to be 0.45 d-1 during the period each particle was in the plankton. The x-axis denotes the birth-polygon as described in Figure 2-3. The dashed vertical lines mark the boundaries between the sub-regions of the estuary. Note that the y-axes are logarithmic.

3.5 Model validation

Mean predicted larval concentrations from field plankton surveys were calculated as the mean of all replicates at a site (2 pair replicates per 24 hour sampling period). Three 24 hour periods were sampled in 2012. In 2009, 3 sites (Parua Bay, Snake Bank, Takahiwai) were sampled at higher frequency, and the remaining sites were sampled during three 24 hour periods.

Mean larval concentrations include all larval bivalves combined. Unfortunately, inexpensive techniques do not yet exist to determine the species of larval bivalves collected in plankton nets, so we are not able to distinguish under the microscope between larval *Macomona*, cockles, pipis and other bivalve species.

Field surveys showed high variability within the harbour (Figure 3-17). Not surprisingly, larval concentrations were relatively high at McDonald Bank and the two Snake Bank sites. While we did not initially anticipate high larval bivalve concentrations at the Takahiwai sites, this could be explained by the high concentrations of adult *Macomona* at the site. The new 2012 upper harbour sampling sites (Otaika and Portland) showed the highest numbers of larval bivalves for all sampling times. While unexpected from the limited upper harbour survey by NIWA, better understanding of the extensive cockle beds in the upper harbour suggested a likely source for this high larval concentration, as well as transport within the main harbour channel. Net samples cluster into 4 groups: 1) highest values at Otaika and Portland in the Upper Harbour; 2) next highest samples at Snake and McDonald Banks; 3) most other sites with between 2000 and 4000 larvae per 24 hour collection, and 4) lowest values at One Tree Point (OTP) and Parua 2. Variability between years was most apparent at One Tree Point, Snake and Takahiwai.

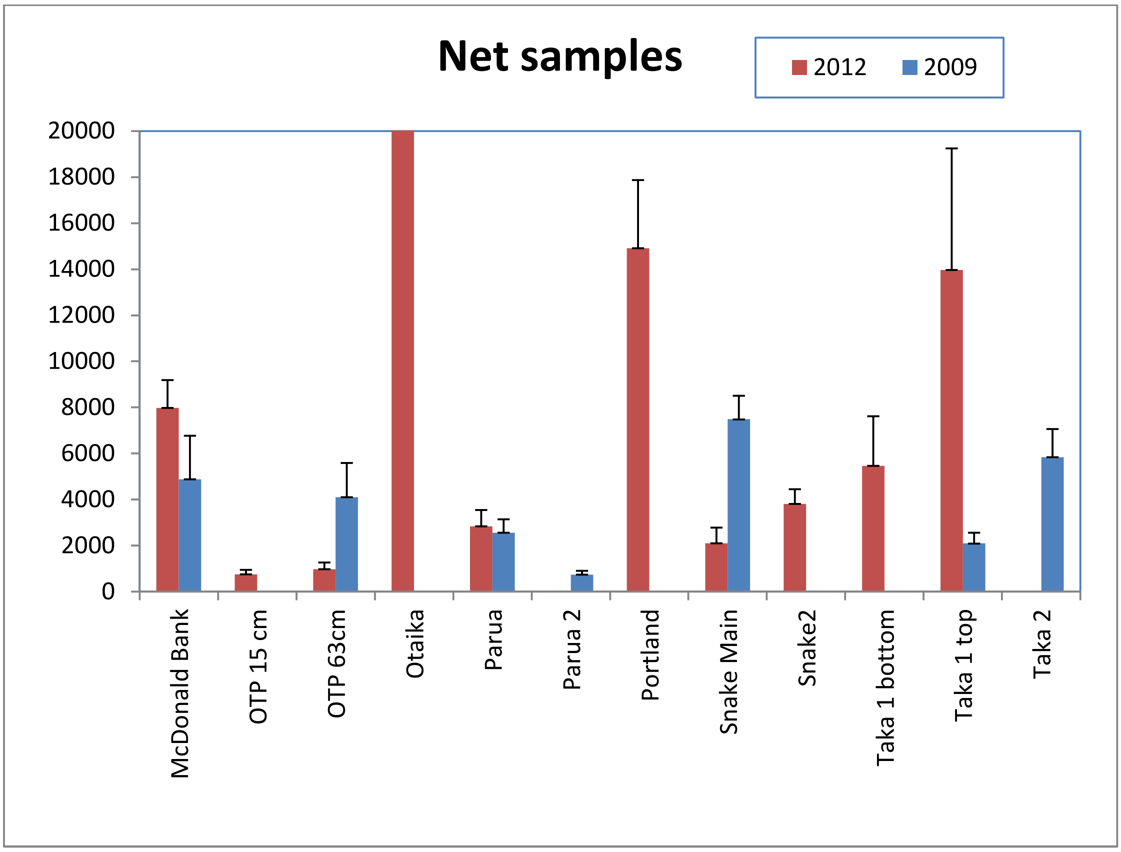

Figure 3-17: Larval concentration of all bivalves in plankton net samples at intertidal sites. Bars are mean (plus standard error) of all 24 hour samples collected at a station. The Otaika value was the highest recorded at over 60,000 larvae per 24 hour sample.

We compared observed and simulated larval concentrations by counting the number of simulated particles (all age-classes) found within a 300 m horizontal radius of each plankton net location and within the vertical strata spanned by the plankton nets (5–25 and 55–75) cm above the local bed. The particle counts were converted to larval concentrations by scaling by the population size of each particle (corrected for mortality) and dividing by the sampling volume (π x (300 m)^2 x 0.2 m). We made this calculation for each of the nine sequential 11.5 hour periods that began between days 13 and 17 from the simulation start (i.e., those days in which simulated larval abundances would have been maximal because the spawning period was complete but no larvae were yet discarded due to old age). Averaging included any 'samples' drawn during periods when the stratum in question was wholly (or partially) above the sea-surface. As such, total settlement between sites is normalised by tidal cycle, rather than being normalised to the time that a site is covered by water.

The model predicts slightly higher larval concentrations for cockles in the upper water column relative to the bottom of the water column. Predicted cockle larval concentrations across wind scenarios are broadly similar, with highest larval concentration consistently predicted for Parua Bay (Figure 3-18). One Tree Point, Portland and Otaika are predicted to have lowest cockle larval concentrations in a majority of the wind scenarios. These relative concentrations disagree substantially with those of field observations.

Predicted larval concentrations of pipi and *Macomona* are different from those of cockles, and compare better to field observations (Figure 3-18). Pipi larval concentrations are predicted to be highest at Snake and McDonald Bank, and at One Tree Point, all locations with observed pipi populations. *Macomona* predicted larval concentrations are predicted to be highest at Southern Coast region including the two plankton net sites at Takahiwai and Takahiwai 2, and at One Tree Point, all of which are also observed locations with high densities of this species.

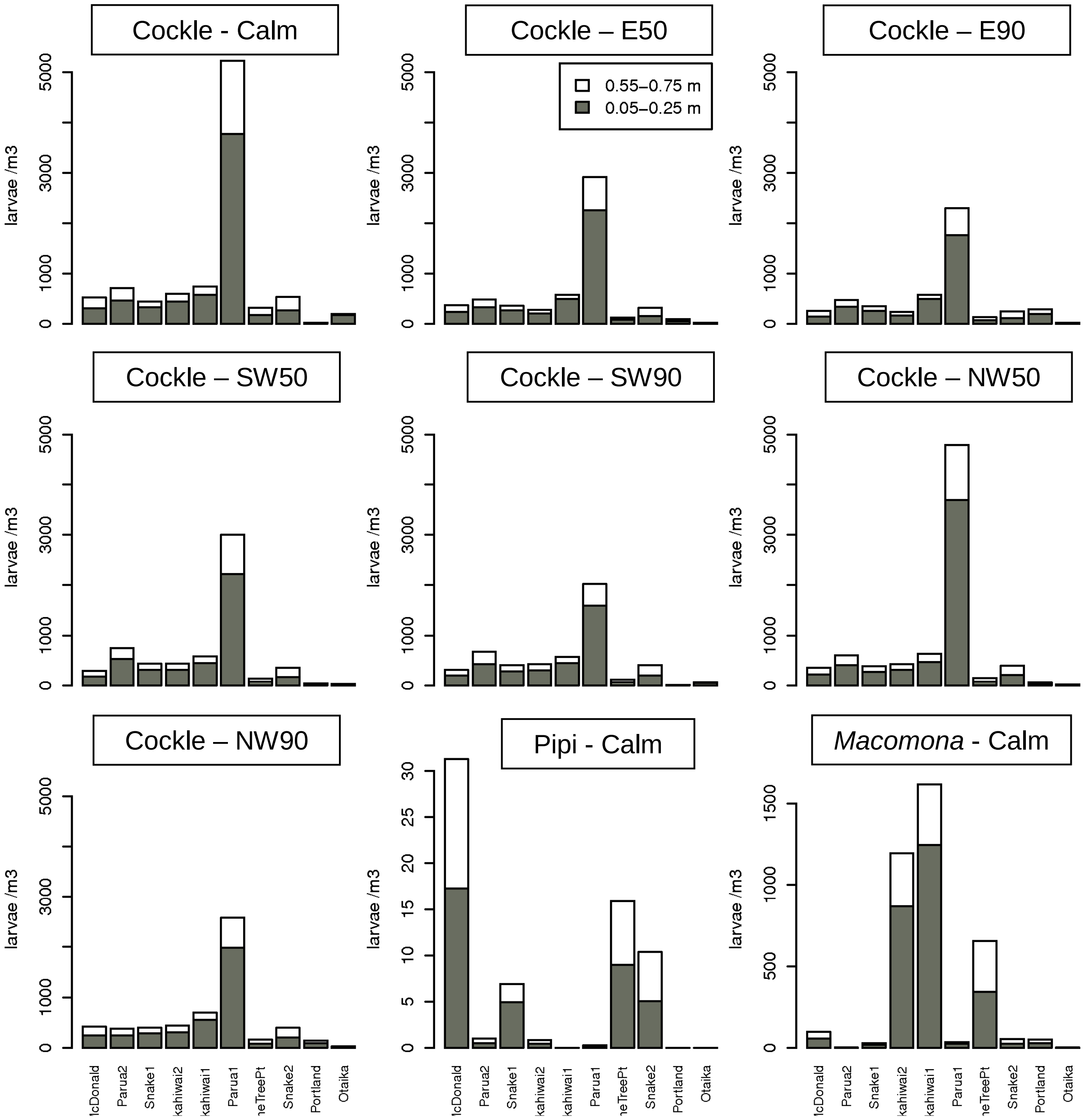

Figure 3-18: Predicted larval concentrations for two depths (0.05-0.25 m above seabed and 0.55-0.75 m above seabed).

Comparing model predictions with field observations suggest two primary areas of uncertainty in adult spawning distributions that may be driving the mismatch between field and model predictions. We suggest the limited surveys of adult spawning populations in the Upper Harbour and in Parua Bay are responsible for this mismatch, in combination with the relatively high likelihood of larval retention in both of these areas. In the Upper Harbour, the few samples taken were all in muddy habitats, though substantial cockle banks are present, just not in locations that were sampled in the NIWA 42 site survey, as it was focussed on the mid- and outer harbour. Presumably, higher resolution of existing shellfish banks in the Upper Harbour would result in better matching of model and field predictions for this harbour region as a larger spawning population would be located here. In contrast at Parua Bay, the few survey locations likely over-predicted the spawning population density in this region, biasing the model results of larval settlement in the region. If model predictions are combined for all species, the high larval abundance observed at the Takahiwai sites matches these predictions, as high *Macomona* abundance was predicted in the southern harbour.

Additional plankton sampling was used to validate larval behaviour used in the model. Plankton pump samples at 3 depths (1, 3 and 5 m) illustrate high variability between collections, and no significant difference between depth except for outgoing bottom samples (Figure 3-19). In this case, one of three replicates was lost, and the relative contribution of one low abundance sampling time [that occurs at all depths] dominated the mean of this tide and depth combination. While sampling to detect vertical differences in plankton distribution was limited to a total of 18 samples with 3 replicates of each tide and depth combination, we opted to model larvae as randomly distributed within the water column based on the high variability and lack of consistent depth pattern between sampling occasions.

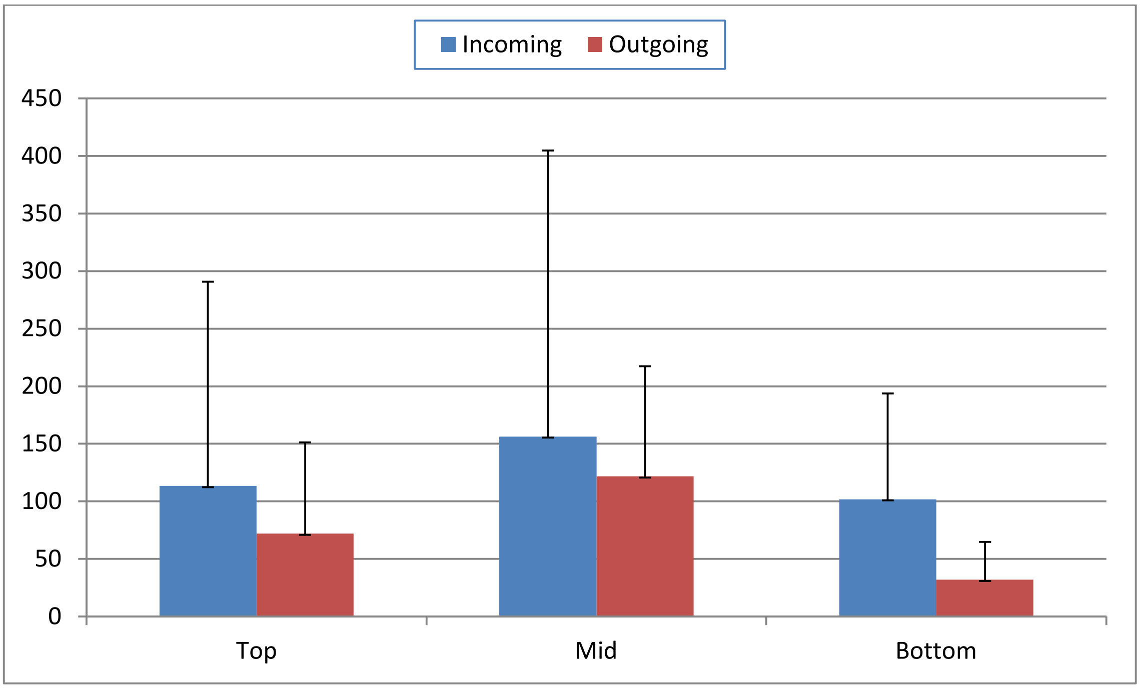

Figure 3-19: Mean larval concentration of 15 minute plankton pump samples taken at 3 depths (1, 3 and 5 m) near the mouth of Parua Bay.

4 Summary

Here, we developed and validated a larval dispersal model for shellfish in Whangarei Harbour. The model predicted high variability between sites in the total settlement success, with high larval settlement success in Snake Bank, McDonald Banks and Parua Bay for most wind scenarios. Settlement in the Upper Harbour was predicted to be low and variable. Connectivity between all regions of the harbour was predicted to be high, with sites near the mouth (e.g., Snake and McDonald Banks) predicted to provide large quantities of larvae for settlement throughout the harbour, but all sites capable of providing larvae for settlement throughout the harbour and vice versa. Settlement and larval connectivity varied most at Takahiwai with some wind conditions resulting in higher self-recruitment, while others resulted in high settlement from neighbouring seaward regions. Highest retention rates (i.e., most recruits provided by the local region) were predicted for Parua Bay and the Upper Harbour.

Surprisingly, model output did not match field data for all sites, with Parua Bay and the Upper Harbour being most different from predictions. It is likely that these differences are explained by uncertainty in the underlying datasets that drove the model. While we are reasonably confident in our predictions of species' preferences for suitable habitats, we admit high uncertainty in our estimates of spawning density as our total sampling effort was limited to 42 sampling sites across the entire harbour, with most of our sampling effort concentrated in the mid and lower harbour. We also had additional samples collected during the 2009 Snake Bank cockle survey by the Ministry of Fisheries adding an additional 69 locations with shellfish and sediment information for this one shellfish bank in the harbour. However, we sampled only 7 sites in the entire Upper Harbour, and these samples did not include any existing shellfish banks in the Upper Harbour. We suggest that the mismatch in model and field validation is because our larval spawning maps over-estimate spawning rate significantly in Parua Bay, and under-estimate spawning rate in the Upper Harbour, and that high resolution habitat and shellfish abundance maps would remedy this mismatch. In addition, the poor resolution of the habitat suitability map in the Upper Harbour, based on limited sampling effort in that region, also resulted in an under-estimate of larval abundance.

5 Recommendations

The objective of this research was to use predictions of larval connectivity to identify habitats where restoration of shellfish is most likely to succeed based on colonisation of larvae, and to identify highly valuable habitats for larvae, juvenile and adult shellfish that can contribute to colonisation of shellfish restoration sites in Whangarei Harbour. The general patterns of modelled settlement and field observations can be used to identify highly valued habitat for larval and juveniles, and for adult spawning populations.

- **Snake Bank, McDonald Bank and Mair Bank**. The model emphasises that Snake Bank and other high density cockle beds near the mouth of the harbour are highly valued habitat for adult spawning populations of cockles, and provide the highest contribution to larval settlement throughout the harbour. For pipi populations, shellfish banks inside the mouth of the harbour (Snake Bank, McDonald Bank) provided the majority of the larvae settling within the harbour, while larvae from sites at the outer mouth of the harbour were primarily exported to Bream Bay, and the model predicted minimal contribution of these sites to the inner harbour.

- **Takahiwai**. Predicted and actual settlement at Takahiwai, a shellfish restoration site, was generally high, and the model predicted high connectivity with seaward sites (e.g., Snake Bank) which contributed high proportions of total settlement to Takahiwai under most wind conditions.

- **Parua Bay**. Parua Bay had high predicted settlement, with highest contribution from within the bay, suggesting that restoration efforts were likely to increase recruitment in the bay due to high likelihood of recirculation and self-recruitment of larvae released from within Parua Bay.

- **Upper Harbour**. While there was a mismatch between model predictions and field observations, the high larval abundance observed at Portland and Otaika suggest substantial larval source populations in the Upper Harbour. Due to the recirculation and self-recruitment predicted by the model, restoration efforts in the Upper Harbour are likely to result in high quality adult populations serving as larval source populations. In addition, restored habitat quality would be likely to result in settlement of juveniles due to the high connectivity to Snake Bank and other shellfish banks via the main channel.

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Appendix A LTRACK Detailed model methods and results

Hydrodynamic input into LTRACK

Transport was driven by a combination of local-to-particle currents (interpolated from the archived hydrodynamic results) and local-to-particle turbulence (simulated by introducing a random-walk component into each trajectory projection). The magnitude of the random-walk component is proportional to the local dispersion coefficient. The horizontal dispersion coefficient was estimated from the Okubo relationship (Okubo 1971, 1974) taking the radius of circle with surface area equivalent to the particle's host water-column as the characteristic length scale. This implies that horizontal dispersion was smaller in regions where the hydrodynamic model (hence particle tracking model) has greatest spatial resolution. This is appropriate since, in models such as LTRACK, dispersion represents unresolved (sub-grid-scale) variations in currents. Vertical dispersion was assumed to scale: in a parabolic manner with relative particle depth, quadratically with the overall water-column depth, linearly with the vertical current shear (vertical gradient of horizontal current speed), and to decline in response to increased vertical water density gradient (Richardson number damping). The maximum time-step for trajectory projections was 15 seconds. A second-order Runge-Kutta scheme was used to solve the stochastic differential equation governing the evolution of particle location (adopting the Stratonovich viewpoint).

Particle (larval) generation in LTRACK

Particles were released from each of several spawning polygons, and tracked until: (a) they were washed out of the model domain, (b) they reached a user-specified maximum viable age (21 days) without first settling, (c) they settled successfully. At any given time, each spawning region has a notional 'balloon' associated with it. This balloon inflates at a rate that equates to the product of spawn-polygon-area (m^2) areal spawn production rate (eggs m^{-2} d^{-1}). Each time the balloon reaches a user-prescribed size, its contents are transferred to a newly generated particle [we will use the term "size" to refer to number of individual larvae associated with a particle]. The particle is assigned a random location within the horizontal perimeter of the polygon and within 5 cm of the seabed. It is then left to drift under the influence of currents and turbulence (swimming behaviour was ignored in these simulations). The balloon is reset to zero size and begins filling once more. A new record (corresponding to the newborn particle) was created in a 'fate file'. Information recorded included: particle ID-code, birth date, birth polygon and birth location (horizontal and vertical).

Particles were assumed to become able to settle from age 12 day. Those that came into contact with the seabed at earlier ages were immediately reflected. Particles which came into contact with the seabed at age >12 d had a more complex behaviour, dictated by the location-specific habitat quality (as perceived by the species in question). By definition, 'habitat quality' is the probability that a ready-to-settle particle will choose to settle irrevocably at the location upon coming into close proximity (0.5 cm) of the seabed at that location.

Particles were discarded upon settlement, export or death-from-old-age. The time, location and fate (settlement, export, death) was recorded in the appropriate record of the fate file. Particles were generated 'quasi-continuously' (as described above) from the beginning of the simulation (day zero) until the end of day 11. There would have been little point continuing to release particles after this day because such particles would not have been able to reach the prescribed maximum viable age before the end of the simulation. Indeed, those released after day 19 would not even have reached the minimum viable age. Our approach avoids the biases that might arise by 'truncating' some particle histories.

In addition to the information stored in the fate-file, further information related to each extant particle was recorded at hourly (simulated time) intervals in a 'location' file. This information included: particle identity, location (in 3D) and local-to-particle sea-surface height and bathymetry. The results recorded in the 'fate' file can be used to calculate many properties: proportion of new born particles that successfully settle, age at settlement, maps of realized settlement locations, connectivity matrices (matrices whose elements record the numbers of particles originating within polygon "i" (column of matrix) and settle in polygon "j" (row of matrix), distance travelled by successful particles, etc.

In undertaking analyses of settlement success, one should take account of 'background' mortality (due to predation or starvation, rather than old-age) during the planktonic stage prior to eventual settlement, death-from-old-age or export. This mortality will 'erode'/reduce a particle's size progressively as it ages. To do so requires that one stipulate a per-capita mortality rate (d^{-1}). Mortality rates for meroplankton are notoriously variable, but the range 0.2–0.6 d^{-1} would encompass the majority of observations (Rumrill 1990, Morgan 1995). We adopted a mortality rate of 0.45 d^{-1}.

Of polygons that contain adult shellfish, the least productive generated only around 10 particles, whilst the most productive generated 1000s of particles. The inevitable result is that the statistical <u>un</u>certainty which we could attribute to the dispersal kernels that we could infer for each source polygon is vastly greater for those polygons that produce fewest particles. The reader will need to bear this in mind should he/she choose to ask questions about individual dispersal kernels. This subtlety becomes less important if the reader is more interested in determining where a recipient polygon is getting its colonists from. For that question, it is only important that each source polygon has spawned the appropriate proportion of the estuary-wide total spawn production – something that is guaranteed by the manner in which the model is constructed

Appendix B Sediment characteristics in Whangarei Harbour from 42 site survey and Snake Bank sub-sampling

Site	Lat	Long	% Gravel	% Coarse Sand	% Medium Sand	% Fine Sand	% Very Fine Sand	% Silt/Clay	% organics	chla microg/ g sediment	phaeo microg/ g sediment
WH1	-35.8442	174.5361	2.713	23.503	48.254	18.951	4.543	2.037	1.572	2.01	2.04
WH2	-35.8280	174.5286	66.645	30.215	1.924	0.586	0.100	0.531	3.064	0.75	1.90
WH3	-35.8266	174.4973	41.770	15.732	16.386	17.487	4.624	4.001	3.020	4.58	3.17
WH4	-35.8115	174.504	12.592	34.099	33.623	16.933	1.559	1.195	1.214	2.87	3.74
WH5	-35.7878	174.4871	11.937	26.337	34.488	22.623	3.048	1.567	1.708	6.30	4.18
WH6	-35.7703	174.4557	15.703	16.991	18.919	27.521	9.965	10.901	2.930	9.98	1.86
WH7	-35.7796	174.4425	14.488	32.660	24.239	13.122	2.614	12.877	3.369	6.82	4.49
WH8	-35.7796	174.4346	9.474	24.371	22.628	27.947	9.184	6.396	1.437	5.39	3.40
WH9	-35.7808	174.4146	28.302	22.881	20.108	20.853	1.759	6.098	2.076	7.10	3.17
WH10	-35.7825	174.4688	20.470	38.829	26.092	10.283	0.753	3.572	1.211	3.50	2.49
WH11	-35.7828	174.469	9.450	19.492	13.535	26.183	12.943	18.397	3.316	6.30	3.85
WH12	-35.7922	174.4658	22.203	33.612	28.907	12.147	0.828	2.303	1.463	4.24	2.40
WH13	-35.7884	174.4394	29.659	20.892	13.838	27.766	5.133	2.712	1.067	5.56	2.45
WH14	-35.7804	174.4073	42.075	10.414	11.766	30.646	2.807	2.292	1.475	8.14	3.87
WH15	-35.7746	174.3995	9.213	9.491	21.007	36.586	18.578	5.125	2.643	7.68	3.30
WH16	-35.7645	174.3829	13.636	4.990	8.871	54.625	8.046	9.832	3.349	5.84	6.66
WH17	-35.7875	174.414	6.630	1.179	1.402	29.878	59.422	1.491	4.017	6.59	2.24
WH18	-35.8113	174.3494	17.508	15.974	8.307	10.841	20.958	26.411	3.365	7.22	2.99
WH19	-35.7962	174.3482	2.089	0.463	6.781	63.339	9.612	17.715	0.776	9.34	3.70
WH20	-35.7905	174.3596	4.421	2.655	31.338	48.511	10.075	3.000	1.100	7.34	2.20

Site	Lat	Long	% Gravel	% Coarse Sand	% Medium Sand	% Fine Sand	% Very Fine Sand	% Silt/Clay	% organics	chla microg/ g sediment	phaeo microg/ g sediment
WH21	**-35.7566**	**174.3532**	**0.292**	**2.627**	**53.807**	**24.680**	**0.773**	**17.821**	**6.375**	**10.32**	**3.45**
WH22	-35.7587	174.3481	6.580	6.962	12.588	26.960	23.746	23.164	2.306	3.78	2.90
WH23	-35.7648	174.3564	13.858	1.387	8.678	31.012	41.988	3.077	0.866	6.08	1.89
WH24	-35.7690	174.3488	23.226	16.694	24.154	33.920	1.189	0.816	1.433	12.73	2.02
WH25	-35.8206	174.4578	0.140	0.235	40.750	55.513	3.156	0.206	0.904	5.85	0.58
WH26	-35.8331	174.4725	0.398	1.149	36.111	54.220	7.609	0.513	0.556	14.79	1.48
WH27	-35.8350	174.4812	3.191	6.104	70.619	18.939	0.838	0.309	0.574	7.05	2.52
WH28	-35.8187	174.474	0.547	1.491	56.860	39.947	0.515	0.640	3.451	8.49	3.49
WH29	-35.8157	174.471	11.959	6.507	27.221	51.001	2.805	0.506	0.562	3.84	1.07
WH30	-35.8107	174.4747	0.367	3.556	50.244	44.123	1.454	0.257	0.798	4.76	1.47
WH31	-35.7933	174.4758	59.517	36.193	2.941	0.683	0.262	0.403	0.682	0.69	1.91
WH32	-35.7997	174.4945	0.912	1.434	14.312	77.571	3.443	2.328	0.651	9.57	3.14
WH33	-35.8085	174.4957	2.781	3.938	27.119	62.573	2.757	0.832	0.490	9.11	3.23
WH34	-35.8053	174.4911	97.866	0.909	0.455	0.455	0.056	0.260	0.909	11.58	1.60
WH35	-35.8439	174.5096	23.437	28.462	34.448	13.257	0.315	0.081	2.217	3.90	1.52
WH36	-35.7749	174.3591	0.335	0.728	7.792	81.602	8.245	1.299	2.060	7.74	2.29
WH37	-35.7737	174.3665	52.512	8.606	5.364	15.710	10.993	6.815	1.771	8.14	2.24
WH38	-35.8072	174.402	0.982	0.285	2.100	81.062	14.292	1.279	0.834	5.73	3.35
WH39	-35.8078	174.3933	0.063	0.208	5.497	79.261	14.508	0.462	0.884	5.33	1.60
WH40	-35.8163	174.409	6.457	0.825	10.747	64.109	16.846	1.016	0.907	4.47	1.76
WH41	-35.8230	174.4201	0.847	0.463	9.161	83.122	5.730	0.677	0.510	5.04	2.10
WH42	-35.8249	174.4226	2.274	3.532	33.447	53.755	6.530	0.462	1.032	8.31	2.13

Site	Lat	Long	% Gravel	% Coarse Sand	% Medium Sand	% Fine Sand	% Very Fine Sand	% Silt/Clay	% organics	chla microg/ g sediment	phaeo microg/ g sediment
SH01	-35.8161	174.473	4.024	3.932	48.335	41.536	1.203	0.971	0.946	10.66	2.47
SH04	-35.8139	174.4722	8.507	2.413	31.822	53.057	2.267	1.934	0.706	10.09	2.26
SH06	-35.8105	174.4736	2.773	0.684	23.105	66.328	4.414	2.695	0.801	7.34	2.19
SH07	-35.812	174.4748	0.131	1.198	35.012	61.992	1.423	0.243	0.729	7.62	2.41
SH08	-35.8163	174.4708	9.989	5.114	33.602	48.205	2.720	0.370	0.928	6.42	3.07
SH09	-35.8183	174.4749	1.350	3.652	73.341	19.562	1.461	0.635	1.008	6.08	1.58
SH10	-35.8109	174.4733	1.233	2.230	29.895	62.781	2.991	0.870	1.187	7.79	0.85
SH11	-35.8165	174.4745	1.964	2.245	29.012	62.542	3.227	1.010	2.725	8.48	1.78
SH12	-35.8193	174.4723	23.813	12.965	43.630	19.207	0.241	0.144	1.059	3.67	1.16
SH13	-35.8175	174.4726	8.614	12.814	56.471	21.100	0.871	0.129	0.696	1.55	0.85
SH14	-35.8169	174.4753	1.292	7.887	78.181	11.528	0.783	0.330	0.664	5.33	1.73
SH15	-35.8152	174.4705	3.495	4.163	20.571	63.692	4.320	3.759	0.874	10.55	2.73
SH16	-35.8183	174.4739	3.087	4.130	68.899	21.819	1.314	0.751	0.848	8.71	1.75
SH17	-35.8158	174.4717	4.457	6.203	37.511	47.990	2.765	1.073	0.952	12.15	2.22
SH18	-35.8161	174.4724	0.528	5.451	51.426	40.021	1.663	0.911	0.994	9.17	1.94
SH19	-35.8128	174.4736	5.743	1.796	27.037	62.460	2.558	0.407	0.989	6.99	1.21
SH20	-35.8165	174.4757	0.802	5.859	76.612	14.795	1.178	0.753	0.997	5.04	1.36
SH21	-35.8141	174.471	26.190	5.840	24.067	40.927	2.558	0.418	0.971	6.76	1.36
SH22	-35.8148	174.4741	2.836	4.029	50.103	41.400	1.376	0.256	0.566	8.37	1.63
SH23	-35.817	174.4713	0.659	1.757	16.256	76.471	4.320	0.537	0.726	4.30	1.77
SH24	-35.8187	174.4736	5.056	5.558	68.978	18.793	0.794	0.821	0.661	8.31	3.37
SH25	-35.8172	174.4759	0.155	9.523	76.402	11.714	1.181	1.025	0.455	3.84	2.06
SH26	-35.8171	174.4739	0.162	1.784	32.482	61.951	3.067	0.554	0.943	10.03	1.69
SH27	-35.8112	174.4722	1.598	3.710	31.728	59.629	2.762	0.572	0.914	8.14	1.38

Site	Lat	Long	% Gravel	% Coarse Sand	% Medium Sand	% Fine Sand	% Very Fine Sand	% Silt/Clay	% organics	chla microg/ g sediment	phaeo microg/ g sediment
SH28	-35.8174	174.4719	0.098	9.234	70.623	18.247	0.148	1.650	0.661	8.83	1.45
SH29	-35.817	174.4747	0.414	5.312	73.656	18.594	1.241	0.784	0.808	8.02	2.10
SH30	-35.8183	174.4722	33.179	9.227	48.557	8.806	0.211	0.021	0.793	1.32	0.37
SH31	-35.8116	174.4735	10.799	2.394	30.719	53.226	2.861	0.000	0.676	5.85	1.24
SH33	-35.8178	174.4739	6.185	3.571	64.865	23.338	1.227	0.813	1.052	11.34	1.84
SH34	-35.8202	174.4733	41.290	18.394	35.681	4.399	0.236	0.000	1.350	4.36	2.70
SH35	-35.8143	174.4742	1.302	2.367	47.300	47.241	1.465	0.325	0.938	9.28	1.05
SH36	-35.8159	174.4739	1.584	2.692	51.797	41.955	1.327	0.644	1.141	10.55	2.28
SH37	-35.8155	174.4733	2.592	2.615	43.827	48.657	1.838	0.471	0.945	10.66	1.77
SH38	-35.8157	174.475	0.299	1.570	36.294	57.634	3.783	0.419	0.840	4.36	1.63
SH39	-35.8121	174.4709	16.267	4.643	19.988	53.413	5.228	0.461	0.750	7.68	1.52
SH40	-35.8124	174.4729	5.784	1.778	28.813	60.240	2.721	0.664	0.651	7.22	1.42
SH41	-35.812	174.4724	0.474	1.313	25.948	68.654	3.191	0.419	0.805	6.19	2.52
SH43	-35.813	174.4723	1.144	3.506	33.565	57.379	3.863	0.544	0.931	8.83	1.74
SH44	-35.8182	174.4728	0.000	2.390	49.275	45.180	2.229	0.926	1.015	8.37	1.76
SH45	-35.8167	174.4728	7.222	4.418	48.721	38.011	1.067	0.561	1.119	10.89	1.82
SH46	-35.8102	174.4745	0.301	0.833	33.392	64.374	1.010	0.089	0.607	8.83	1.32
SH47	-35.8119	174.4731	4.276	2.344	32.288	58.321	2.375	0.396	0.884	6.08	1.01
SH48	-35.8143	174.4703	10.411	3.311	21.340	60.231	3.750	0.957	0.930	6.65	1.42
SH49	-35.8125	174.4723	1.062	1.036	24.967	68.313	4.250	0.372	0.699	7.68	1.53
SH50	-35.8193	174.474	0.580	12.310	72.197	12.816	1.056	1.041	1.192	13.76	2.74
SH51	-35.811	174.4741	0.135	1.290	34.091	61.190	2.735	0.559	0.667	5.96	1.06
SH52	-35.8195	174.4731	2.855	6.970	68.990	19.064	1.050	1.071	0.923	7.34	1.33
SH53	-35.8124	174.4745	0.318	1.049	42.411	54.820	1.296	0.106	0.688	5.96	0.86

Site	Lat	Long	% Gravel	% Coarse Sand	% Medium Sand	% Fine Sand	% Very Fine Sand	% Silt/Clay	% organics	chla microg/ g sediment	phaeo microg/ g sediment
SH55	-35.8184	174.4759	2.487	12.309	69.184	14.003	1.442	0.577	1.064	4.81	2.28
SH56	-35.8197	174.4743	1.436	6.058	75.304	15.596	1.022	0.584	0.808	6.88	1.43
SH57	-35.8105	174.4727	16.308	1.792	18.616	57.975	4.144	1.165	1.072	4.24	2.20
SH58	-35.8195	174.4756	34.836	8.539	36.217	18.618	1.382	0.408	1.208	4.30	2.84
SH59	-35.8202	174.4741	41.067	4.252	34.651	18.277	1.417	0.336	1.692	4.18	3.08
SH60	-35.8202	174.4748	7.818	9.164	52.778	28.007	1.947	0.286	1.377	4.13	3.59
SM01	-35.81	174.4703	23.622	4.821	18.876	49.497	2.736	0.447	1.081	5.73	2.36
SM02	-35.8098	174.4728	6.465	2.619	19.394	66.939	4.064	0.518	1.563	6.19	2.72
SM03	-35.8163	174.4698	7.103	5.520	23.583	57.546	4.330	1.918	1.507	na	na
SM04	-35.8198	174.4761	17.234	9.376	49.191	22.561	1.216	0.422	1.278	4.30	2.80
SM05	-35.8118	174.4698	8.901	5.080	18.689	61.375	5.176	0.779	1.144	6.53	2.17
SM06	-35.8076	174.4696	0.856	2.454	19.630	71.875	4.676	0.509	0.970	na	na
SM07	-35.8085	174.4683	4.554	24.365	41.884	26.255	2.138	0.805	1.206	3.72	1.47
SM09	-35.8093	174.4734	10.255	3.153	35.406	48.744	2.165	0.277	0.861	6.02	2.52
SM11	-35.8081	174.4739	0.344	1.633	34.550	60.855	2.180	0.440	0.961	11.69	0.92
SM12	-35.8147	174.4755	1.081	1.600	59.456	34.539	2.951	0.374	1.338	4.76	2.22
SM13	-35.8089	174.4704	3.923	2.656	24.379	64.374	3.401	1.266	1.517	4.70	2.94
SM14	-35.8181	174.477	3.766	9.123	60.449	24.092	1.672	0.897	1.190	5.39	4.39
SM15	-35.8128	174.4696	7.188	4.339	19.190	64.587	3.192	1.504	1.094	na	na

Appendix C Bivalve size distributions from 42 site survey of Whangarei Harbour

	Austrovenus stutchburyi						*Macomona liliana*						*Paphies australis*					
Site	**<5 mm**	**Std Error**	**5 to 20 mm**	**Std Error**	**>20 mm**	**Std Error**	**<5 mm**	**Std Error**	**5 to 20 mm**	**Std Error**	**>20 mm**	**Std Error**	**<5 mm**	**Std Error**	**5 to 20 mm**	**Std Error**	**>20 mm**	**Std Error**
1	2	2	1	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1
2	1	1	0	0	0	0	0	0	0	0	0	0	2	2	3	2	0	0
3	5	3	3	2	1	1	0	0	0	0	0	0	5	5	1	1	1	0
4	1	1	0	0	0	0	0	0	0	0	0	0	9	3	1	1	2	2
5	2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
6	3	2	2	2	3	1	1	0	2	1	0	0	0	0	0	0	0	0
7	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1
8	1	0	7	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0
9	2	1	2	1	2	1	0	0	0	0	0	0	9	6	2	2	0	0
10	0	0	7	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0
11	3	2	1	1	4	3	0	0	0	0	1	1	0	0	0	0	0	0
12	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
13	1	0	0	0	3	1	1	1	2	1	1	0	0	0	0	0	0	0
14	0	0	1	0	0	0	1	0	2	1	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	1	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
20	2	1	0	0	1	1	1	0	0	0	2	1	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	1	0	3	1	1	1	1	0	1	0	3	1	0	0	0	0	0	0
24	2	1	0	0	0	0	0	0	0	0	0	0	6	4	0	0	0	0
25	1	1	0	0	0	0	0	0	0	0	0	0	7	3	2	0	2	1
26	0	0	0	0	4	2	0	0	0	0	0	0	22	20	0	0	0	0
27	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	2	1
28	5	4	0	0	10	4	1	0	0	0	0	0	0	0	0	0	0	0
29	5	3	1	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	7	4	0	0	1	0
32	1	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0	0

	Austrovenus stutchburyi						*Macomona liliana*						*Paphies australis*					
Site	**<5 mm**	**Std Error**	**5 to 20 mm**	**Std Error**	**>20 mm**	**Std Error**	**<5 mm**	**Std Error**	**5 to 20 mm**	**Std Error**	**>20 mm**	**Std Error**	**<5 mm**	**Std Error**	**5 to 20 mm**	**Std Error**	**>20 mm**	**Std Error**
34	3	2	1	1	4	1	1	1	1	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	27	12	5	3	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	2	1	6	3	0	0
37	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
40	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0	0
41	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
42	0	1	0	0	3	1	3	2	0	0	1	0	0	0	0	0	0	0