Risks to Estuarine Biota Under Proposed Development in the Whitford Catchment

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Risks to Estuarine Biota under Proposed Development in the Whitford Catchment

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Contents

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1 Executive Summary

NIWA was commissioned by Manukau City Council and Auckland Regional Council to "*address the issue of risk to the ecology of the Mangemangeroa, Turanga and Waikopua estuaries and the wider coastal embayment, from sediment runoff from the surrounding catchment during the earthworks phase of potential rural development scenarios.*" Ecological effects are addressed, with particular focus on the burial of benthic biota by sediment from the catchments.

Two proposed development scenarios were identified, based on the current subdivision rules of the Manukau Operative District Plan. Under Scenario 1, the current subdivision rules in Chapter 12 'Rural Areas' of the Manukau District Plan 2002 were applied, as they relate to the four different rural zones (Rural 1 – 4 zones) included in the Whitford Catchment. Scenario 2 applied the current subdivision rules in Chapter 12 'Rural Areas' of the Manukau District Plan 2002 as they relate to the Rural 2, Rural 3 and Rural 4 zones within the Whitford Catchment. However, in Scenario 2 the Rural 2 rules (average lot size of 4 hectares) were applied to all of the Rural 1 zoned land included in the Study.

The study was divided into 4 interlinking components. 1) A computer model of the Whitford catchment was used to predict freshwater inflows and sediment runoff to the three tributary estuaries. 2) A second computer model was used to predict the fate of sediment in the estuary/embayment system. 3) An ecological survey was carried out to determine the abundance and diversity of the bottom-dwelling organisms (e.g., shellfish) present in the Whitford embayment and tributary estuaries. Existing knowledge of species sensitivity to terrestrial sediment deposition was also collated. 4) Using the output from these components, the risk of ecologically damaging sedimentation occurring during the earthworks phase of development was estimated for the two proposed development scenarios and compared against existing land use.

The main points arising from the initial study components are:

- There are a total of 431 and 1044 potential new house sites (in addition to 5.4 km and 15 km of new roads) under Scenarios 1 and 2, respectively. In any one year, 54 and 174 houses (plus 0.9 km and 2.5 km of new roads) will be developed under Scenarios 1 and 2, respectively.
- Predicted mean annual sediment input to the Whitford embayment under the Existing land use is about 9000 tonnes/year. This is predicted to increase by 15% under Scenario 1, and by 47% under Scenario 2. The increases under the development scenarios reflect the density of new housing and extent of new roads during the modelled stage of development.

- The model predicts sediment yield from bare earth exposed by earthworks to be 10 to 100 times greater than that from the Existing land use.
- The amount of sediment runoff, delivered to the tributary estuaries during storms, is the major factor governing the thickness of sediment deposition. Wind is the primary factor governing the distribution of sediment throughout the embayment.
- Results from the ecological survey indicate that the Whitford embayment has a diverse range of habitats which enhance its ecological and recreational value. Areas of high ecological diversity include the main intertidal sandflats of the Whitford embayment. The entrance areas of the Mangemangeroa, Turanga and Waikopua estuaries are dynamic environments and may be viewed as ecological transition zones between different habitat types. They are also likely to be particularly sensitive to sediment impact as these communities contain a high proportion of sensitive species.

The main points arising from the risk analysis are:

- The analysis is designed to assess risk over the discrete period of the earthworks phase of potential development. The risk of sediment damage to the ecological diversity is compared between the existing land use and two proposed development scenarios. The analysis was performed on six regions within the Whitford embayment and the tributary estuaries, selected with regard to biological and physical characteristics.
- For each region, a graph is presented showing the expected annual frequency (number of times per year) that various thicknesses of sediment deposition will be exceeded. Also shown on these graphs is the corresponding expected change in biodiversity.
- Scenario 1 and Scenario 2 proposed land use options deliver more sediment to the embayment than the Existing land use (Existing < Scenario 1 < Scenario 2). All sediment thresholds are therefore exceeded more frequently under Scenario 1 and Scenario 2 than under the Existing land use. In some cases, the predicted percentage increase in risk associated with changing the land use from Existing to Scenario 1 or Scenario 2 can be quite high.
- All of the deposition thresholds will be exceeded most frequently near the source of sediment inflow, i.e., where the streams enter the tributary estuaries of the Whitford embayment, and within the tributary estuaries themselves. Under Existing land use, approximately 4 times each year, sediment deposition in these upper reaches is expected to exceed 1 mm for over 1% of the area of the region, in the aftermath of a rain storm.
- Most likely to experience significant loss of taxa are the shallow intertidal regions of the embayment and the entrances to the tributary estuaries. For example, an event causing >10% reduction in biological diversity over 1% of the area is predicted to occur just less than once per year under the Existing land use, just more than once a year under Scenario 1 and 1.5 times a year under Scenario 2 (approximately a 50% increase over both the Existing land use and Scenario 1).
- The outer embayment presents the least risk of ecological damage.

The analysis indicates that ecologically damaging sediment deposition events are already occurring quite frequently in the Whitford tributary estuaries and inner embayment. Sediment

cores confirm that sedimentation in the upper reaches of the tributary estuaries has been rapid in recent decades. Although there is no corresponding historical ecological data, it is likely that the estuary and embayment ecology has been degraded since early European times.
Compared to the Existing land use, the frequency (and therefore risk) of an ecologically damaging sedimentation event occurring during the earthworks phase of potential rural development is expected to increase under Scenario 1, and increase further still under Scenario 2.

It is likely that the implementation of land management measures can reduce sediment run-off and, therefore, may lead to a decrease in the deposition of sediment in the tributary estuaries and embayment. These measures may be implemented in the short term, being applicable to the earthworks phase of development, or, applied in the longer term once development is complete. Potential on-site mitigation measures for the earthworks phase of development include restricting the amount of bare-earth exposed, use of hay bales and silt fences, and seasonal restrictions upon earthworks with earthworks stabilisation in the off-season. Longer-term catchment-wide measures include tree planting upon erosion prone slopes, stock exclusion, and riparian retirement. A previous modelling study at Okura predicted that short term on-site measures would reduce sediment input to the estuary, during the earthworks phase of development, by 19 to 63%, depending upon the combination of measures adopted. However, the efficiency of control measures was shown to be highly dependent upon the size of rainfall event. During very large events, which deliver much of the sediment load to the estuary, efficiency was relatively low. It is not possible to extrapolate results from the Okura study and thereby predict the reduction in ecological risk that may result from using on-site controls within the Whitford catchment. This is because the efficiency of control measures is strongly dependent upon soil type and slope angle, which differ between the Okura and Whitford catchments. The hydrodynamics of the Okura and Whitford estuaries are also fundamentally different, particularly in terms of the wave and current patterns that disperse sediments throughout the estuaries.

Finally, it is important to remember that the risk analysis used in this study requires significant simplification and loss of information. A number of important cautionary points are presented.

2 Introduction

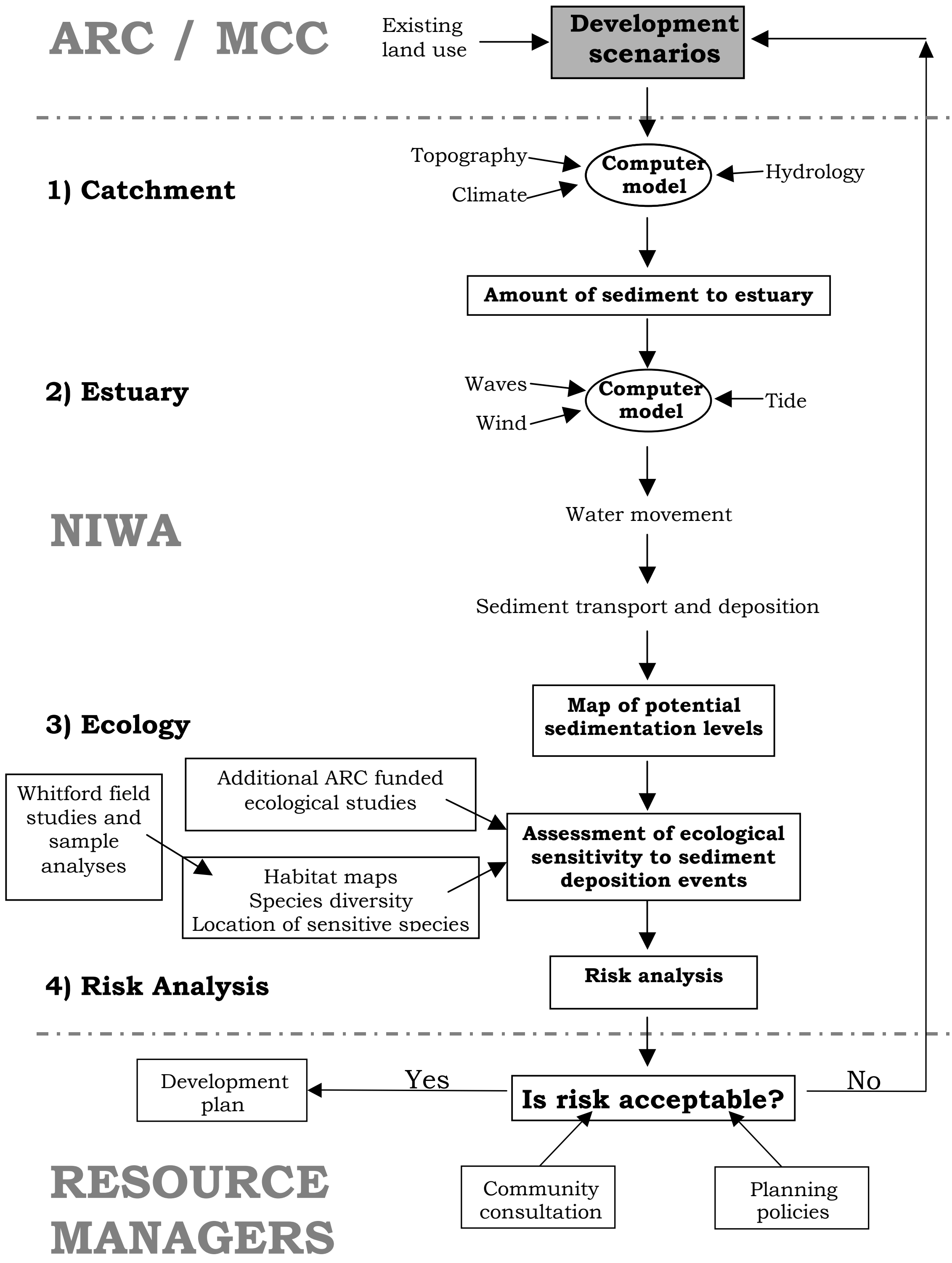
NIWA was commissioned by Manukau City Council and Auckland Regional Council to "address the issue of risk to the ecology of the Mangemangeroa, Turanga and Waikopua estuaries and the wider coastal ('Whitford') embayment, from sediment runoff from the surrounding catchment during the earthworks phase of potential rural development scenarios." Ecological effects are addressed, with particular focus on the burial of benthic biota by sediment of terrestrial origin, to a depth that causes significant mortality or changes to their abundance.

Two proposed development scenarios were identified, based on the current subdivision rules of the Manukau Operative District Plan. Under Scenario 1, the current subdivision rules in Chapter 12 'Rural Areas' of the Manukau District Plan 2002 were applied, as they relate to the four different rural zones (Rural 1 – 4 zones) included in the Whitford Catchment. Scenario 2 applied the current subdivision rules in Chapter 12 'Rural Areas' of the Manukau District Plan 2002 as they relate to the Rural 2, Rural 3 and Rural 4 zones within the Whitford Catchment. However, in Scenario 2 the Rural 2 rules (average lot size of 4 hectares) were applied to all of the Rural 1 zoned land included in the Study.

The Whitford embayment is located between Howick and Beachlands, within the Auckland region. Its three tributary estuaries (Mangemangeroa, Turanga and Waikopua) drain the surrounding catchment and the embayment opens out into the Tamaki Strait to the north.

The study was divided into 4 interlinking components, illustrated in Figure 2.1. A computer model (described in Section 3 of this report) of the Whitford catchment was used to predict freshwater inflows and sediment runoff to the three tributary estuaries, for the existing land use and two proposed development scenarios. A second computer model, this time of the estuary/embayment system, was used to predict the transport, dispersion and deposition of the terrestrial sediment by tidal currents, waves and wind-driven currents (Section 4). An extensive ecological survey was also carried out to determine the abundance and diversity of the benthic fauna communities present in the Whitford embayment and tributary estuaries. Existing knowledge of species sensitivity to terrestrial sediment deposition from laboratory and field experiments was also collated (Section 5). Using the output from these components, the risk of ecologically damaging sedimentation occurring during the earthworks phase of development was estimated for the two proposed development scenarios and compared against existing land use (Section 6).

Figure 2.1: Flow diagram of the approach used within this report to study ecological effects of proposed land development on the Whitford embayment and tributary estuaries.



3 Catchment Modelling

The objective of this component of the study was to predict the effect of potential rural intensification in the Whitford catchment upon sediment loads to the estuary. The modelling focused upon the earthworks phase of development since this is when most sediment loss is likely to occur. The daily predictions of catchment sediment loss are fed to the estuary hydrodynamic model (Section 4), which simulates sediment transport and deposition in the estuaries and wider embayment.

Our approach was to use a computer simulation model called WAM (Watershed Assessment Model). WAM was developed by Soil and Water Engineering Technology (Gainesville, Florida) in association with Mock, Roos and Associates (West Palm Beach, Florida). This model is an upgraded version of the initial Basin-New Zealand model developed by Cooper and Bottcher (1993). A description of WAM can be found in Bottcher et al. (1998) and some previous applications viewed at www.swet.com. In New Zealand, WAM (or its variants) have been used to address a variety of environmental issues: predicting the effects of riparian retirement on sediment and nutrient loads at Rotorua (Cooper and Bottcher 1993); predicting the effects of land use on nitrogen loss to Lake Taupo (Elliott et al. 2000); predicting the effects of rural intensification options on sediment loads to Okura estuary (Stroud et al. 1999a, b).

3.1 Model Description

WAM (Figure 3.1) uses a rasterised representation of a catchment whereby uniform grid cells (of a user-defined size) are assigned the dominant land use, slope angle and soil type at that location in the catchment. Incorporated within WAM is a field-scale physically based model GLEAMS (Knisel 1993) which predicts daily hydrological and sediment losses for each cell. GLEAMS calculates a daily water balance proportioning rainfall between surface runoff, storage in the soil profile, evapotranspiration, and percolation below the root zone.

WAM delivers grid cell surface runoff to the nearest receiving stream reach based upon flow distance. The distance is used to calculate the fraction of surface flow that is delivered to the stream reach in each time step following a runoff event. The distance to delay-time relationship for surface runoff delivery is based on the time of concentration and potential surface storage using a standard triangular hydrograph approach. A similar approach is used to delay delivery of sub-surface flow generated in each cell to the stream, assuming an exponential recession curve.

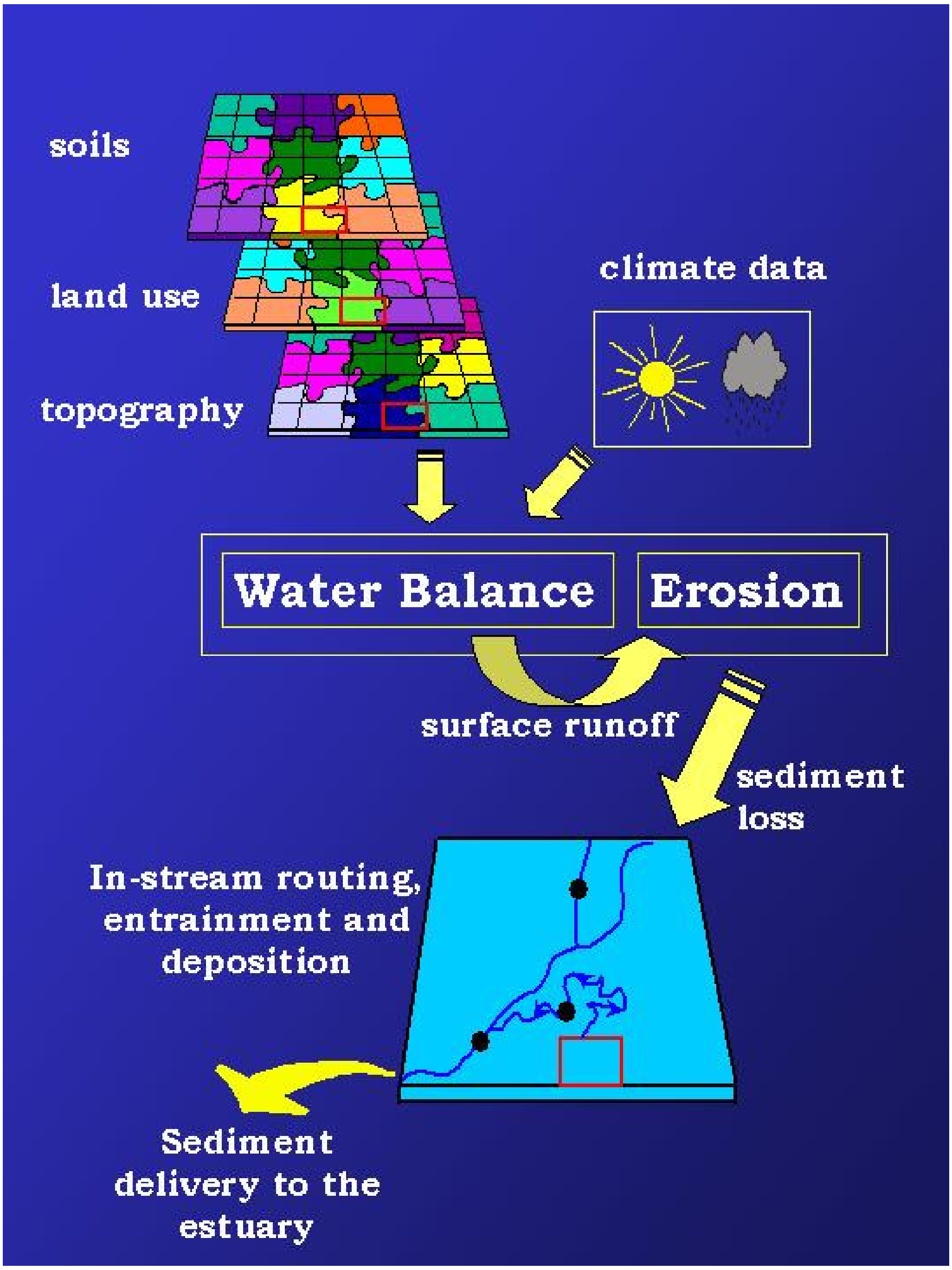
Once in-stream, water is routed through the reach network using a modified linear reservoir routing technique for solving the equations of uniform channel flow. These equations are solved for each reach using a variable time step that is based on stream velocity.

In addition to the routing of water, WAM simulates the routing and fate of sediment from the land surface to, and down, the stream network. Predictions of surface runoff are coupled with the soil, vegetation and slope properties of each cell to calculate particle detachment, and hillslope sediment transport and deposition. This component of the model uses standard equations for sediment transport capacity. In addition, attenuation of sediment in ponds, wetlands and riparian buffer strips is accounted for. Processes of sheetwash and rill erosion are represented but soil loss from mass movement (e.g., landslips) is not. However, reference to aerial photography of the Whitford catchment (scars are easily identified on aerial photos) shows that landslips are not a significant source of sediment.

Within the stream network, a sub-model uses hydrological routing information to predict the net sediment balance for each stream reach, for each time step, based upon predicted flow, a velocity-dependent erosion term, and a deposition term dependent upon settling velocity, retention time and mean water depth.

WAM for Whitford has been established using a 25 × 25 metre grid, providing the scale necessary to adequately represent the terrain and the earthworks associated with individual site developments and road construction during rural intensification.

Figure 3.1: The WAM Model Structure.



3.2 Model input data

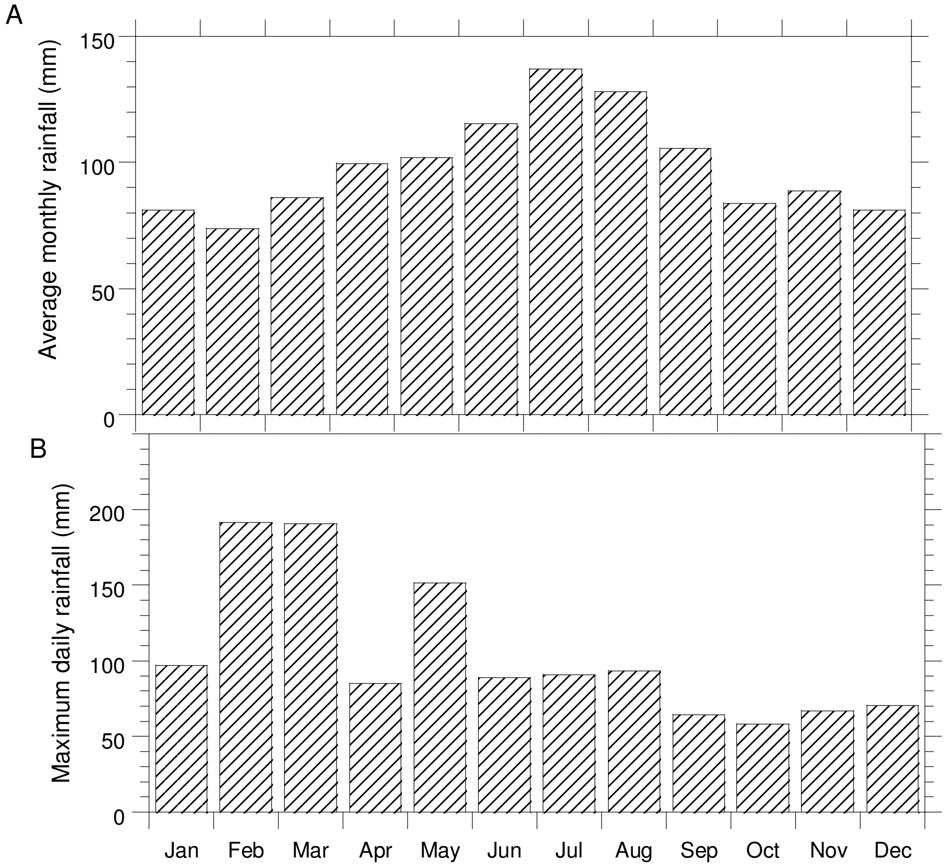
3.2.1 Climate

The climate data required by the model are daily rainfall (cm), mean monthly daily maximum and minimum temperatures (°C), mean monthly daily radiation (MJ/m2/day) and mean monthly daily wind speed (km/day). These climate data were obtained from NIWA's climate database for the years 1963 to 2001 inclusive. Model output from the initial year (1963) was discarded since the model requires a few months of simulation to initialise.

Daily rainfall data were obtained from Cockle Bay (site C64991) from 1963 when the station opened until August 1999 when the station closed and from Ardmore (site C7409) from September 1999 to 2001. Gaps in the rainfall record were filled using the accumulated rainfall total recorded over the gap period and rainfall records from the nearest sites. Other climate data are required on a mean monthly basis. Temperature data were obtained from the Otara site (C64981) from 1963 to July 1986 (when the station closed) and from the Ardmore site from August 1986 to 2001. Radiation data were obtained from Auckland Airport (C74082) for the whole period. Wind data required by the model were obtained from numerous sites in the Auckland area depending on availability of data (Auckland Albert Park A64871, Otara C64981, Hunua C75003, Mangere C64971, Wiri C64985). Gaps in the temperature, radiation and wind data were filled by long-term monthly average values.

Average annual rainfall for the area from the combined Cockles Bay and Ardmore rainfall record (1963 to 2001) is 1189 mm per year with a minimum total of 838 mm and a maximum of 1588 mm. Thus, on a long term basis the soil moisture status will show considerable variability and, therefore, the catchment's hydrological response to a particular sized rainfall event (or sequence of events) may be expected to vary. The rainfall is unevenly distributed through the year, with the highest monthly rainfalls occurring from April to September (Figure 3.2 a). Nevertheless, large rainfall events can occur outside this period, particularly rain associated with cyclones arriving in February and March (Figure 3.2 b).

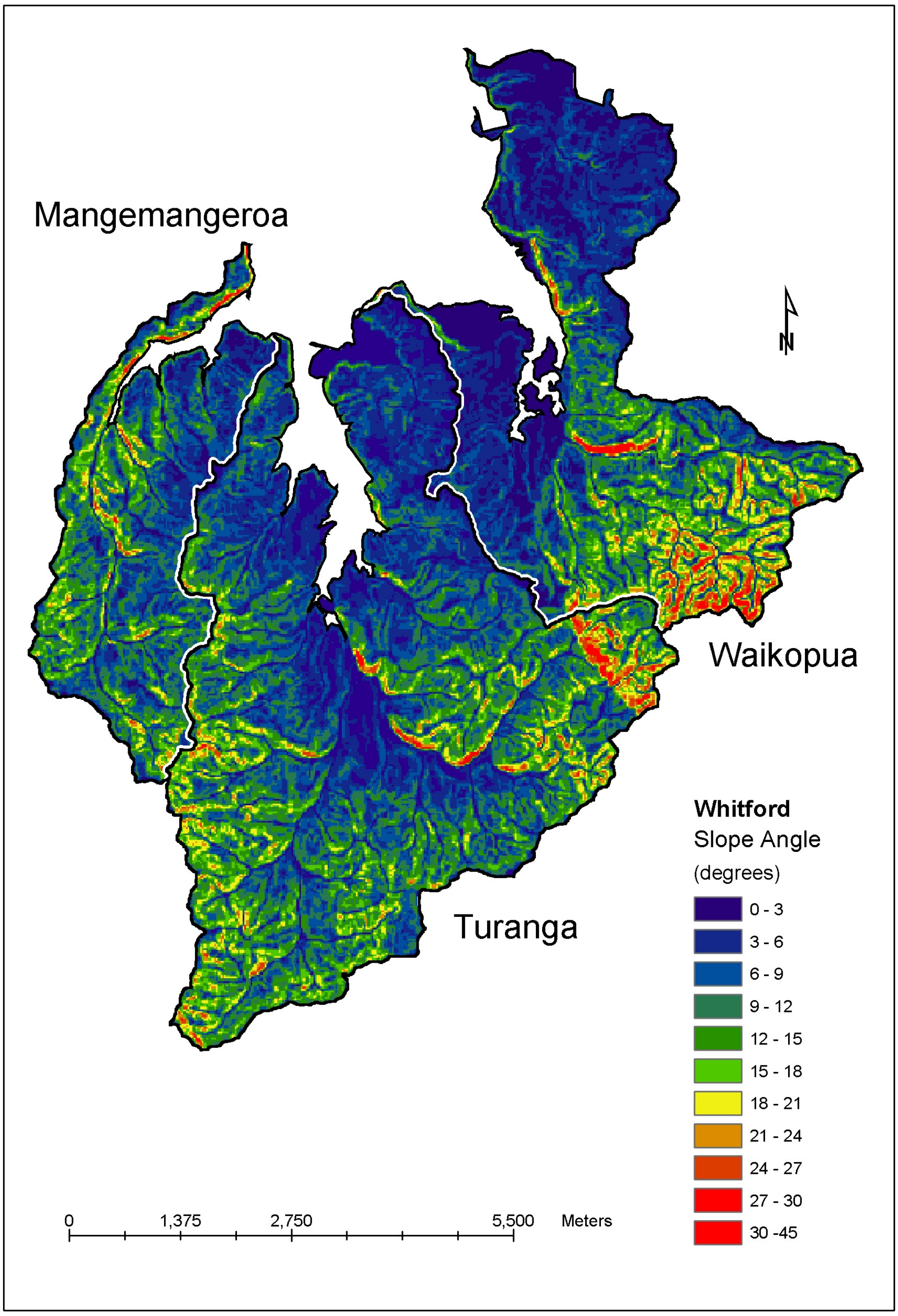
Figure 3.2: Rainfall characteristics for Whitford. (A) mean monthly rainfall; (B) maximum daily rainfall for each month. Data taken from combined Cockle Bay and Ardmore record 1963 to 2000 inclusive.



3.3 Topography

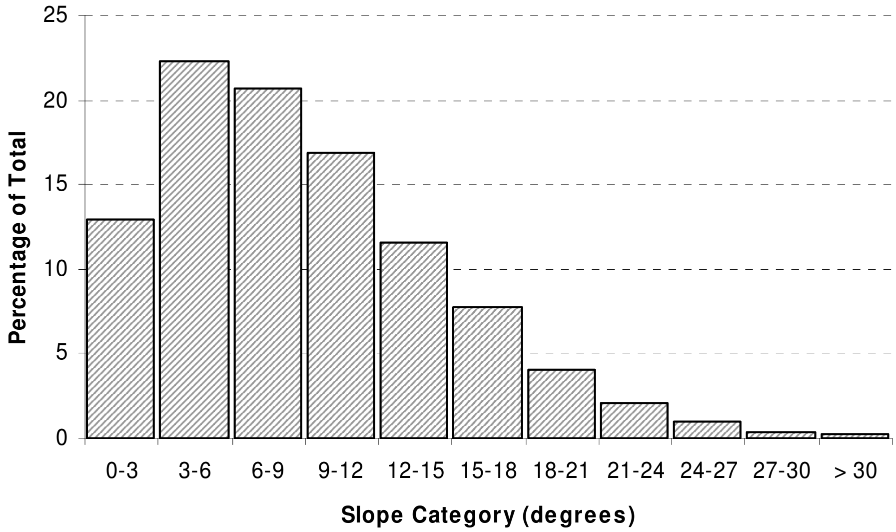
A Geographical Information System (GIS) was used to derive a digital elevation model (DEM) using digital maps of 5 metre contours, spot heights and streams supplied by Manukau City Council. From the DEM, the slope angle for each cell was determined. The cell slopes were arbitrarily grouped in intervals of 3 degrees and the spatial distribution of these groups used as input to WAM (Figure 3.3). Most of the hill slopes in the catchment are classified as undulating (4 – 7 degrees) or rolling (8 – 15 degrees) but some steeper areas do occur. The frequency distribution of the slope classes is shown in Figure 3.4.

Figure 3.3: Slope angle in the Whitford catchment. The three subcatchments, Waikopua, Turanga and Mangemangeroa are delineated.



The DEM was also used to generate catchment boundaries for Whitford and its three subcatchments; Waikopua, Turanga and Mangemangeroa (Figure 3.3). These three were furthered subdivided into 22, 22 and 13 subcatchments respectively, each with an associated reach. The subcatchments are used in WAM for routing sediment through the reach network and the model provides predictions of flow and sediment concentration at the outlet of each subcatchment.

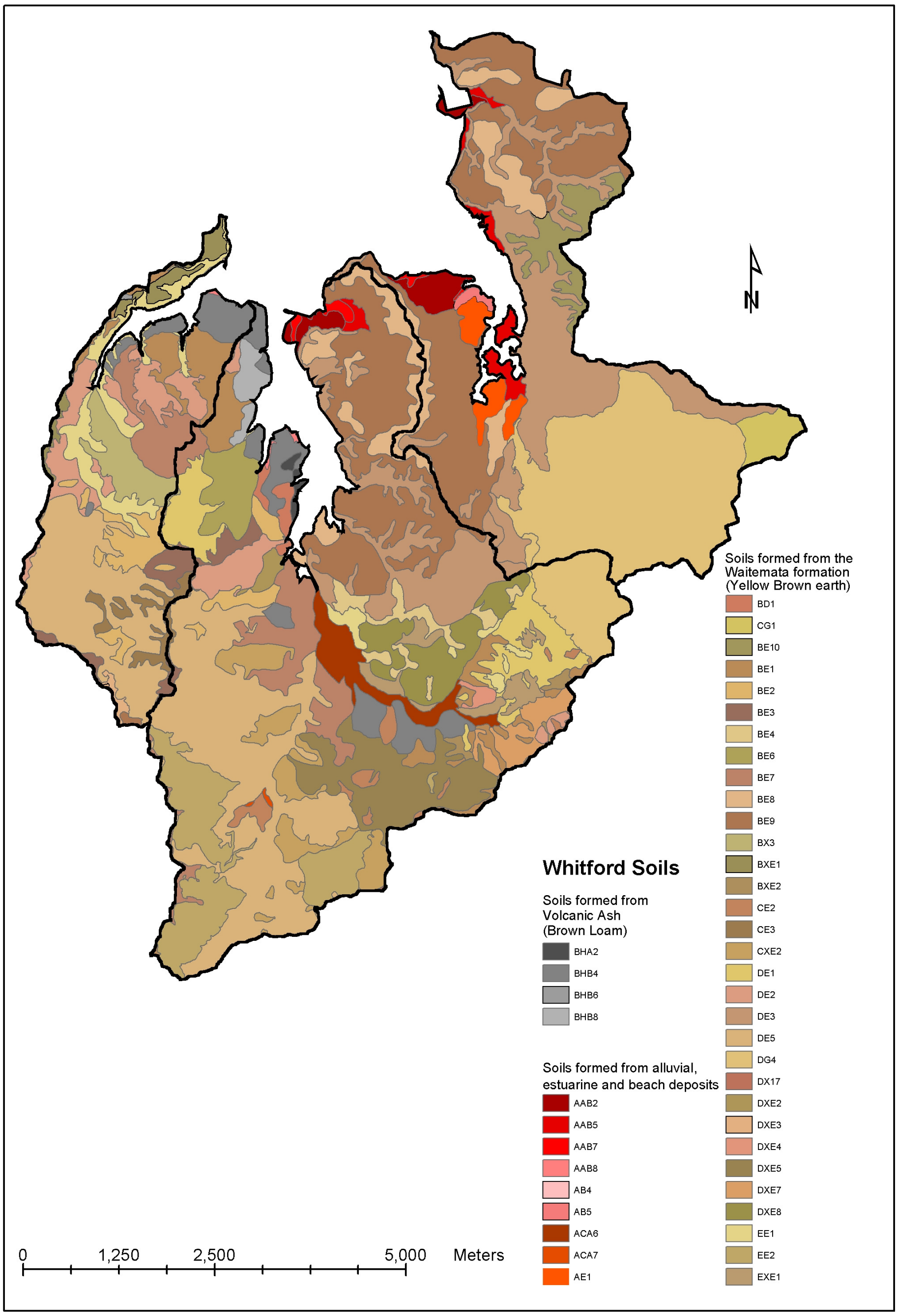
Figure 3.4: Frequency distribution of model slope classes in the Whitford catchment.



3.4 Soils

Soils information for the catchment was obtained from existing databases held by Landcare NZ (mostly the soil survey and accompanying 1:20,000 soil map carried out for Manukau City by the DSIR in 1979) and, where required, interpreted for use in the model by Malcolm McLeod (Soil Scientist, Landcare Research, Hamilton). The spatial pattern of soil types is shown in Figure 3.5.

Figure 3.5: Soils of the Whitford catchment (Provided by Landcare Research, Hamilton).

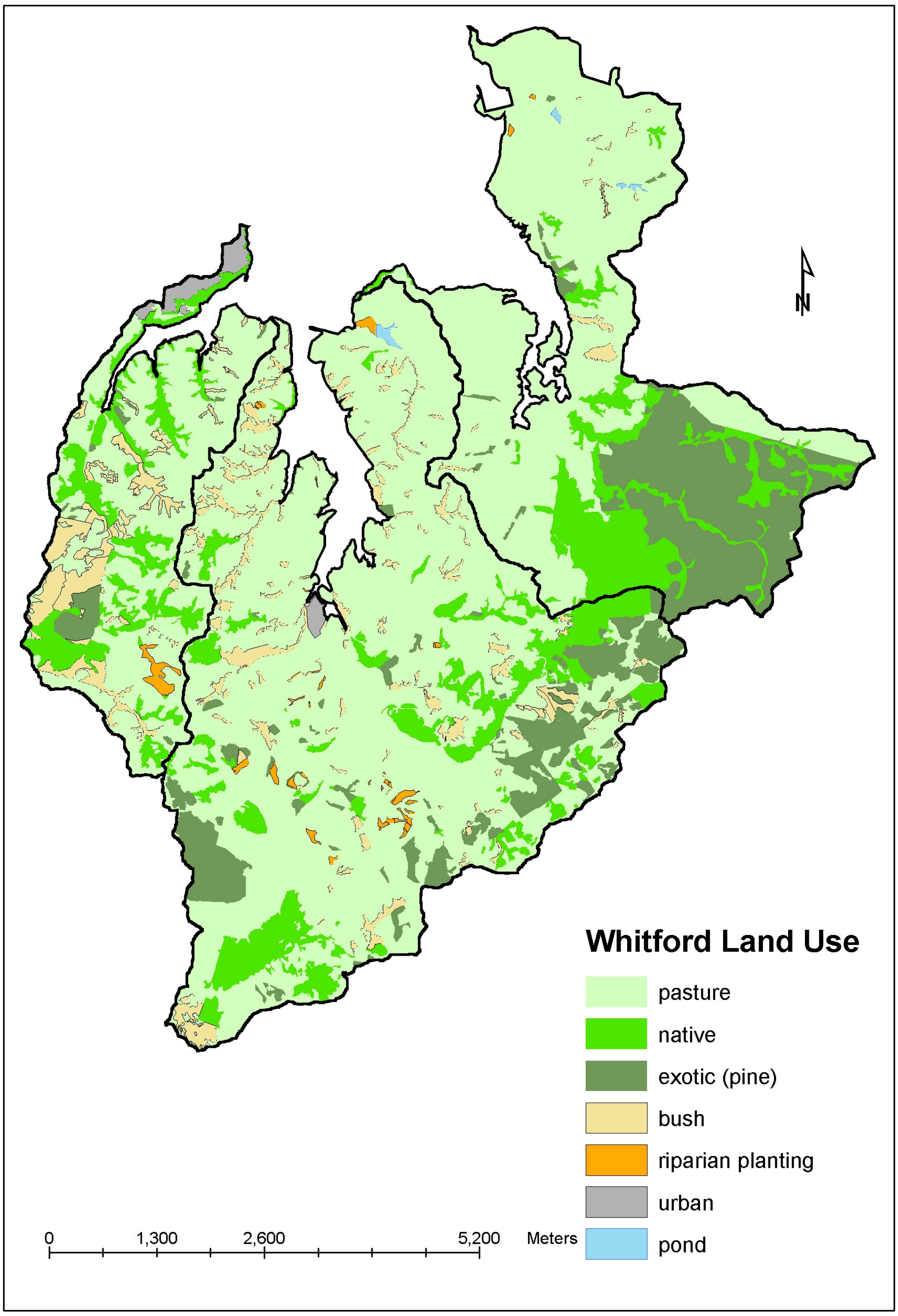


Most of the soils in the catchment are brown clays derived from erodible sandstone and mudstone parent materials known as the Waitemata formation. However there are also soils formed from volcanic ash deposits and small areas of coastal sandy soils derived from estuarine or beach deposits. Most of the soils are imperfectly, poorly or very poorly drained due to a clay-dominated subsoil that restricts water movement. This restrictive layer may underlie a more freely draining silt-clay topsoil and occurs at quite shallow depths (0.2 to 0.6 metres). The ability of these soils to either rapidly transfer incoming rainfall to groundwater or to store it within the soil profile is therefore limited, rendering them susceptible to saturation and transfer of excess water by surface runoff. During the earthworks phase of site development topsoil is generally removed exposing clay-dominated subsoil and this practice was simulated in the modelling. Because subsoil clay has little organic matter associated with it, it is easily detached from the soil surface and entrained within surface runoff. The fine particle size suggests that once particle detachment occurs, transport across the land and through the stream network would generally be efficient.

3.4.1 Existing Land Use

The existing land use data for the catchment was obtained from a digital orthophoto (pixel size 1 m) taken in March 2000, along with information supplied by catchment residents, the land cover database (a classification of land cover with a minimum mapping unit of 1 hectare) and visits to the catchment. The digital orthophoto was also used to map existing wetlands, riparian buffer zones and ponds and this information was incorporated in the model. Whilst the catchment is currently characterised by predominantly pastoral land, numerous small pockets of native and exotic (pine) forest are present. In the headwaters of the Waikopua subcatchment, native and exotic trees are found extensively (Figure 3.6).

Figure 3.6: Whitford Existing (current) land use.



3.4.2 Future Land Use

Two potential future rural intensification scenarios (Scenarios 1 and 2) were identified by the resource management agencies for the Whitford catchment – Manukau City Council (MCC) and Auckland Regional Council (ARC). The location of all proposed development (housing and roads) under each scenario was provided by MCC, thus providing the number of proposed house developments in each land parcel. The development information is summarised in Tables 3.1 and 3.2, and the location of housing under Scenario 2 is illustrated in Figure 3.7.

Under Scenario 1, rural residential development is based upon the current subdivision rules of the Manukau Operative District Plan. Therefore, applicable subdivision rules were applied to each of the rural zones (1 - 4) located across the Whitford catchment. The subdivision rules were not applied rigorously, as this exercise was only intended to illustrate a broad picture of the existing potential for subdivision within the Whitford Catchment. As such, only the generalized, main development standards were applied to each of the zones. For example, the Rural 1 zone requires that for the creation of rural – residential lots, the existing site must be 20 hectares or more and held in a separate Certificate of Title on 5 June 1989. The Rural 2 zone requires that land be held in a separate Certificate of Title on 5 June 1989. Because it would have been an expensive and time consuming exercise to attain information on Certificate of Titles, the rules were applied using the most current information available. As such, there would have been properties that may or may not be eligible to qualify for subdivision based on the Certificate of Tile criteria. Based on existing information, it was assumed that each lot would not attain the full number of horticultural lots permitted on each site as it would be difficult to approve such lots. Therefore, all land within the Rural 1 zone which had slopes greater than 8 degrees were determined not to be eligible for horticultural lots. Rules relating to Native Bush Lots were also not applied. Also note that the number of lots resulting from this exercise is only an indication of the current potential for development within the Whitford Catchment, rather than an exact figure.

Under Scenario 2, the Rural 2 zone rules are applied to the entire Whitford Catchment Rural 1 area while the balance of the Whitford Catchment's Rural 2, Rural 3 and the Rural 4 zones areas are treated the same as was applied in Scenario 1, i.e., developed to the Operative District Plan capacity for those Zones. Again, the subdivision rules were not applied rigorously, as this exercise was only intended to illustrate a broad picture of the likely development under the application of the Rural 2 rules. Thus, an average lot size of 4 hectare was applied to the entire study area of Rural 1. No account was taken of the Certificate of Title requirement.

Development under Scenario 1 is scheduled to occur over 6, 17 ½, and 5 years in the Mangemangeroa, Turanga, and Waikopua subcatchments, respectively. Development under Scenario 2 is scheduled to take place over a 6-year period in all subcatchments.

For both development scenarios, "no development" areas were identified by MCC. These included public open space, Department of Conservation land, reserves, and Crown land. In addition, MCC advised that 80% of new building sites would be within 100 metres of an existing or proposed road, and on slopes less than 15 degrees. Using a GIS, the proposed development maps were modified to account for these constraints. At some locations, however, it was not possible to site all the proposed development and account for the road and slope constraints. At these locations one or both of the constraints were not applied.

For the type of housing proposed for the development area, the MCC advised that, on average, approximately 0.25 ha of bare earth is exposed per site (this includes house platform, site drainage works, and driveway). In establishing both scenarios, 0.25 ha earthworks sites (4 model grid cells at 25 x 25 m each) were modelled at the location of each randomly chosen house development site. On the MCC's advice, road length was converted to area assuming a 20-metre width of disturbed land. Because it is not MCC's current practice to enforce site-specific controls on building works, no sediment control measures were incorporated within the model for the housing development sites. However, MCC advised that the earthworks associated with new roads would have sediment control measures such as hay bales, silt fences, and bunds or trenches. These were incorporated into the model.

WAM is not able to dynamically simulate changes in land use over time. Instead, a fixed land use is modelled in conjunction with a long-term climate record. This approach required that the MCC identify the number of ongoing house and road developments in the modelled year. This information was provided by MCC at a Project Control Management Group meeting and is summarised in Tables 3.1 and 3.2. The house and road development sites to be modelled were randomly selected from the maps of total proposed development. Checks were conducted to ensure this process introduced no bias to the model predictions.

For the Whitford catchment as a whole, the proposed development under Scenario 2 is greater than that under Scenario 1, with a higher density of housing and roads (Tables 3.1 and 3.2), and a greater amount of ongoing development during the modelled year. At the subcatchment level, however, development in the Mangemangeroa (in contrast to the Waikopua and Turanga) is the same under both scenarios.

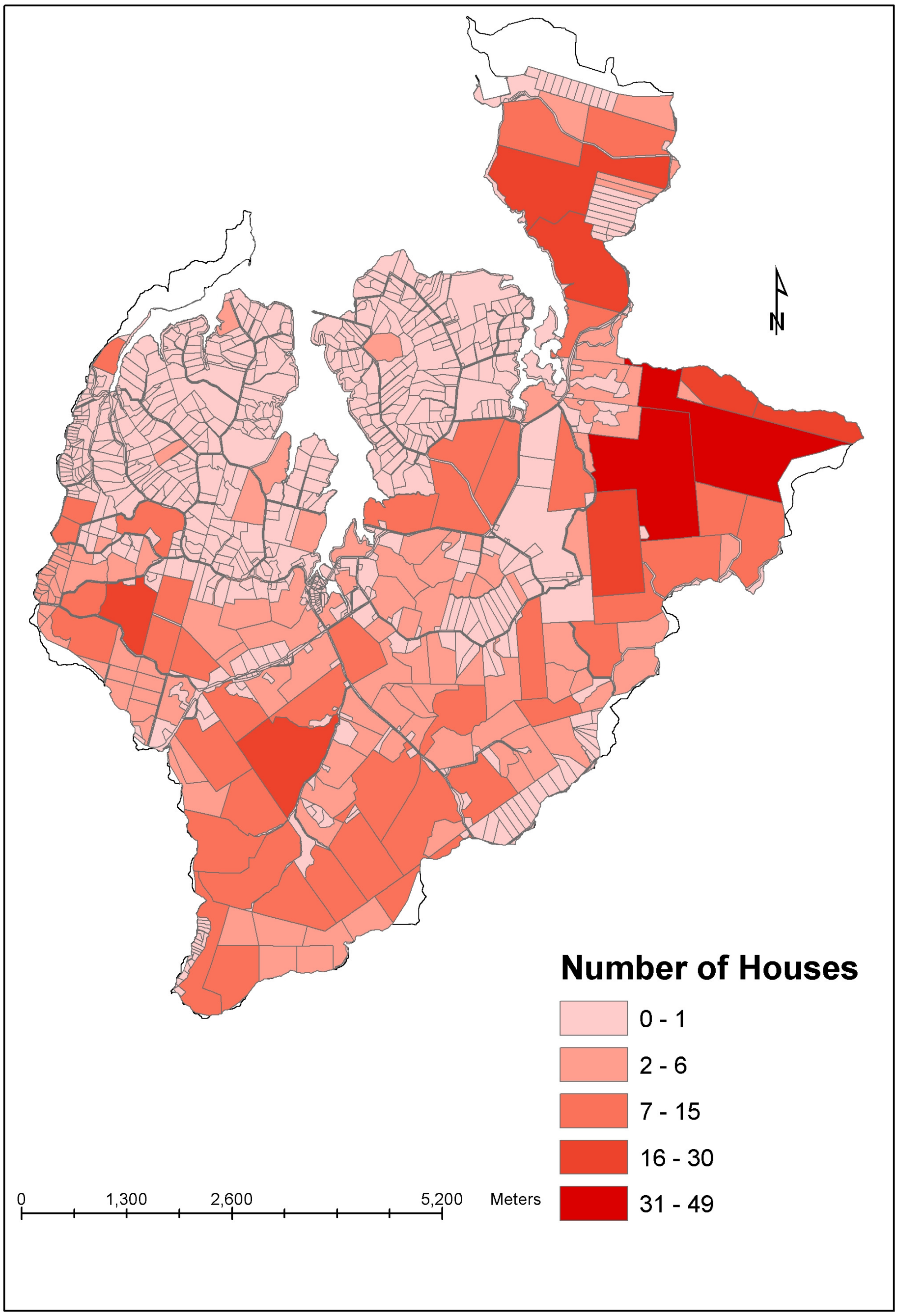
Table 3.1: Description of development under Scenario 1.

	Total number of proposed house developments	Number of ongoing house developments (earthworks sites) in modelled year	Extent of ongoing road development in modelled year (km)	Density of ongoing house developments in modelled year (ha/house)
Waikopua	52	10	0	178
Turanga	175	10	0	310
MMroa	204	34	0.9	28
All Whitford	431	54	0.9	108

Table 3.2: Description of development under Scenario 2.

	Total number of proposed house developments	Number of ongoing house developments (earthworks sites) in modelled year	Extent of ongoing road development in modelled year (km)	Density of ongoing house developments In modelled year (ha/house)
Waikopua	323	54	0.2	33
Turanga	517	86	1.4	36
MMroa	204	34	0.9	28
All Whitford	1044	174	2.5	34

Figure 3.7: Rural intensification under Scenario 2. The numbers on the map indicate the number of proposed house sites in each land parcel.



3.5 Model results

WAM simulations were conducted for the existing land use and both rural intensification scenarios. The model was driven by the long-term climate record (section 3.2.1) and daily predictions provided on a cell, subcatchment and catchment basis.

3.6 Existing Land Use

Predicted mean annual sediment loss, delivered to the estuary, under the current (Existing) land use is presented in Table 3.3. Mean annual sediment loss from the Whitford catchment is about 9000 tonnes/yr, with a specific yield (sediment loss per unit area) of 1510 kg/ha/yr (151 tonnes/km2/yr), a figure that lies within the range (100-3000 kg/ha/yr) typically observed under predominantly pastoral land (e.g., Griffiths 1982, Van Roon 1983, Wilcock 1986, Hicks 1994).

Table 3.3: Predicted sediment loss under the Existing (current) land use.

Catchment	Mean Annual Sediment Loss (tonnes/year)	% of total sediment loss	Mean Annual Sediment Loss (kg/ha/yr)	Catchment Area Ha [% of total]
Waikopua	1553	18	872	1780 [31%]
Turanga	5494	62	1772	3100 [53%]
MMroa	1759	20	1852	950 [16%]
All Whitford	8806	100	1510	5830 [100%]

Differences in specific yield between the subcatchments are attributed to variation in land use, soil type and slope angle. In particular, native and exotic forest found extensively in the headwaters of the Waikopua give rise to a relatively low predicted sediment loss per hectare from this subcatchment. The Turanga contributes the greatest absolute sediment load to the estuary (62%) due to its relatively large area.

Table 3.4 illustrates the range of predicted mean annual sediment loss under bush, pine and pasture, across the Whitford catchment. This range reflects variations in soil type and slope angle, for example, only pine is found on the steepest slopes. Upon the same soil and slope, these predicted losses increase in the following sequence; Pine < Bush < Retired_Pasture < Pasture_Pond < Pasture_Riparian (buffer strip) < Pasture alone.

Table 3.4: The variation in predicted mean annual sediment loss with land use

Land use	Sediment Loss Range t/km^2/yr	[kg/ha/yr]	Slope Range (°)
Pine	0.5 - 250	[5 – 2500]	0 - 36
Bush	0.5 – 100	[5 – 1000]	0 - 18
Retired_Pasture	0.5 - 150	[5 – 1500]	0 - 18
Past_Pond	2.0 – 200	[20 – 2000]	0 - 18
Past_Riparian	3.5 – 200	[35 – 2000]	0 - 12
Pasture	6.5 – 1100	[65 – 11000]	0 - 27

Model validation is provided by observed flow and suspended sediment data derived from instrumentation in the Mangemangeroa stream between July 2000 and April 2002. This monitoring work was conducted under the Foundation for Research, Science and Technology research programme, CO1X0024, Effects of Sediments on Estuarine and Coastal Ecosystems.

Predicted flow volume on days encompassing a storm event correlate well with observed flow (Figure 3.8). Similarly, predicted daily sediment load during events shows a reasonable correlation with observed values (Figure 3.9). These relationships provide confidence in the parameterisation and, therefore, the performance of the model.

Figure 3.8: Relationship between observed and predicted flow volume during storm events in the Mangemangeroa stream.

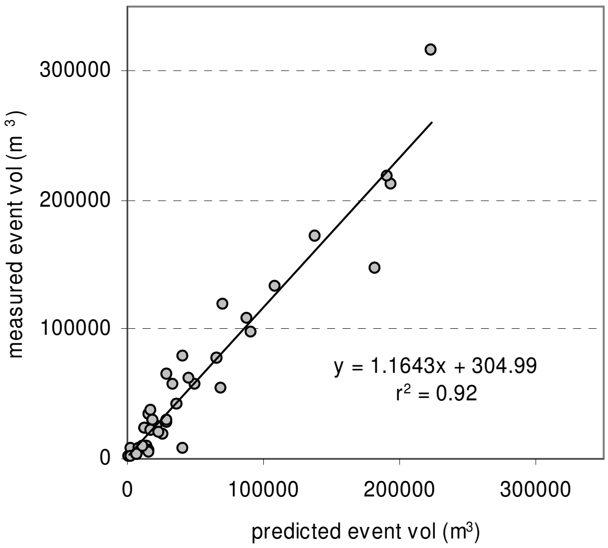
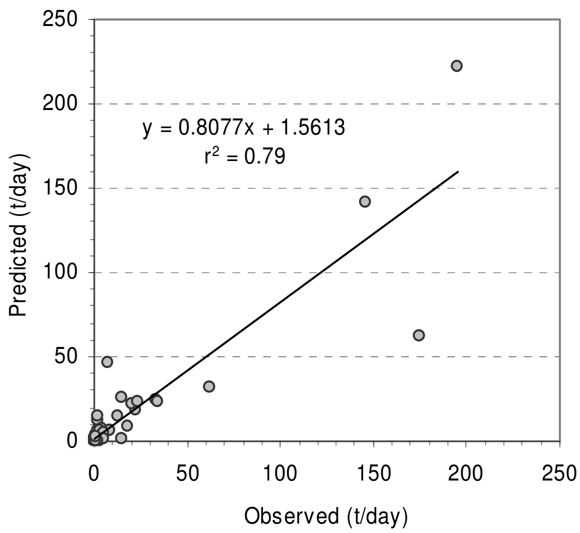


Figure 3.9: Relationship between observed and predicted sediment yield during storm events in the Mangemangeroa stream.



3.6.1 Scenarios 1 and 2

The impact of the scenarios is presented in Table 3.5. Mean annual sediment input to the Whitford embayment is predicted to increase (relative to that under the Existing land use) under Scenario 1 by 1342 tonnes/year (15 %) and, under Scenario 2 by 4157 tonnes/year (47 %). The results reflect the density of proposed new housing and extent of new roads during the modelled stage of development in each subcatchment. The relatively large percentage increase in the Waikopua under Scenario 2 (Table 3.5) reflects, in part, development on land currently forested. Predicted sediment yield from the Mangemangeroa is the same for both scenarios since the proposed development does not vary between scenarios.

Although greater surface runoff is predicted from earthworks sites relative to Existing land uses, at the catchment scale the model predicts flow increases to be negligible under the scenarios.

Table 3.5: Predicted sediment loss under the Existing land use and Scenarios 1 and 2.

Catchment	Existing (tonnes/year)	Scenario 1 (tonnes/year)	Scenario 1 % Increase	Scenario 2 (tonnes/year)	Scenario 2 % Increase
Waikopua	1553	1708	10	2591	67
Turanga	5494	5762	5	7694	40
MMroa	1759	2678	52	2678	52
All Whitford	8806	10148	15	12963	47

Figures 3.10 and 3.11 illustrate mean annual sediment loss from each cell across the catchment under the Existing land use and Scenario 2, respectively. Figure 3.11 highlights substantial yields from bare soil earthworks sites, which range between 2,000 and 39,000 tonnes/km2/yr (20,000 to 390,000 kg/ha/yr). These earthworks yields are 10 to 100 times greater than those from the Existing land use (pasture, bush, forest) and the magnitude of this increase is the same as that reported by Ng and Buckeridge (2000) in a review of sediment yields from construction sites across the Auckland region. The wide variation in predicted sediment yield from earthworks is attributed to variation in soil type and slope angle. For example, mean annual sediment yield from a clay soil of relatively low erodibility ranges from 8000 kg/ha/yr on a 3° slope to 120,000 kg/ha/yr on a 12° slope. In contrast, sediment yield from a clay soil with a relatively high erodibility ranges from 18,000 kg/ha/yr on a 3° slope to 220,000 kg/ha/yr on a 12° slope.

Figure 3.10: Predicted mean annual sediment loss from each grid cell under the Existing land use.

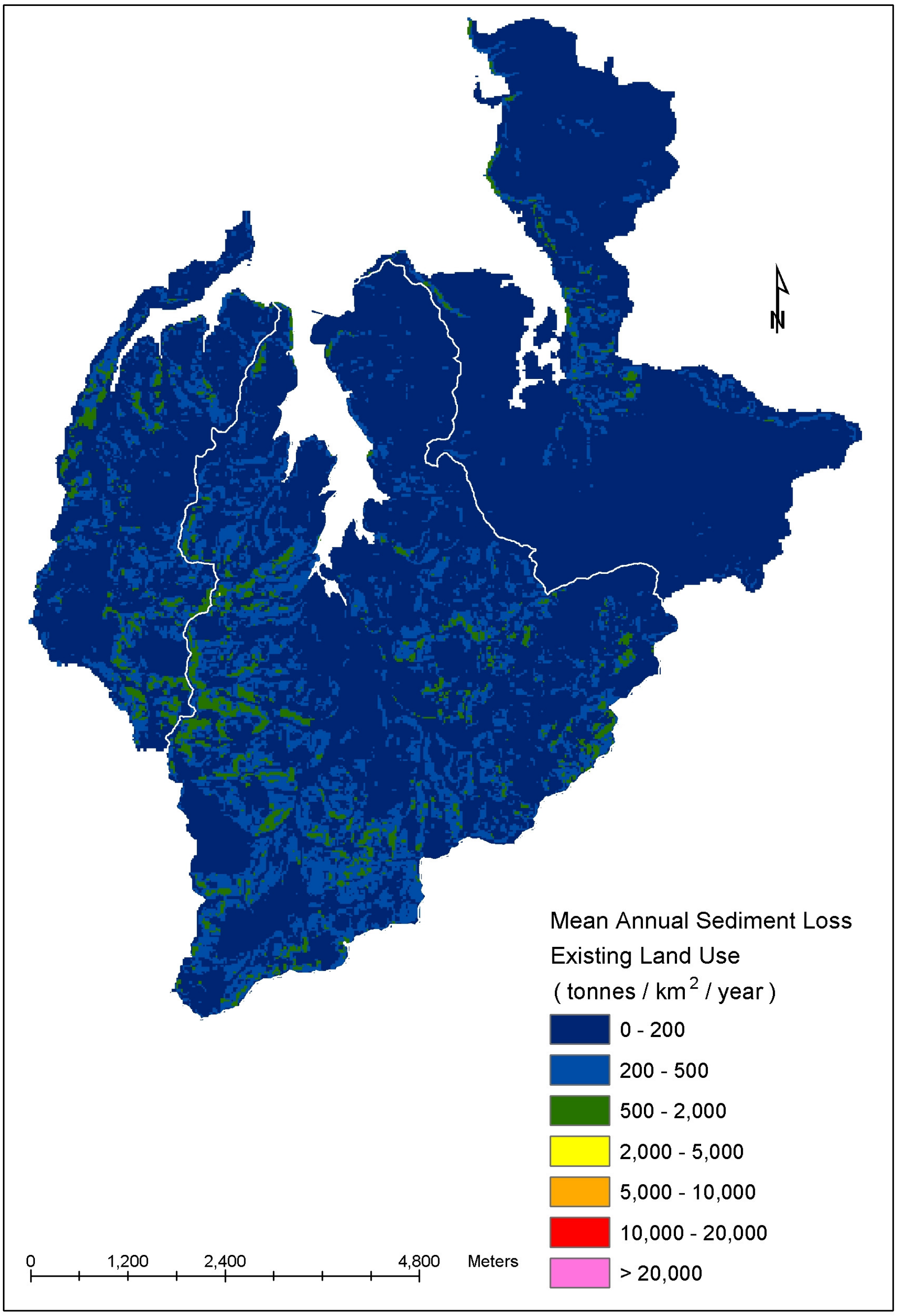


Figure 3.11: Predicted mean annual sediment loss from each grid cell under rural intensification – Scenario 2. This figure illustrates simulated loss from earthworks sites during the modelled stage of development. It does not illustrate loss from the total number of proposed developments. Refer to Table 3.2 for details of the modelled stage.

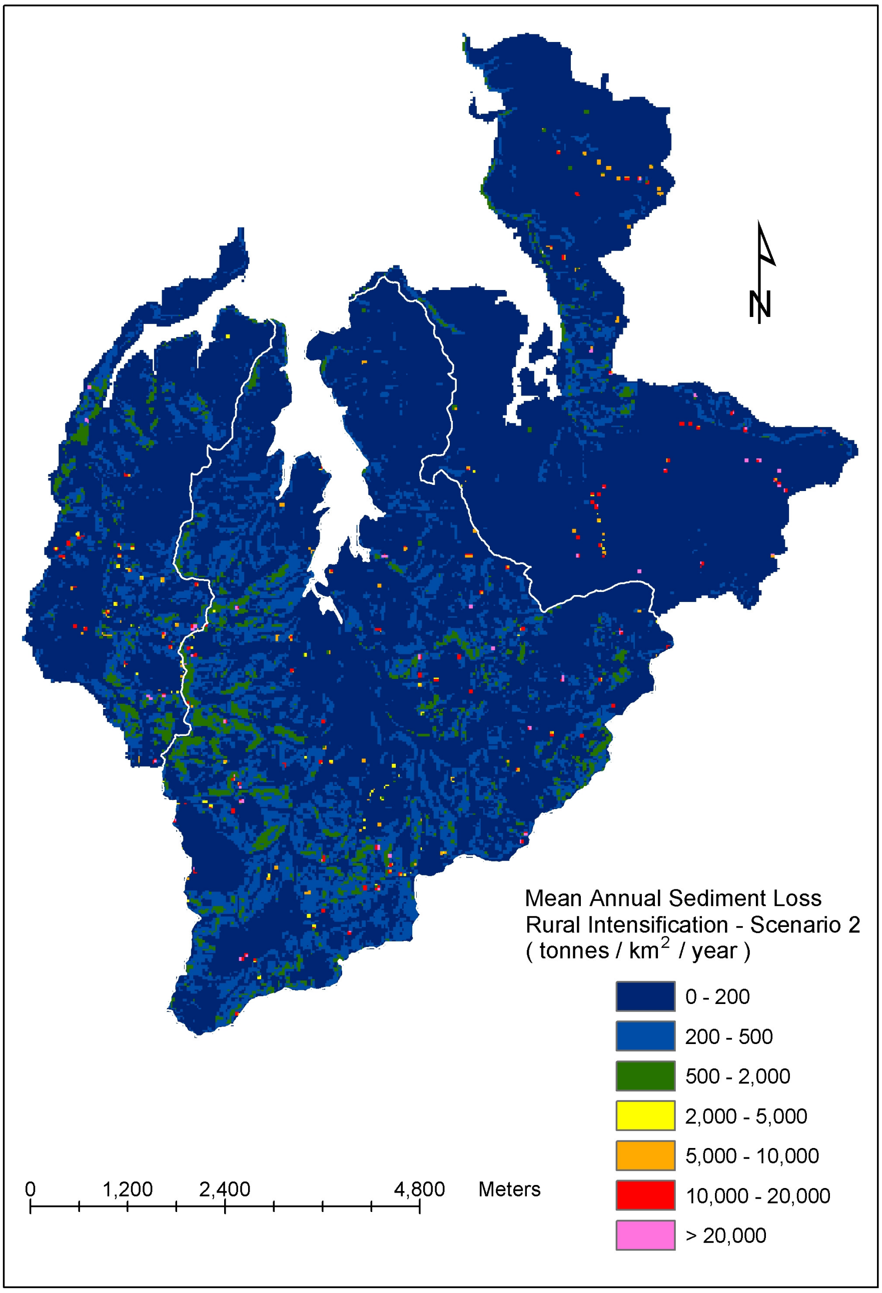
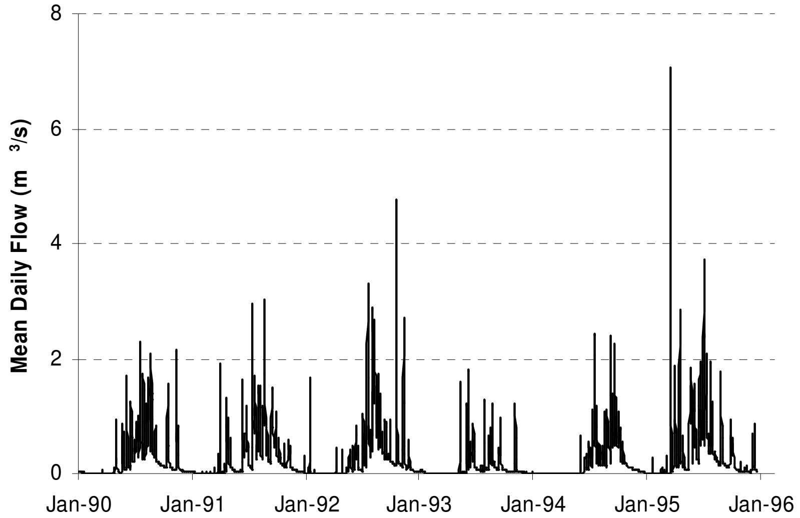


Figure 3.12: Upper: Predicted mean daily flow (m3/s) from the main outlet of the Turanga subcatchment, under the rural intensification of Scenario 2.

Lower: Predicted sediment delivery (tonnes/day) from the main outlet of the Turanga subcatchment, under the rural intensification of Scenario 2.



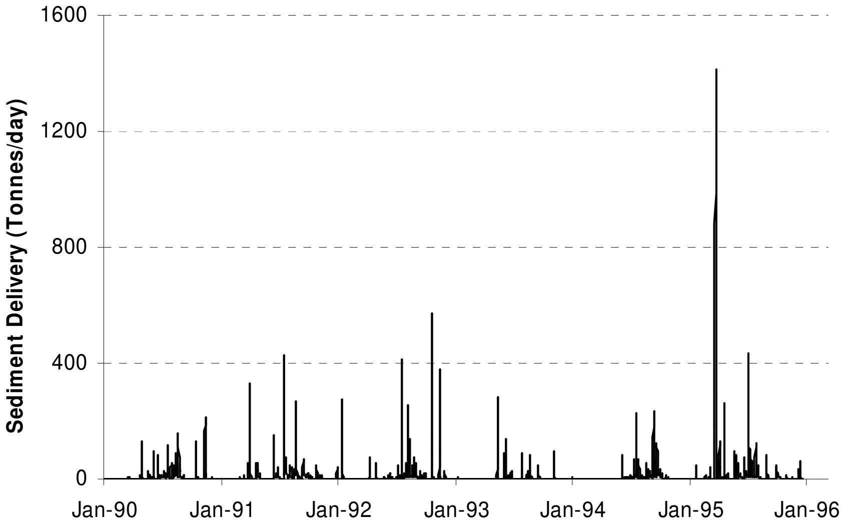
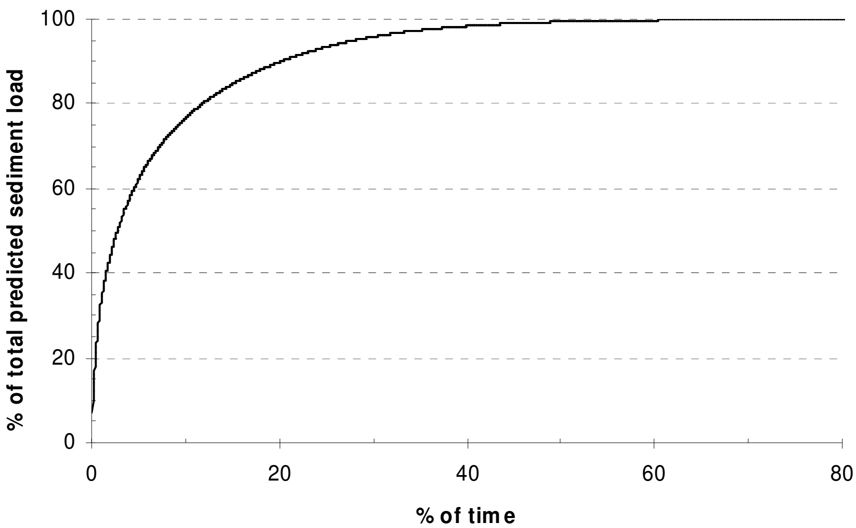


Figure 3.12 illustrates a time series (1990-1995) of predicted flow and sediment yield from the main outlet of the Turanga catchment. The six years of data illustrate that individual events can deliver substantial sediment loads to the estuary. Further analysis of results from the Turanga support this finding with Figure 3.13 illustrating that 50% of the long-term sediment load under Scenario 2 is delivered to the estuary in 3% of the time, whilst 80% of the sediment load is delivered in about 12% of the time. Most sediment delivery in the Turanga is, therefore, delivered in large sized events, and this is also true of the other subcatchments under both the existing land use and rural intensification scenarios.

Figure 3.13: Percentage of the total predicted sediment yield (1990-1995) delivered to the estuary plotted against the percentage of the 6-year period, under the rural intensification of Scenario 2.



4 Estuary/embayment sedimentation

The objective of this component of the study is to predict the fate of sediments, originating from surrounding catchments, within the Whitford embayment and tributary estuaries.

Our approach has been to take terrigenous sediment runoff, predicted by the catchment model (Section 3), and use an estuary/embayment model to predict the transport, dispersion and ultimate deposition of the sediment by tidal currents, waves and wind-driven currents. These patterns of terrigenous-sediment deposition are linked with distributions of benthic fauna and their responses to sedimentation in Section 5, to predict ecological consequences.

4.1 Methodology

4.1.1 Overview of Estuary/Embayment Model

The estuary/embayment model has hydrodynamic, wave and sediment-transport components (or "modules"). The model encompasses the Whitford embayment and its tributary estuaries, namely Mangemangeroa, Turanga and Waikopua. Each model component was calibrated and verified against field data. Input to the model includes sediment and freshwater runoff from the catchments, wind (to generate waves and wind-driven currents), and an astronomical tidal forcing (to generate tides and associated tidal currents). The estuary/embayment model is run on a "scenario basis", meaning that it is run for a particular combination of tides, winds and freshwater /sediment runoff. Ninety such simulation scenarios are run to predict ecological impacts for the existing land use and the two proposed development options (Scenario 1 and Scenario 2).

For any given simulation, dispersal of terrigenous sediment is modelled in two stages.

In the first stage, which is called the "sticky-bed" simulation, sediment is discharged into the upper reaches of each of the three estuaries and then dispersed throughout the estuaries and the Whitford embayment by tidal currents and wind-driven currents while simultaneously settling to the bed under the pull of gravity. When a sediment particle makes contact with the seabed it stays there ("sticks") for the remainder of this first stage of the simulation, unless it contacts an area of the bed where tidal currents are strong enough to prevent deposition, in which case the particle is not allowed to settle. Note that the term "sticky-bed" is not a reference to the cohesiveness of the sediment but is purely a modelling technique. The sticky-bed simulation is an intermediate step in the modelling procedure and the results are therefore not presented. Some physical significance may however be given to the map of sedimentation that results when all particles have settled and stuck to the bed. This can be thought of as an indication of the sediment deposition that would occur in the immediate aftermath of a flood, assuming no resuspension of bed sediment by tidal currents and/or waves.

In reality, currents and waves may in fact resuspend, disperse and redeposit the terrigenous sediment delivered during floods. These processes occur between floods and, indeed, while a flood is in progress. The second stage of the modelling procedure, which is called the "sediment-transport" simulation, addresses the resuspension, redispersal and redeposition of terrigenous sediment that was delivered to the estuaries and embayment during the first stage of the procedure. The second-stage (sediment transport) sedimentation map more accurately reflects the real long-term fate of terrigenous sediment and is therefore the appropriate map to use in predicting ecological impacts.

During the second stage of the modelling procedure, only the terrigenous sediment delivered to the estuary following the first stage of the procedure is resuspended, dispersed and redeposited. Consequently the pre-existing marine sediment in the estuaries/embayment is treated by the model as being immobile and does not, therefore, add to the sedimentation predicted by the model. There are several reasons for taking this approach:

- The geochemical properties of the terrestrial sediments differ from those of the pre-existing marine sediments, and it appears that this is a key factor in determining the level of ecological effects (see Section 5.4 and 5.5). Hence, deposition of a layer of terrestrial sediment thicker than the critical thickness will cause ecological effects whereas deposition of a super-critical layer of marine sediment will not, at least to anywhere near the same level of effect. Because we are interested only in ecological effects, it therefore makes sense to address dispersal/deposition of the terrestrial sediment only.
- Regardless of our focus on ecological effects, marine sediments may indeed be resuspended and redispersed under the same conditions that mobilise the alien, terrestrial sediments and the layers of sediment ultimately deposited may therefore consist of mixed terrestrial/marine sediments. Field data (Oldman and Swales, 1999) indicate that, during floods, sediment concentrations discharged by the various freshwater sources are at least an order of magnitude larger than marine-sediment observed in the embayment during periods with similar winds and waves but no rainfall. This suggests that, during floods, which are the focus of this investigation, terrigenous sediments dominate the estuaries/embayment system.
- Model simulations with a mobile pre-existing marine-sediment bed showed average changes of bed level of less than 1 mm under the range of conditions to be considered herein. This can be construed as the likely deposition thickness, additional to terrestrial-sediment deposition. The deposition layer due to pre-existing marine-sediment is neglected by assuming that the marine sediments in the estuaries/embayment are immobile.

4.1.2 Choice of Simulation Scenarios

Each simulation scenario is defined by a combination of input conditions (tides, winds and freshwater/sediment runoff from the land). It is not possible to know a priori what combination of input conditions (i.e., which simulation scenario) will result in the largest ecological impact or present the greatest risk. Hence, a range of scenarios needs to be simulated.

Tide: Three tide ranges are addressed: spring, neap and mean. Measurements from the Pine Harbour Water Level Recorder (WLR) show the amplitude of the M2 tidal constituent to be 1.116 m and the S2 amplitude to be 0.149 m. The spring tide range is therefore 1.265 m, the neap tide range is 0.967 m and the mean tide range is 1.116 m.

Wind: Measurements from Musick Point meteorological station give the 98-percentile wind speed (averaged over 4 days) as 14.1 m/s. We chose 14 m/s (27 knots, or a 'near gale') to represent a wind storm, which may come from each of the four compass directions NE, SE, SW and NW. We also use 0 m/s to represent the lowest wind speed (calm conditions).

Runoff: A flood event is parameterised in the model by the total freshwater volume discharged (Q, units of m3) and its duration (units of days). A flood event is defined to occur when the daily mean flow from the Mangemangeroa catchment exceeds 1 m3/s. This definition was chosen from analysis of the 37-year time series of daily mean flow predicted by the catchment model (see Section 4.3). Analysis of the 161 events that occurred during the 37-year period 1964–2000 showed the smallest events had duration of 2 days and discharge less than 2 × 105 m3. The largest event had duration of 5 days and discharge 10-12 × 105 m3. Table 4.1 shows the combinations of duration and discharge selected for the simulation scenarios.

Table 4.1: Flood discharge and event duration used in model simulations.

Discharge ($\times 10^5$) [m^3]	Duration [days]	Rank
0-2	2	1
2-4	3	2
4-6	3	3
6-8	4	4
8-10	4	5
10-12	5	6

The mass of sediment eroded from the catchment and delivered by streams to the estuaries (and then to the embayment) is related to the freshwater runoff. There will be a different relationship between freshwater runoff and sediment runoff for the Existing land use and for the development Scenarios 1 and 2. Details are given in Section 4.1.3.

The combination of 3 tides, 5 winds and 6 floods results in a total of 90 simulation combinations. Each combination needs to be simulated under the present land use and under both of the proposed land development scenarios described in Section 3.2.5.

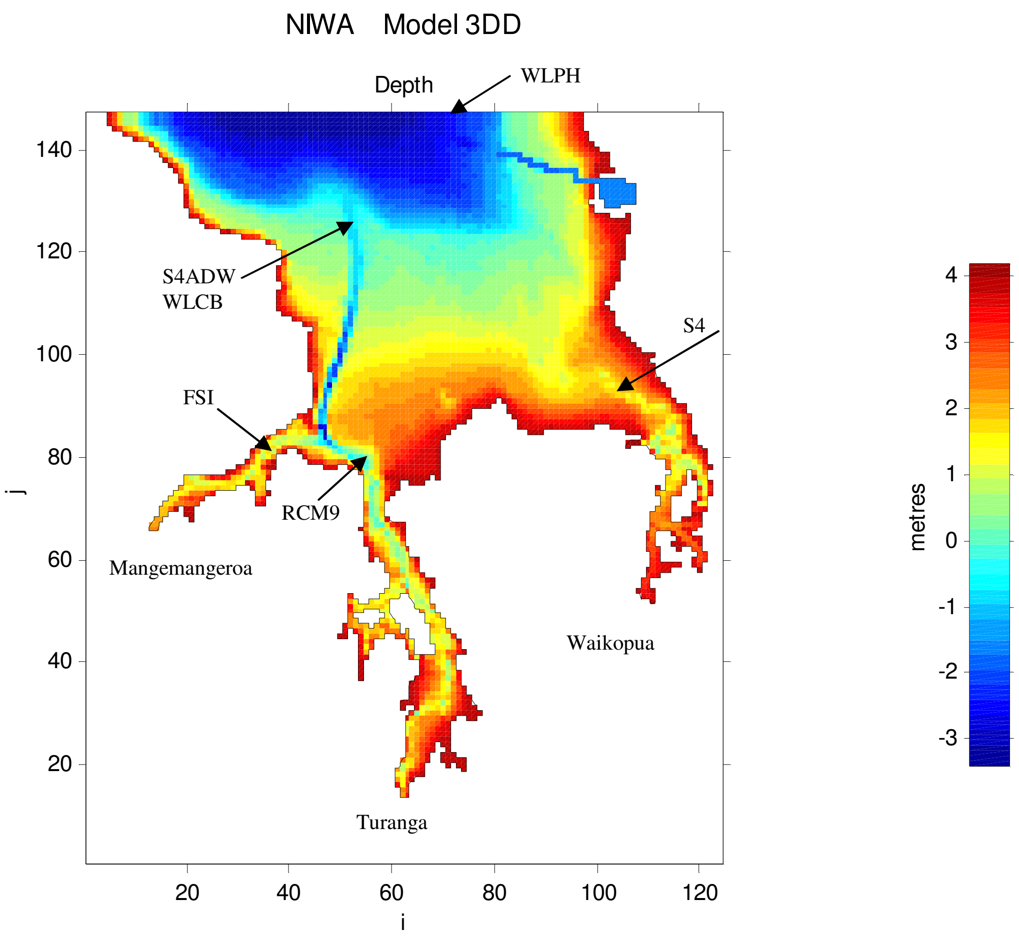
4.1.3 Details of Estuary/Embayment Model

The estuary model used in this study was built from the 3DD suite of computer models (Black 1995). It consisted of a hydrodynamic module (built from model 3DD), a wave module (built from model WGEN), a sticky-bed module (built from model POL3DD) and a sediment-transport module (also built from model POL3DD).

Bathymetry

The bathymetry of the Whitford embayment (including the three tributary estuaries) is represented on a 50 × 50 m square grid (Figure 4.1). Bathymetry was obtained from charts, field surveys, aerial photographs and the 1:50,000 digital topographic map series of New Zealand. Bathymetry data from field surveys include data collected from a boat within the Whitford Embayment and Turanga estuary, a jet-ski survey of the Mangemangeroa estuary and EDM surveys of Turanga and Waikopua estuaries.

Figure 4.1: Bathymetry of the Whitford Embayment and tributary estuaries, as used in the 50 m model. Depths are relative to Chart Datum. Also indicated are the locations of the current meters and the water-level recorder (see Table 4.3 for explanation of instrument abbreviations).

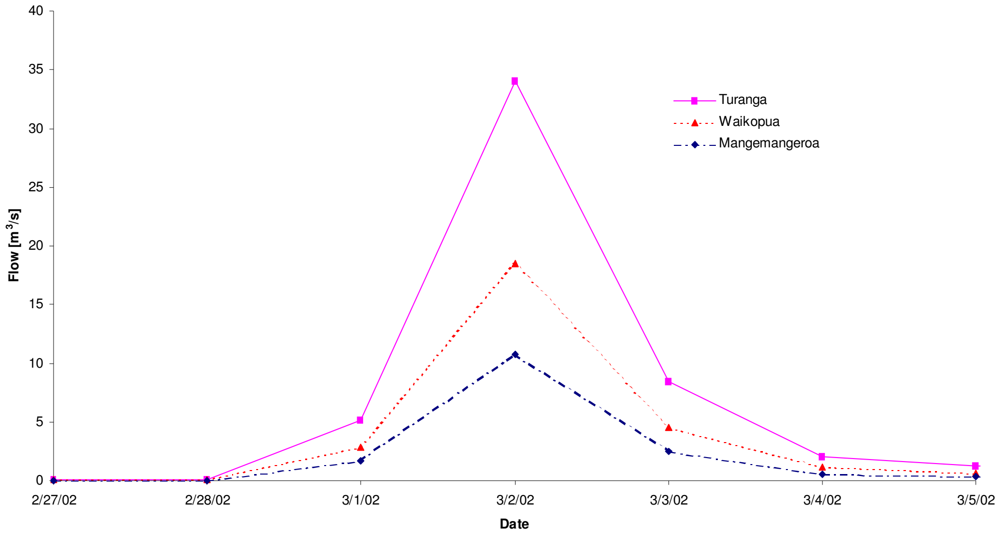


Hydrodynamic module

The hydrodynamic module was used to predict currents and water levels within the estuaries and embayment. Sinusoidal tidal water levels were imposed at the open-water boundary, with neap, mean and spring ranges, as appropriate for the scenario being run.

Freshwater flood events were discharged into the Mangemangeroa, Turanga and Waikopua estuaries as triangular hydrographs, with peak flow occurring at 1/3 of storm duration. Analysis of individual events from the catchment model shows that the flow from each catchment area is in phase and linearly related, i.e., flows into Turanga are, on average, 3.2 times larger than the Mangemangeroa, and flows into Waikopua were 1.7 times larger than the Mangemangeroa. These ratios are similar to the scaling factor estimated from catchment area, as used in the interim phase of this study. This similarity will be due, in part, to the assumptions inherent within the catchment model, and the spatially uniform rainfall adopted in the catchment modelling. A typical event is shown in Figure 4.2.

Figure 4.2: A hydrograph showing a typical runoff event, as predicted by the catchment model, for each of the three tributary estuaries. The ratio of peak flow between each of the tributary estuaries was found to be approximately constant.



Wave module

Model WGEN (Black, 1997) is a numerical model for predicting wave growth subject to wind stress in fetch-limited conditions. Its use within the Auckland area (Maraetai Beach) is described by Gorman and Belberova (1999). Applied to the 50 × 50 m Whitford bathymetry, the wave module was used to predict wave characteristics (significant wave height, wave period, wave direction, and wave-orbital speed at the seabed), for a given wind speed and direction, which remained constant for each simulation scenario.

Sticky-bed module

In this first sediment module, sediment "particles" were discharged into each of the three tributary estuaries in relation to the freshwater hydrographs used in the corresponding hydrodynamic simulations. The model assigns a mass to each particle, which is then dispersed around the embayment by the freshwater inflow, tidal currents and wind-driven currents. Because sediment particles have higher densities than either freshwater or saltwater they will gradually sink to the bed at a rate that is governed by the particle settling speed. Particle analysis of sediments sampled from the Upper Mangemangeroa estuary

(Oldman and Swales, 1999) showed that surficial sediment typically had a uniform particle diameter of 0.02 mm (20 microns). Within the model, all particles were assigned a settling speed of 0.2 mm/s, which corresponds to a particle diameter of 0.02 mm. In the sticky-bed module, once a particle contacts the bed it cannot subsequently be re-mobilised. Particles were prevented from sticking to the bed in "no-stick" areas, defined as areas of the seabed where the tidal current speed (specified 100 cm above the bed) exceeds 12 cm/s at any time of the simulation. Test simulations showed that the majority of the terrigenous sediment released into the model domain settled within two tidal cycles (~25 hours) of release. No sediment is allowed to escape from the embayment into the Tamaki Strait during the sticky-bed simulations.

At the end of the sticky-bed simulations, the pattern of deposited particles was converted into a mass distribution of deposited sediment. In the subsequent sediment-transport simulation this sedimentation pattern was re-distributed.

The ratio of sediment (Mangemangeroa : Turanga : Waikopua) discharged into each of the tributary estuaries was found to be approximately the same for each of the development options. Therefore the pattern of deposited sediment will also be the same for each of the development options. The significant change between the different land uses is the total mass delivered for each event. The sediment deposition for Scenario 1 and Scenario 2 can therefore be calculated by scaling the simulation results of the Existing land use by the total mass delivered for each event for Scenario 1 and Scenario 2 (Table 4.2). This method is only applicable if the delivery ratios into the tributary estuaries are approximately constant between development scenarios. However, the implications of this assumption become less important due to re-working of sediments which occur during the time between flood events. During this period, sediment may be resuspended, transported throughout the estuary and deposited some distance from its initial deposition location. A slight change in the initial deposition pattern (e.g., due to variations in delivery ratios between the tributary estuaries) will become inconsequential during the subsequent re-distribution process, as bathymetry, winds, waves and tidal currents will be the dominant factors of ultimate deposition.

Table 4.2: Scale factor (with respect to Existing Scenario) for the total mass delivered to the embayment for each event size for Scenario 1 and 2.

	Scale factor	
	Scenario 1	Scenario 2
E1	1.1775	1.5584
E2	1.1398	1.4494
E3	1.1140	1.3696
E4	1.0832	1.2711
E5	1.0978	1.3221
E6	1.0824	1.2712

Sediment-transport module

The next stage in the modelling procedure is to take the layer of terrigenous sediment deposited by the sticky-bed module and allow it to be resuspended, dispersed and redeposited (possibly in other locations) by waves and currents subsequent to the flood event being modelled. Although some sediment may be endlessly "recycled" by recurring tides and waves, most terrigenous sediment eventually finds preferred areas in which to settle, such as sheltered mangrove fringes, where currents and waves are not energetic enough to resuspend the settled sediment. For each scenario, the patterns and levels of sediment deposition were established within the first 4 tidal cycles (50 hours). That is, after that time, the spatial distribution of sedimentation does not change to any significant extent. Analysis of the wind record showed that the longest time that the wind direction is likely to remain in a given quadrant is approximately 4 days. Because each scenario represents a constant wind from a constant direction we therefore present results at the end of a 4-day simulation, which is the longest time a constant wind is likely to persist. Within this time-period, some of the sediment is exported out of the embayment, where it is "lost" to the Tamaki Strait. Under calm conditions less than 10% of the sediment is exported out of the embayment. This can increase to up to approximately 40% under strong winds. Note that the model does not account for any sediment retuning to the embayment, or the exchange of marine sediment that will occur between the Tamaki Strait and the Whitford Embayment.

4.1.4 Model calibration/verification

Field data collected specifically for this study were used to calibrate and verify the hydrodynamic, wave and sticky-bed modules. The dataset included measurements from DOBIE wave gauges, the instrumented ALICE sediment-transport tripod, current meters and tide gauges (Table 4.3). Data from earlier work (including sedimentation rates derived from sediment cores) within the Mangemangeroa estuary by Oldman and Swales (1999) were used to verify the sediment-transport module.

In summary, good agreement between predicted and measured currents was obtained. In addition, good agreement was obtained for freshwater mixing and sedimentation rates within the Mangemangeroa estuary and for suspended-sediment concentrations within the wider Whitford embayment using a combination of Einstein and Nielsen formulae in the sediment-transport model.

The model was calibrated against actual measured conditions over two semi-diurnal tidal cycles from 21 November 2000 15:10 to 22 November 2000 16:20. Measurements showed that the tidal water level variations imposed at the northern boundary of the model is the key process driving current flow in the embayment.

Current velocities are critical to sediment transport and settling, therefore it is important that the model be well calibrated for current velocities. Figures 3.3 to 3.7 show model calibration at the available current-meter and tide gauge sites (see Figure 4.1). Figure 4.3 shows that the water level condition applied at the boundary to the model (Figure 4.3a) results in a good match of water levels at the S4ADW site (Figure 4.3b). Calibration of velocities is shown for the S4ADW site (Figure 4.4) the S4 site (Figure 4.6) the RCM9 site (Figure 4.5) and FSI site (Figure 4.7). Given that these figures are a comparison between depth-averaged velocities (i.e. as predicted by the model) and near-bed velocities (i.e. as recorded by the current meters) the match between modelled data and observed data is good.

The site with the best calibration was at the mouth of the Mangemangeroa Estuary (Figure 4.7). This is attributed to the high-resolution bathymetry data available for this area. Also, model calibration against S4-measured-velocities was considerably improved by the inclusion of the Waikopua EDM survey data, also highlighting the importance of accurate model bathymetry.

Table 4.3: Abbreviations and descriptions of the field instruments used for hydrodynamic model calibration. See Figure 3.1 for deployment location.

Instrument abbreviation	Instrument description
S4ADW	InterOcean S4ADW electromagnetic current-meter
RCM9	Aanderaa RCM9 rotor-vane current-meter
S4	InterOcean S4 electromagnetic current-meter
FSI	Falmouth Scientific Instruments acoustic current-meter
WLPH	Aanderaa WLR7 total pressure gauge water level rec.
WLCB	Aanderaa WLR7 total pressure gauge water level rec.

Figure 4.3: (A) Measured tide levels at Pine Harbour as applied to the boundary of the model and (B) comparison of simulated and measured water levels at Cockle Bay, for the period 21 Nov 2000 15:10 to 22 Nov 2000 16:20.

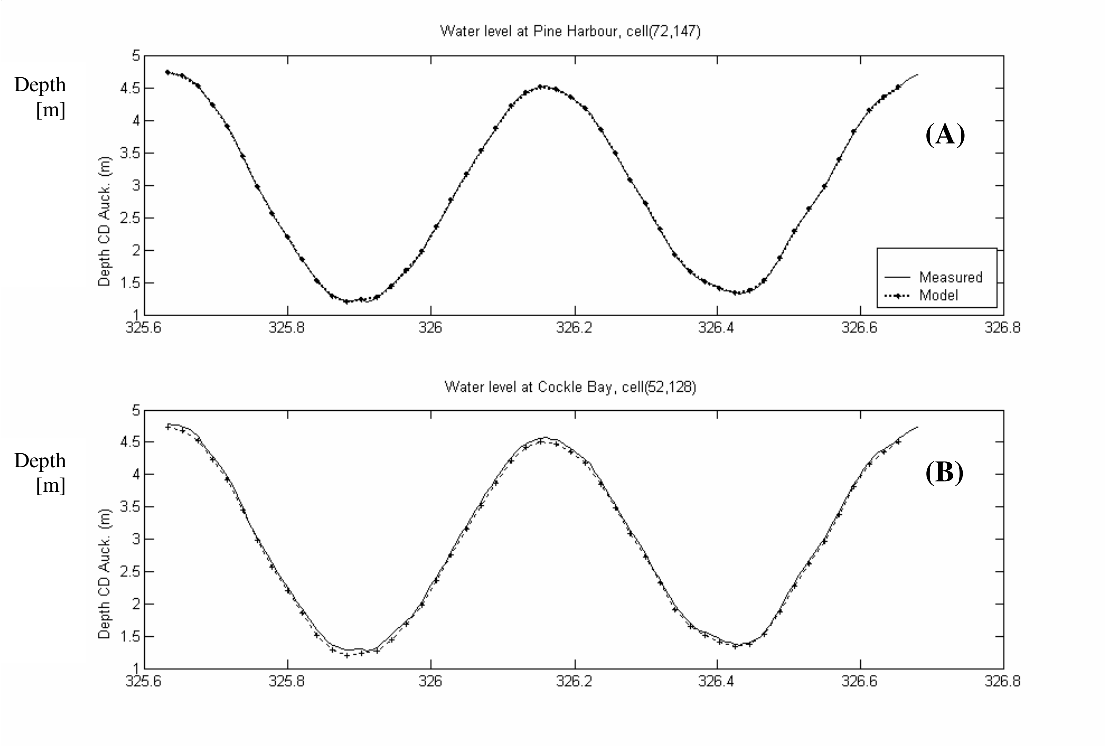


Figure 4.4: Comparison of simulated and measured current velocities at the S4ADW current-meter site for the period 21 Nov 2000 15:10 to 22 Nov 2000 16:20. A positive X-velocity component denotes an easterly flowing current and a positive Y-velocity denotes a northerly flowing current.

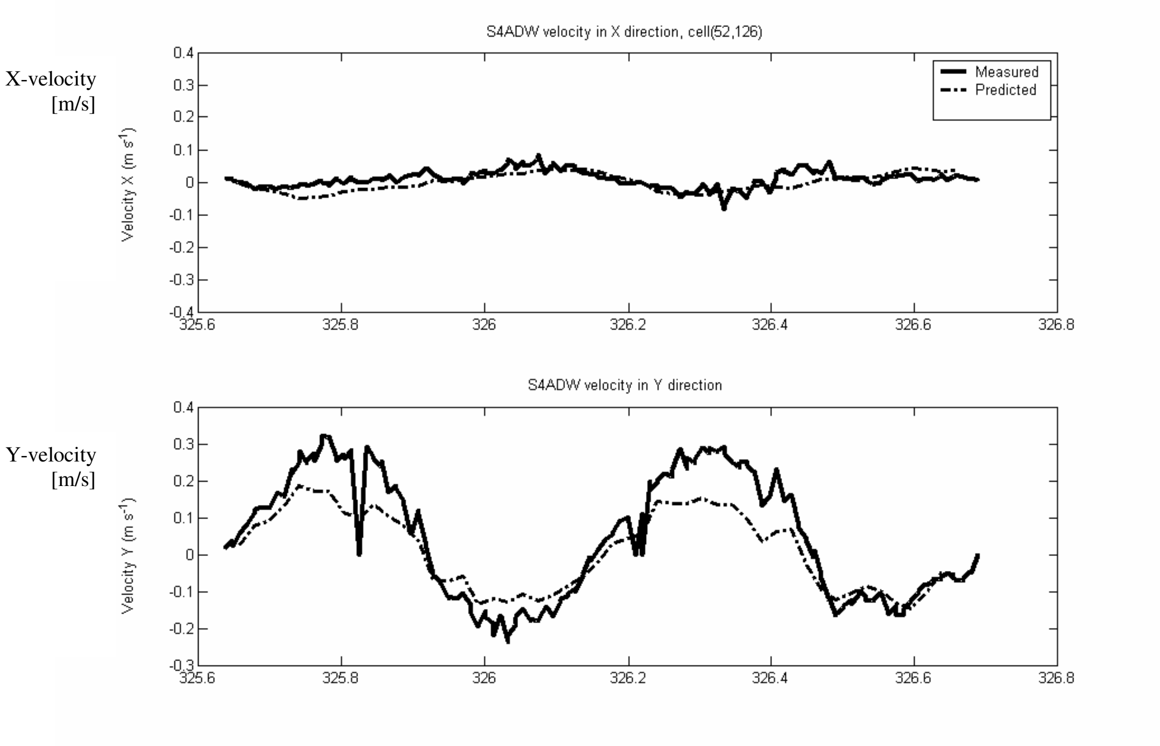


Figure 4.5: Comparison of simulated and measured current velocities at the Aanderaa RCM9 current-meter site for the period 21 Nov 2000 15:10 to 22 Nov 2000 16:20. Spurious data measurements are apparent at low tide (e.g., Julian Day 326.4) when the water surface approached the instrument.

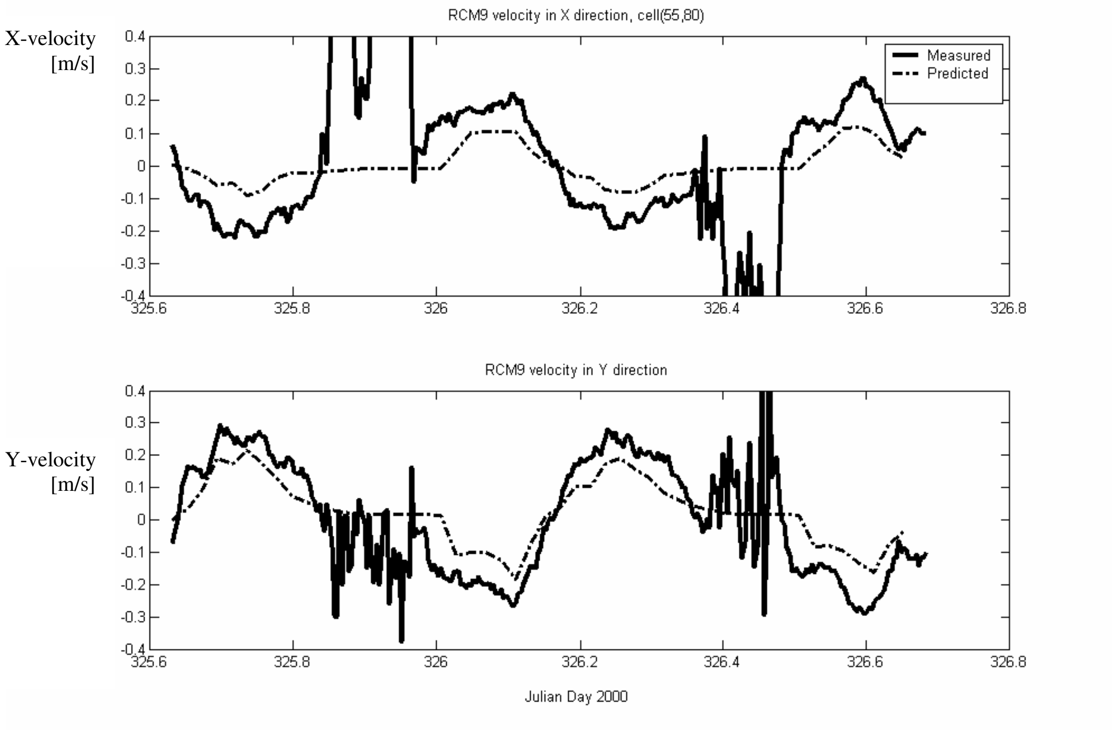


Figure 4.6: Comparison of simulated and measured current velocities at the S4 current-meter site for the period 21 Nov 2000 15:10 to 22 Nov 2000 16:20. Spurious data measurements are apparent at low tide (e.g., Julian Day 326) when the water surface approached the instrument.

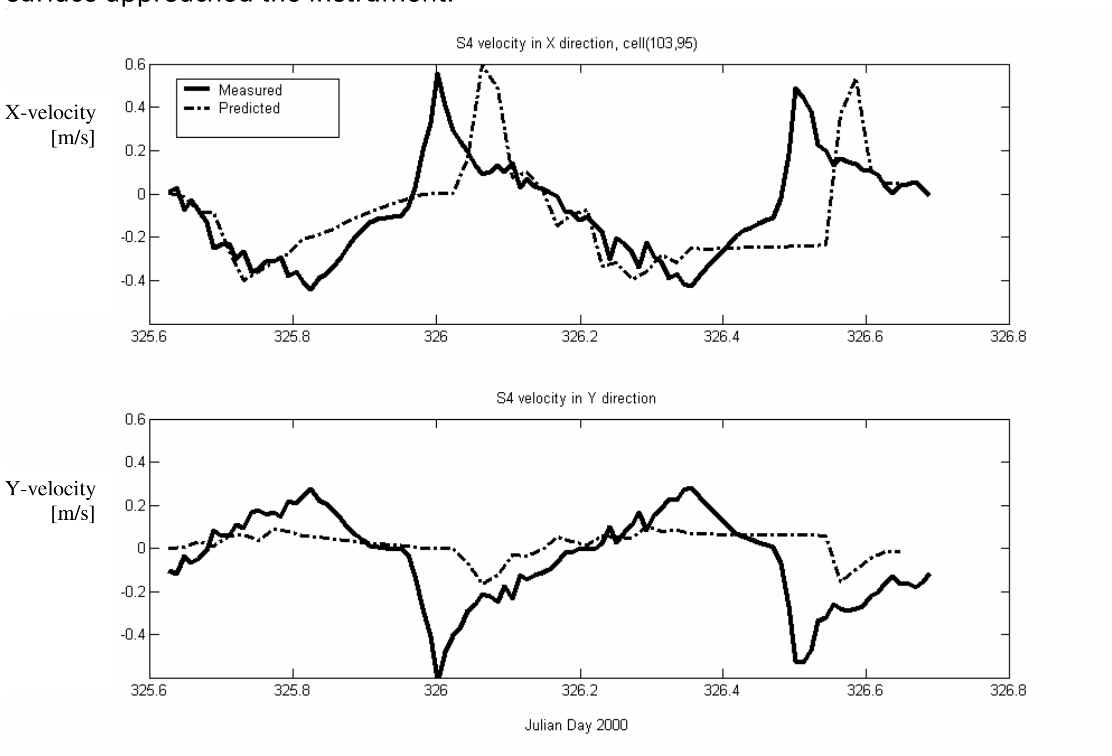
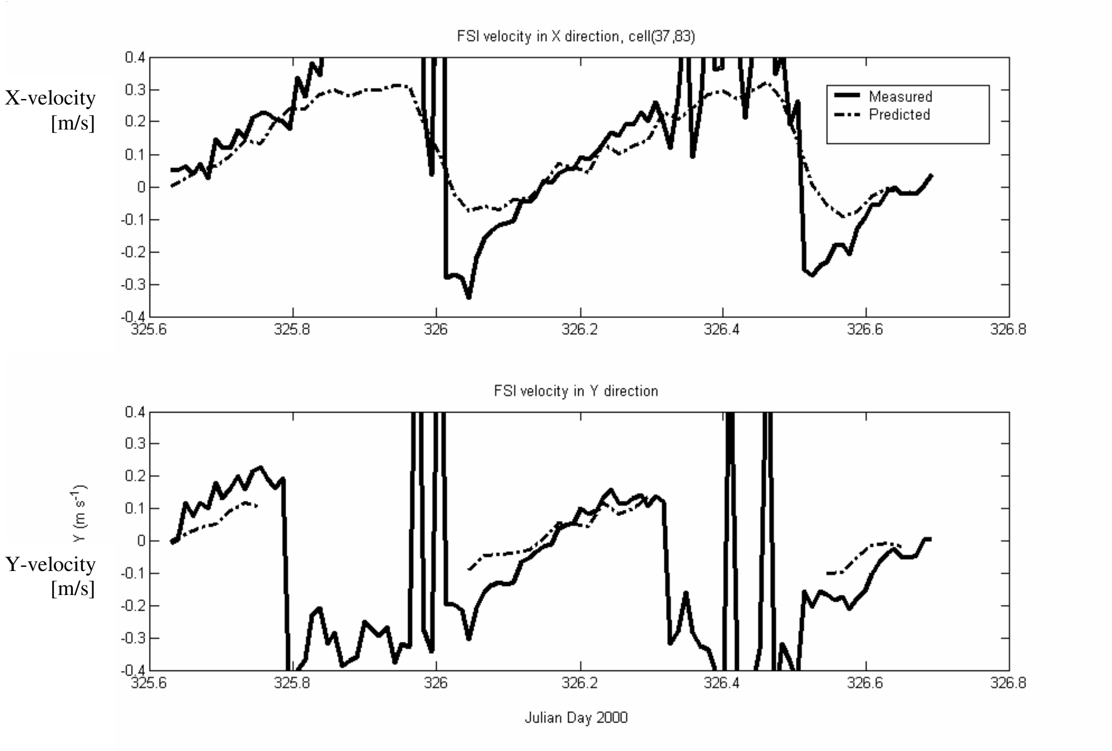


Figure 4.7: Comparison of simulated and measured current velocities at the FSI current-meter site for the period 21 Nov 2000 15:10 to 22 Nov 2000 16:20. Spurious data measurements are apparent at low tide when the water surface approached the instrument.



4.2 Results

A total of 270 hydrodynamic patterns and sedimentation maps were output from the estuary model simulations. To distil this information, a procedure to estimate risk has been developed. This combines the degree of sedimentation with the risk of damage to local ecology and is presented in Section 5. However, here we briefly demonstrate the relative effects of each of the three forcing functions, namely the effect of tide range, wind and freshwater runoff magnitude. The model predicts that any increase in sediment runoff is of primary importance to the degree of deposition, whereas wind is predicted to be the primary factor in the location and dispersal patterns of deposition. The effect of tidal range is predicted to be relatively minor.

4.2.1 Effects of tides on predicted sedimentation patterns

By way of example, Figure 4.8 shows sedimentation predicted at the end of the sediment-transport simulations, under calm winds and high freshwater runoff for neap, mean and spring tides for the Existing land use.

As the tide range increases, three factors determine where sediment will be deposited. Firstly, a greater area of the embayment becomes available for deposition (areas higher on the intertidal flats become inundated at higher water levels). Secondly, increasing water levels cause higher tidal-current speeds. Thirdly, wave energy at the bed becomes reduced (increased attenuation of wave energy through the water column). In terms of total sediment deposited within the various sub-environments, these processes tend to balance each other out so that the percentage of sediment deposited (as a percentage of the total mass released from the catchments) remains almost the same.

4.2.2 Effect of freshwater runoff on predicted sedimentation patterns

Figure 4.9 shows the predicted sedimentation under calm winds and spring tides for each of the freshwater runoff events (rank 1 to 6).

Increased freshwater runoff leads to an increase in the mass of sediment delivered to the tributary estuaries, and therefore an increase in sediment available for deposition within the estuaries and embayment. A secondary effect is the increase in freshwater flow within the estuary channels, thereby flushing the estuaries of sediment to a greater extent. This results in a trend for less sediment (as a percentage of the total that has been released) to be deposited within each of the tributary estuaries with increasing freshwater runoff. The decrease in percent sediment deposition within the tributary estuaries is offset by an increase in (1) the area of the subtidal embayment where deposition occurs and (2) the percentage of sediment deposited in the subtidal embayment.

4.2.3 Effect of wind on predicted sedimentation patterns

Figure 4.10 shows the predicted sedimentation for each of the wind scenarios, under a spring tide and a rank-6 runoff event. In the absence of winds, sediment is dispersed entirely by tidal currents, which in turn are influenced by the bathymetry of the embayment. Hence, in the majority of the embayment, which is shallow with a smooth gentle slope, deposition is relatively uniform. Significantly higher deposition is predicted to occur when the faster flowing channel water (from Mangemangeroa and Turanga) reaches deeper water and the water speed drops. Higher levels of deposition will also be expected on channel fringes within each of the tributary estuaries, where the speed of water movement will also be less due to friction from the bed.

Superimposed on this tidal forcing, a wind blowing from the NW will drag the surface water towards the SE, into the Waikopua estuary. More material is therefore predicted to be deposited in this area under these conditions. For strong winds, and in shallow regions, the wind-affected surface layer will be a significant proportion of the water depth (up to 100%). A secondary effect of a NW wind is to generate an anticlockwise circulation, whereby water forced into the SE corner of the embayment escapes back into the Tamaki Strait along the eastern side of the embayment, past Pine Harbour. Wind not only advects the surface layer, but will also generate waves, which then generate bed-orbital currents that may resuspend previously deposited sediment. The resuspended sediment may then be mixed throughout the water column and advected by the wind-driven surface current or tidal currents. Waves therefore do not transport sediment very far, but allow more sediment to be transported by tide and wind currents, therefore accentuating the movement of sediment by these processes alone.

A similar, but reversed pattern is generated under a strong NE wind. The wind-driven surface layer, and its suspended sediment, is pushed into the Mangemangeroa and Turanga estuaries. A clockwise circulation is also established, with water and sediment moving north along the west bank of the embayment to escape into the Tamaki Strait.

Under both SW and SE winds the wind-driven surface layer and its suspended sediment is blown out of the tributary estuaries, across the embayment and out into the Tamaki Strait. Some sediment, however, may be trapped locally within each estuary, and blown into a downwind shore where it is later deposited. Again, a secondary circulation is established within the embayment; for a SW wind, water and sediment is driven out of the NE corner of the embayment, and water from the Tamaki Strait enters through the NW corner. The opposite occurs, but to a lesser extent, on a SE wind. Also note that, for a SE wind, the area of high deposition at the seaward end of the channel is not present, as was found under calm conditions. This is due to high levels of turbulence by wind-driven currents and waves keeping the sediment well mixed within the water column.

Figure 4.8: Effect of tide range on sedimentation patterns. Plots show deposition (units of mm, shown on a log10 scale) as predicted by the sediment-transport module for neap, mean and spring tides. The Existing land use simulation of calm wind, rank-6 runoff (very large storm) is used as an example.

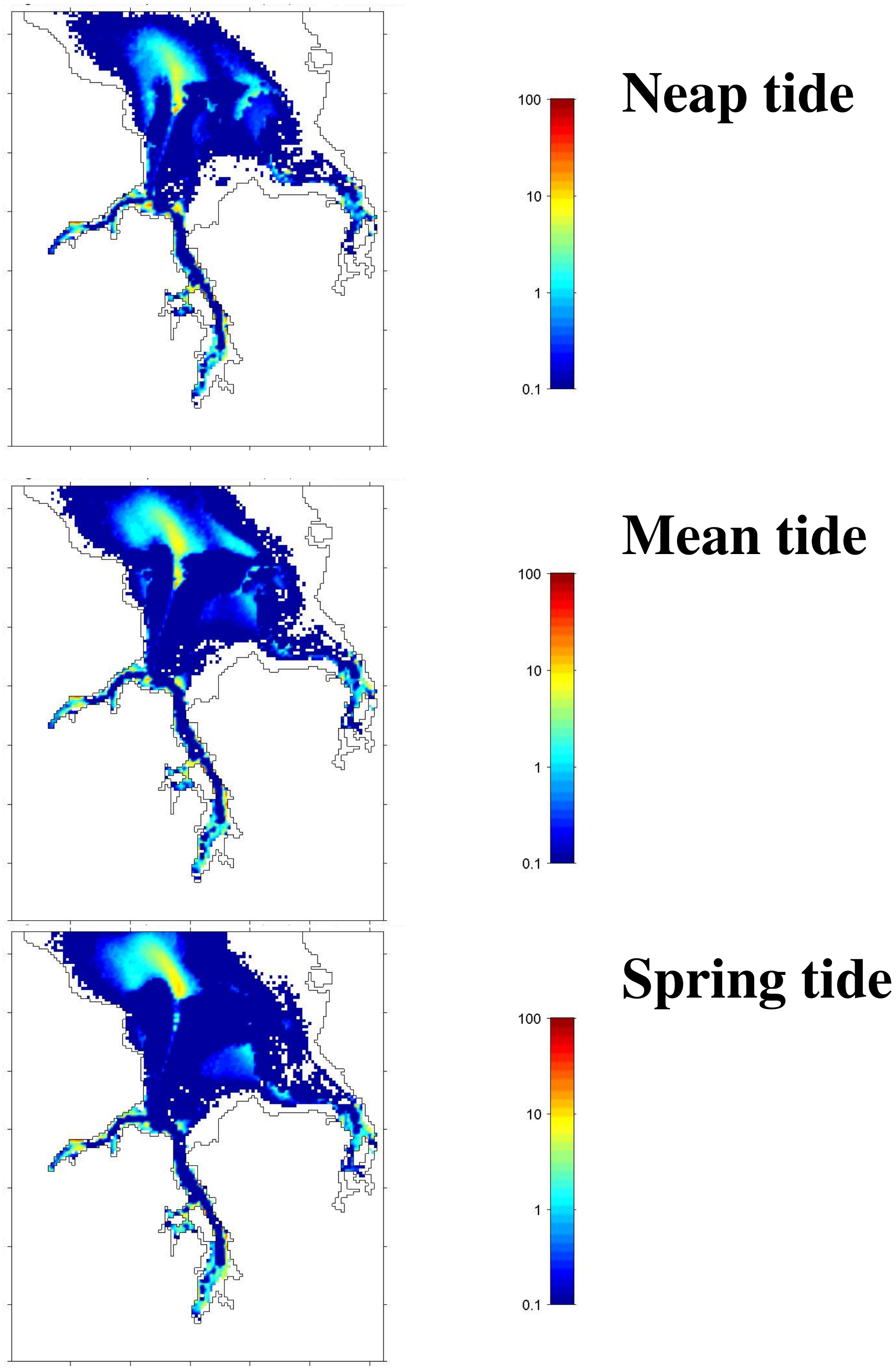


Figure 4.9: Effect of freshwater run-off on sedimentation patterns. Plots show deposition (units of mm, shown on a log10 scale) as predicted by the sediment-transport module for each of the run-off events, ranked 1 to 6. The Existing land use simulation of calm wind and spring tide is used as an example.

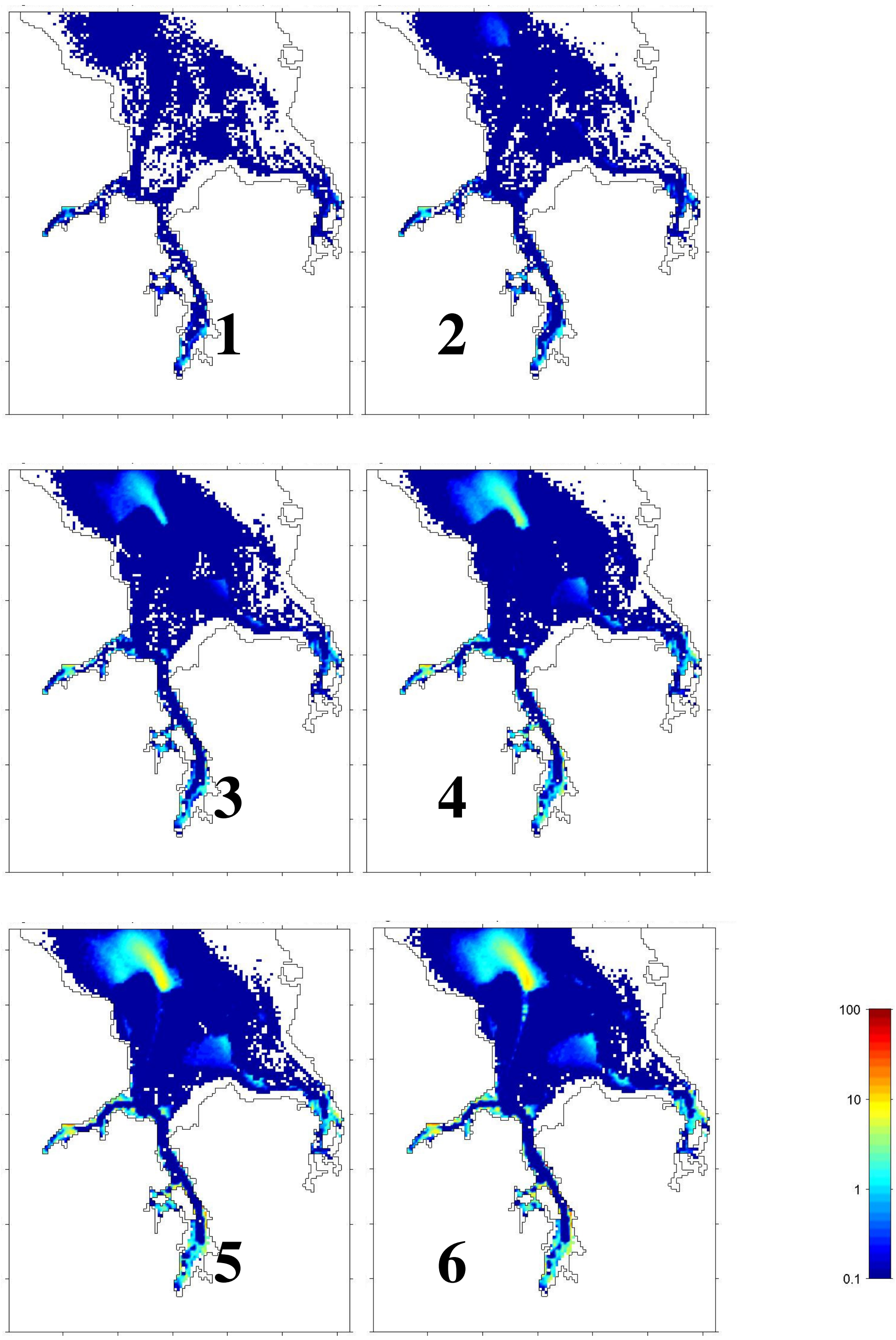
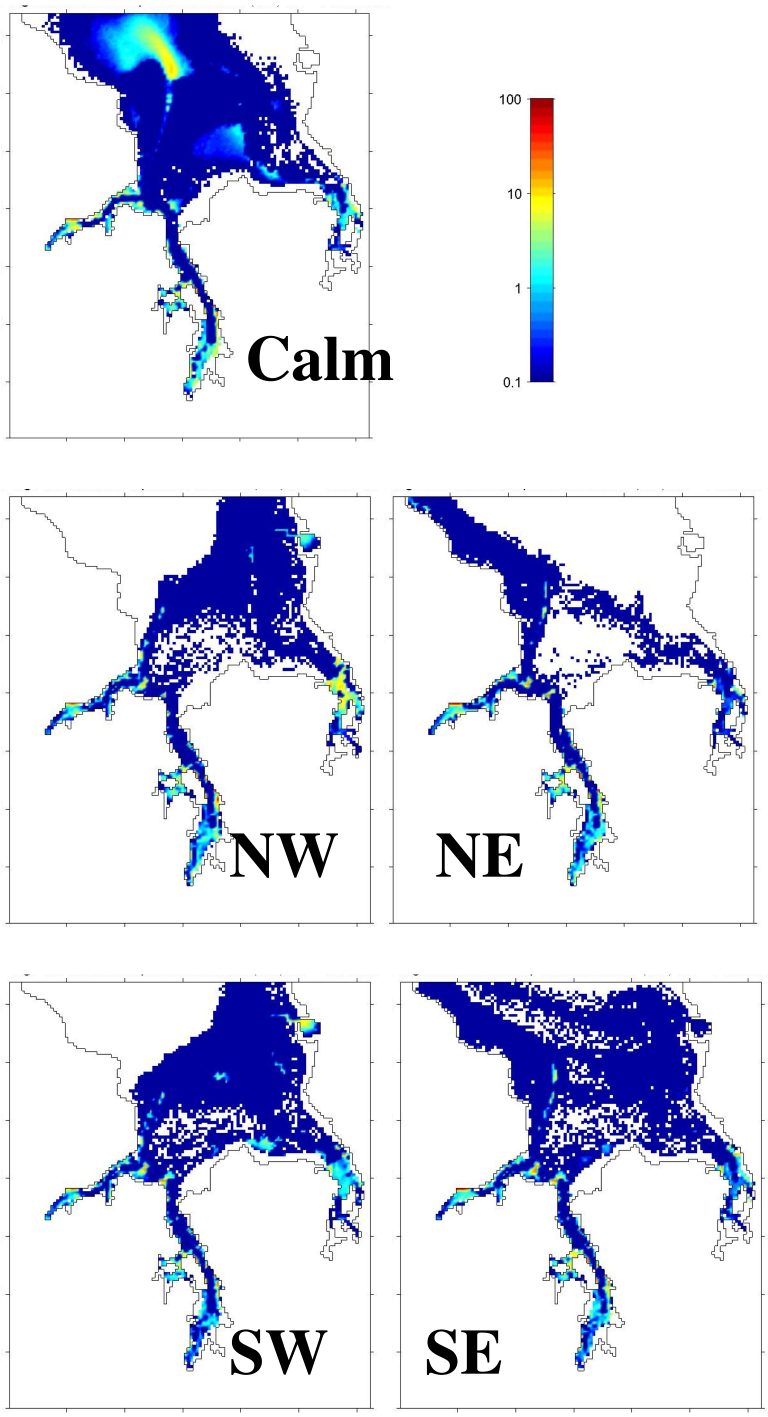


Figure 4.10: Effect of wind on sedimentation patterns. Plots show deposition (units of mm, shown on a log10 scale) as predicted by the sediment-transport module for each of the wind scenarios. The Existing land use simulation of spring tide and rank-6 run-off is used as an example.



4.3 Comparison with other Auckland region study sites.

The Whitford embayment differs, in the broad physical sense, from other sites in the Auckland region that are, or have been, the focus of integrated catchment–estuary studies (Mahurangi, Okura, Upper Waitemata Harbour, Long Bay). The principal difference concerns the geometry of the Whitford embayment. Compared to Mahurangi and Okura estuaries, in particular, the Whitford embayment is very exposed to wind and resultant wave generation. Furthermore, the exposure is to the northeast, which means that the northeast winds that bring heavy rain (and accompanying sediment runoff) also bring waves into the embayment, which helps to disperse terrestrial-sediment plumes and hinder deposition of that same sediment within the embayment. Another difference is the width of the connection between the Whitford embayment and the deeper, offshore waters (the Tamaki Strait). This broad connection promotes a more effective exchange of inshore and offshore waters than more indented drowned-valley estuaries (Okura, Mahurangi, Upper Waitemata Harbour). Of previous study sites, the Long Bay open-coast area is the most similar to the Whitford embayment, it being exposed (also to the east and northeast) and with an immediate connection to the coastal ocean. Studies of sediment-dispersal at Long Bay have shown that terrigenous-sediment plumes are widely dispersed and that waves play a critical role in mediating sedimentation processes.

5 Marine Ecology

The objective of this component of the study was to:

"Describe the habitats and associated animal communities present in the Whitford embayment and its tributary estuaries, and provide some information on the likely responses of the animal communities to sediment deposition."

Our approach was to conduct an extensive survey of the benthic macrofauna and combine this information with both existing knowledge on species sensitivity to sediment deposition as well as with the patterns of sediment deposition from the hydrodynamic modelling to predict ecological consequences. Without good historical information, such as long-term monitoring data, it is not possible to define current temporal trends in the ecology of the embayment. As we do not know if the ecology of the estuary is in decline, in some quasi-stable state or recovering, it is not possible to definitely comment on how current trends may interact with the environmental risks posed by the various development scenarios considered in the report. In this situation we must rely on our expert opinion, based on analysis of the current status of the ecology. It is clear that the Whitford embayment already has undergone significant broad-scale degradation of habitat due to historic activities in the catchment (Oldman and Swales 1999). Despite these habitat changes, the Whitford embayment still contains a number of different benthic communities and still supports a number of suspension-feeding shellfish. The important point is that the embayment is not sufficiently degraded that risk of increased sediment loading poses no threat of further losses of important species and biological diversity. Indeed with improved catchment management there is the potential for recovery. Reducing the sediment load to the estuary is likely to result in improved shellfish stocks and enhanced biodiversity. Given its current status, it is likely that careful management of catchment inputs and in-embayment activities are likely to maintain populations of sensitive species, as well as habitat and species diversity.

5.1 Background

Natural estuarine environments are rich in both structural and ecological diversity and play an important role in the functioning of coastal ecosystems. There is a growing awareness and evidence that sediments pose a threat to the ecology of estuaries (GESAMP 1994, Ellis et al. 2000). Estuaries are particularly vulnerable to increased levels of sedimentation, as they act as natural retention systems. Accelerated deposition of land-derived sediment leads to habitat modification and impacts on estuarine ecology by killing, displacing, or damaging components of the macrobenthic community, resulting in changes to the abundance and distribution of benthic organisms and potentially the functioning of the system. Broad-scale degradatory habitat changes can result in stressed populations, especially adjacent to habitat transition zones. Thereafter relatively "small" changes in sedimentation rates may have ecologically significant effects.

Previous surveys and experiments conducted in Okura estuary and more recent work conducted in the Whitford embayment demonstrate negative impacts of fine terrestrial sediments on benthic communities. The magnitude of impact depends on the depth of mud deposited (silt and clay sediment fractions), spatial extent of effect, persistence of deposits, the frequency of depositional events and the sensitivity of the impacted community. Ecological repercussions can be both short-term catastrophic and long-term chronic in nature. Potential ecological responses include both structural and functional changes to benthic communities. For example, loss of sensitive species1, changes in biodiversity, reduced oxygenation of surficial sediment, shifting microbial activity to anaerobic processes, diminished light levels and restricted photosynthesis by microphytobenthos (microalgae), and interference with feeding processes across the sediment surface (Norkko et al. 1999, 2002; Berkenbusch et al. 2001, Gibbs et al. 2001; Hewitt et al. 2001).

Previous studies of catastrophic events conducted in Okura estuary have shown that mud deposits thicker than 2 cm which cover underlying sediments for 5-7 days will smother the natural sediments, turn it anaerobic and kill all resident macrofauna with the exception of mobile crabs and shrimp (Norkko et al. 1999, 2002). Recovery from such a catastrophic event is slow and dependent on the spatial scale of disturbance, sediment mixing by resident animals and site-specific hydrodynamic conditions. The generality of these findings have all been emphasised in recent FRST-funded research; e.g., Thrush et al. (in press), Hewitt et al. (in press), Cummings et al. (in press).

Events producing thinner mud layers occur more frequently than the catastrophic events described above. Berkenbusch et al. (2001) conducted a study in Whitford investigating the impact of thinner mud layers on benthic communities. They showed that the macrobenthic community and biogeochemical variables responded to the addition of < 1 cm layers of terrigenous mud although these effects were less dramatic than for > 2 cm layers. Three millimetre thick layers changed the abundance of common taxa and macrobenthic community structure over 10 days and 5 mm layers reduced the abundance of common taxa by around 40% over 10 days. A cumulative affect of frequent additions of mud on macrobenthic communities was observed with the magnitude of ecological effect being larger with monthly, repeated depositions of mud, compared to a single deposition (Berkenbusch et al. 2001).

[1] i.e., species whose abundance is negatively related to increased concentrations of fine particles within the sediment. For the Whitford embayment specific taxa are defined in Table 4.2.

5.2 Field survey of macrobenthic communities and associated environmental variables

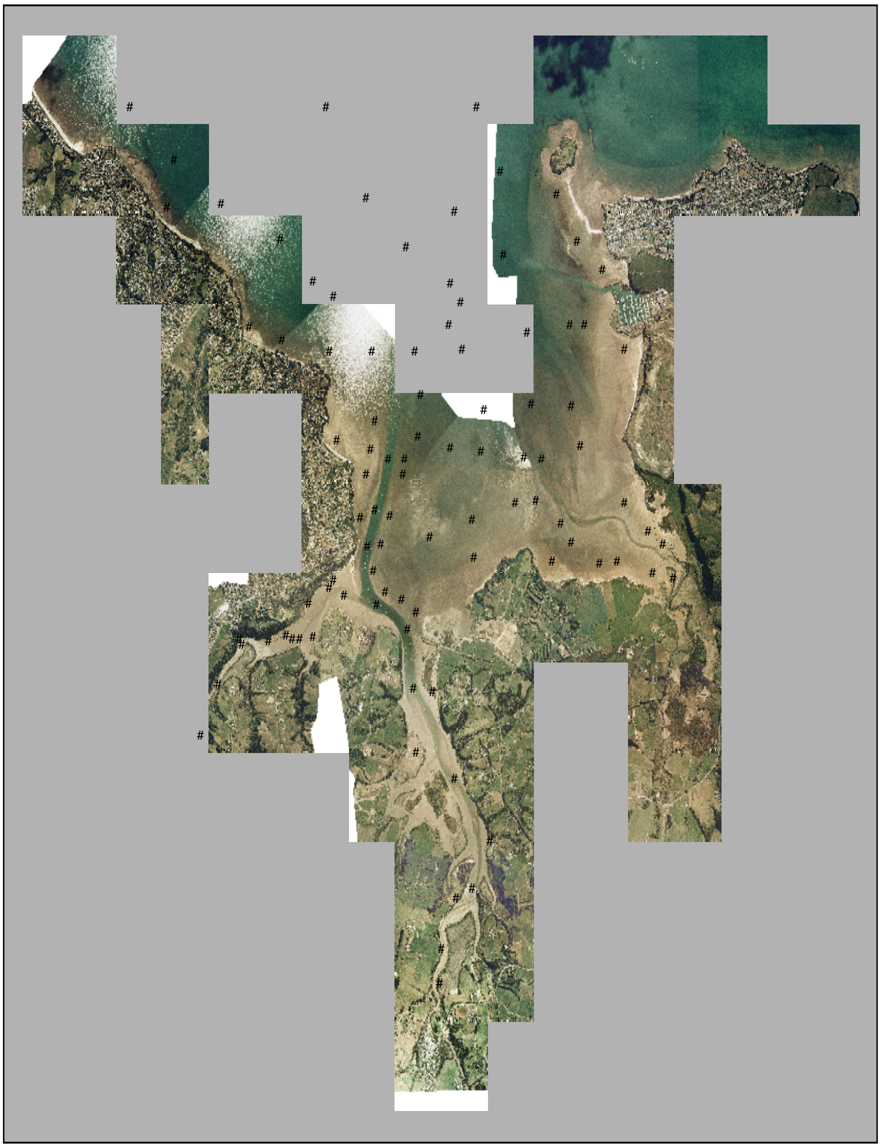
A total of 95 different sites throughout the estuary were sampled for benthic macrofauna and associated sediment characteristics (Figure 5.1). These sites were positioned in the subtidal zone in the main embayment, the outer intertidal sandflats, the main outer channels, the inner estuary intertidal mudflats (Mangemangeroa, Turanga and Waikopua) and the inner estuary subtidal channels. The survey thus covered all the major marine habitat types within the embayment, except for fringing vegetation (see Craggs et al. 2001). However, macrofaunal data from 5 mangrove sites in the Mangemangeroa estuary are available from ongoing NIWA research and have been included in this report.

From each site three macrofaunal cores, spaced 5 m apart, were taken to a depth of 15 cm. For the intertidal sites a 13 cm diameter corer was used; in the subtidal areas a 10 cm diameter corer was used. Smaller core samples (2 cm diameter and 2 cm deep) near each macrofauna core were analysed for sediment chlorophyll a, sediment particle size, and organic matter. The macrofauna samples were sieved on a 0.5 mm mesh, preserved in 70% isopropyl alcohol (IPA) and stained with 0.2% Rose Bengal. Animals in the samples were sorted and identified to the lowest level practicable. As a measure of food supply to the benthic animals, chlorophyll a was determined. Chlorophyll a was extracted from sediments by boiling in 95% ethanol, and measured spectrophotometrically. An acidification step was used to separate degradation products from chlorophyll a (Sartory 1982). Although it was necessary to use different sized core samplers at the intertidal and subtidal sites, numbers of macrofauna from the subtidal sites presented throughout this report have been adjusted to enable direct comparisons between all sites.

Samples for particle size analysis were pre-treated by digesting sediments in 6% hydrogen peroxide for 48 hours to remove organic matter, and dispersed using Calgon. Subsequently, % volumes for sediment fractions (gravel, coarse, medium and fine sand, silt and clay) were determined by wet-sieving (particle size > 63 µm) and by using a Galai particle analyser (Galai Cis - 100; Galai Productions Ltd., Midgal Haemek, Israel) for particle sizes < 63 µm. Organic content of the sediment was measured as loss on ignition (LOI) in 12 hours at 400 °C, after drying the samples at 40 °C until a consistent weight was achieved (36 hours).

Video transects run across the subtidal area revealed few epifauna. The sediment was predominantly muddy with some biogenic structures (burrows and holes).

Figure 5.1: Mosaic of aerial photos of Whitford Embayment, taken in 2001 at about low tide. Dots indicate the location of the 95 sampling sites.



5.3 Habitats and animal communities of the Whitford Embayment

Seven different habitat categories have been defined. These are Estuary intertidal, Estuary subtidal, Embayment intertidal, Embayment channel, Embayment shallow (< 3m chart datum), Embayment deep (> 3m chart datum) and Mangroves. These habitats were tested for differences in community composition (see Norkko et al. 2001 for details). Each habitat was significantly different from the others in terms of macrofaunal community composition. Using multivariate statistical techniques (Canonical correspondence analysis), we then determined the relationship between macrofaunal community structure and the environmental variables measured at each site. Environmental variables included sediment grain size, sediment organic content, sediment chlorophyll a content, and geographical position (latitude and longitude). Of the environmental variables, sediment characteristics emerged as the major factor discriminating macrofaunal communities (Norkko et al. 2001). For example, sediments with high mud content support distinctly different communities from those found in coarse sand habitats. Sediments containing high mud content (i.e., defined by Norkko et al. 2001 as being around 30% of sample volume) generally occur in areas experiencing low levels of wave action. Such 'low-energy' depositional environments are typically found at the intertidal margins of the upper reaches of the estuaries, and in deeper subtidal areas away from the mouth of estuaries (Figure 5.2). In contrast, the main intertidal flats are characterised by sandy sediments, reflecting their exposure to wind-wave disturbance, and are typically low in mud content (Figure 5.2). Habitats containing high mud content are also often rich in organic matter (Figure 5.3), as areas with high concentrations of mud are often depositional areas, also accumulating organic detritus.

Figure 5.2: The percentage of fine mud sediments (particle diameter < 63µm) in Whitford Embayment surficial sediments.

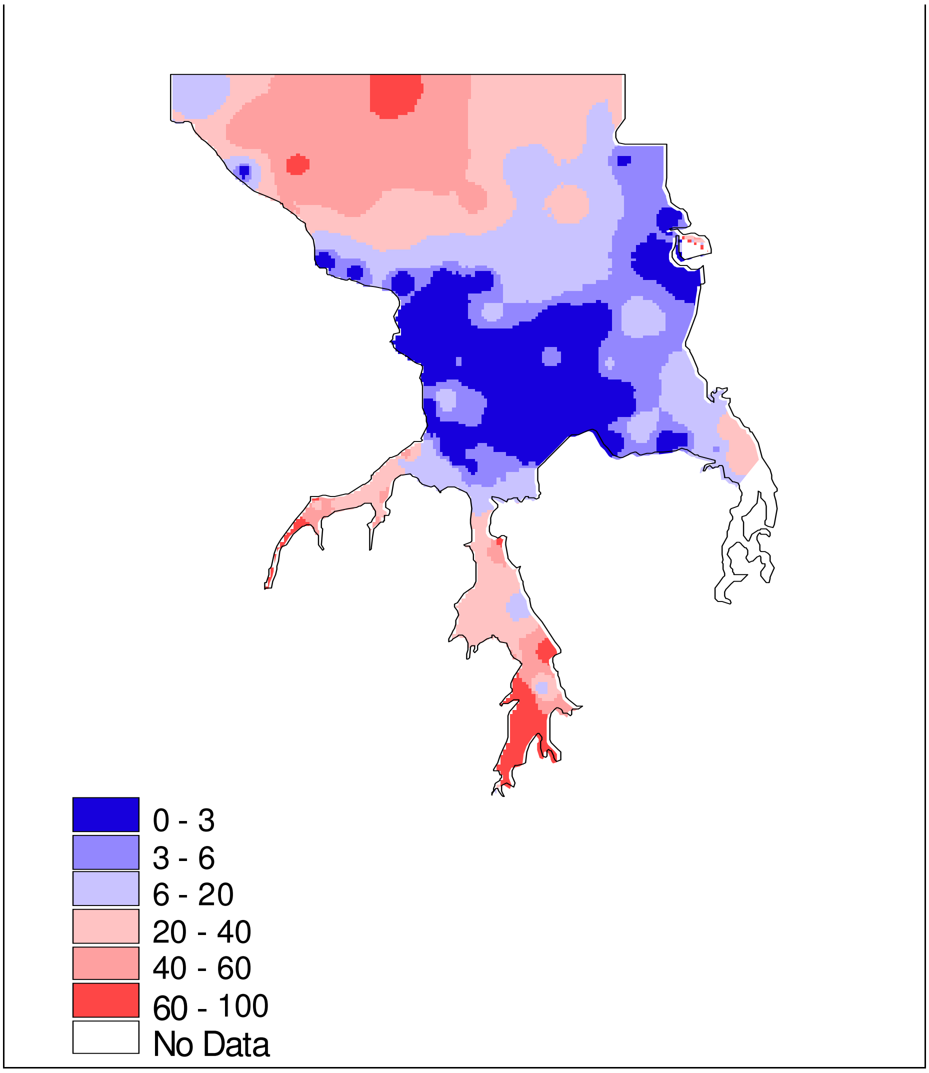


Figure 5.3: The percentage of organic content in the sediments (measured as loss on ignition %) in the Whitford embayment.

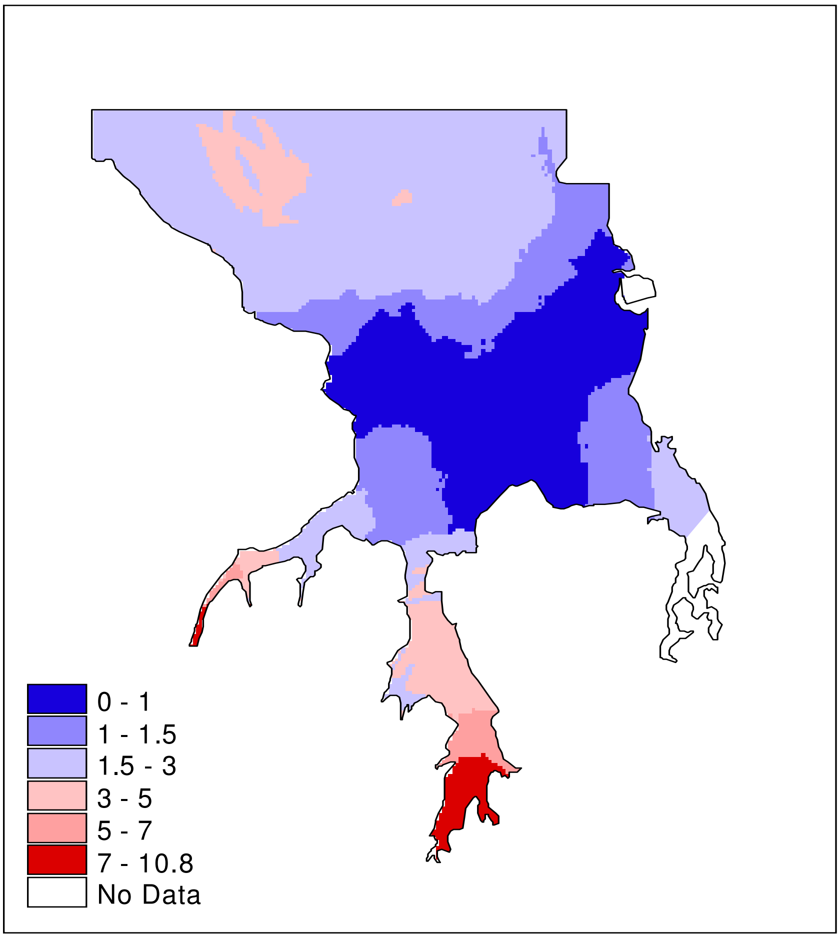
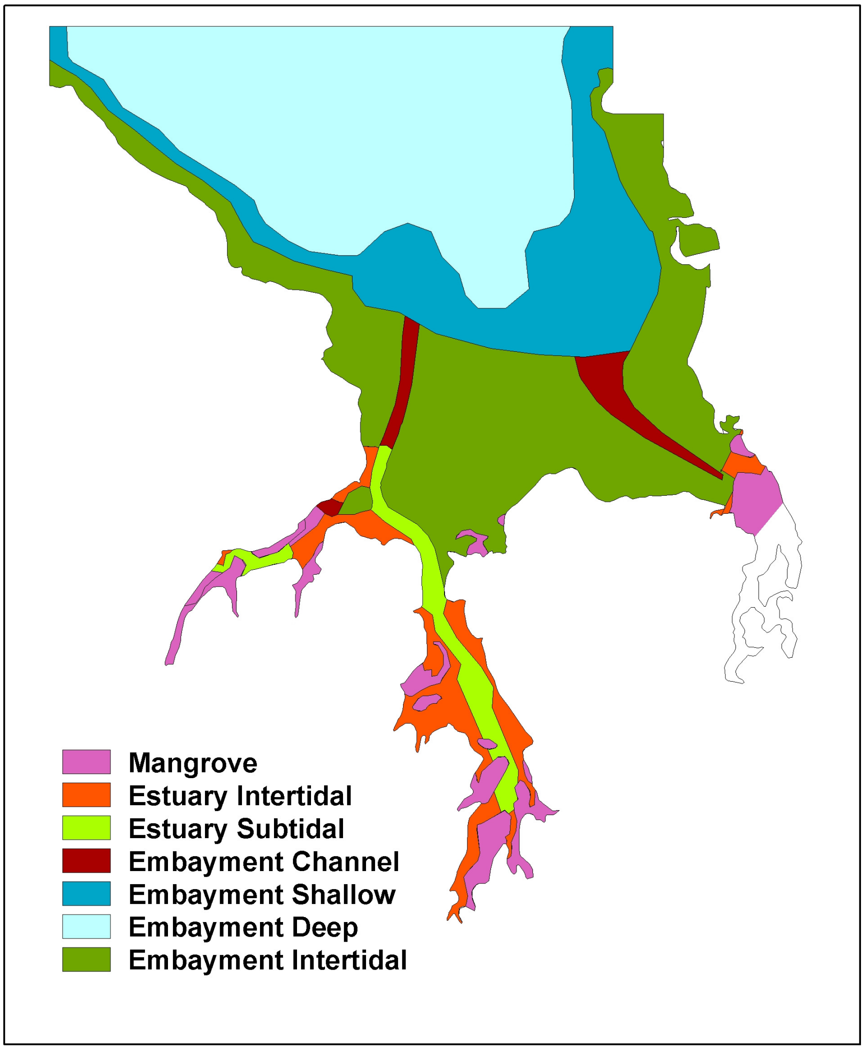


Figure 5.4: The distribution of major habitats in the Whitford Embayment.



The different habitat types exhibited distinctly different environmental characteristics and macrofaunal communities (Table 5.1). The differences between these habitat categories are particularly clear when examining the spatial distribution of mud in the Whitford Embayment and its tributary estuaries. On average, the mudflats of the "Estuary intertidal" have the highest mud content (>64%) whereas the sandflat sediments of the "Embayment intertidal" have the lowest mud content (2.5%). High mud contents are also present in the "Estuary subtidal" and "Embayment deep". The coarsest sediments are found in the "Embayment channel" and the "Embayment intertidal" (Table 5.1). The physical characteristics of the "Mangrove" habitat sampled in Mangemangeroa are similar to those found in the "Estuary intertidal" habitat (Table 5.1).

Table 5.1: Sediment characteristics, depth and the average number of taxa and individuals associated with the main marine habitat types identified in the Whitford Embayment and tributary estuaries. Number of taxa and number of individuals are mean values per core. Sediment grain sizes and organic content (OC) are expressed as percentages. Benthic chlorophyll a is expressed as mg g-1 sediment. Data are presented as the mean ± standard error (in brackets).

	Estuary Intertidal (n=12)	**Estuary subtidal (n=8)**	**Embayment intertidal (n=40)**	**Embayment channel (n=4)**	**Embayment shallow (n=9)**	**Embayment deep (n=17)**	**Mangrove (n=5)**
Clay & silt	64.1 (7.8)	15.5 (3.9)	2.5 (0.5)	8.4 (2.1)	3.8 (1.3)	33.3 (5.0)	50.4 (13.3)
Medium & fine sand	35.3 (7.8)	70.4 (5.6)	93.2 (1.4)	72.7 (13.2)	93.7 (1.9)	65.3 (5.3)	49.1 (13.3)
Coarse sand & gravel	0.2 (0.1)	14.1 (7.5)	4.2 (1.4)	18.9 (11.6)	2.4 (1.8)	1.4 (0.6)	0.5 (0.1)
Chlorophyll *a*	10.8 (0.5)	8.1 (1.4)	7.9 (0.6)	3.9 (1.0)	7.7 (1.0)	5.3 (0.4)	10.1 (1.1)
OC (%)	5.8 (0.9)	2.2 (0.2)	1.0 (0.1)	1.3 (0.1)	0.7 (0.1)	2.4 (0.2)	4.9 (1.2)
Depth (m)		2.1 (0.4)		3.0 (0.6)	1.7 (0.2)	4.7 (0.2)	
Number of taxa	11.2 (1.7)	11.6 (0.9)	18.1 (1.0)	25.3 (2.3)	11.0 (2.0)	12.7 (0.6)	13.6 (2.1)
Number of individuals	50.0 (8.6)	32.2 (11.6)	60.5 (8.2)	80.8 (21.6)	21.8 (5.7)	14.9 (2.6)	37.8 (10.4)

These clear differences in mud content between habitat types are matched by the distribution of organic matter in the sediment (Table 5.1). Also the average number of taxa and number of individuals differs between habitats. This analysis simply illustrates the diversity of habitats within the embayment. The table indicates that muddy habitats exhibit similar levels of diversity to some of the other sandier habitats in the embayment. The important issue is to maintain and enhance the diversity of habitats within the embayment, rather than have a system dominated by ever increasing proportions of muddy and mangrove habitats.

Table 5.2: Rankings of the five most numerically dominant macrofaunal taxa and their sensitivity to fine silts/clays in each habitat category. Na = not applicable. S = sensitive, I = no response; P = slightly positive response; PP = highly positive response to increasing mud content of the sediment (see Norkko et al. 2001). Percent similarity = percentage of community similarity accounted for by each individual taxa. Cumulative percentage similarity = cumulative percentage of macrobenthic community similarity accounted for by taxa. Note that the mangrove community found in Mangemangeroa has been extrapolated to the other mangrove areas. Further work might alter this.

Habitat & dominant taxa	**Faunal group**	**Species sensitivity**	**Percent similarity**	**Cumulative percentage similarity**
Estuary intertidal				
Paracorophium excavatum	Amphipod	PP	26.5	26.5
Helice crassa	Crab	PP	22.3	48.8
Aquilaspio aucklandica	Polychaete	I	12.0	60.8
Nereid	Polychaete	P	6.8	67.6
Heteromastus filiformis.	Polychaete	I	5.6	73.2
Estuary subtidal				
Capitellid	Polychaete	I	21.6	21.6
Oligochaeta	Oligochaete	PP	13.2	34.8
Aquilaspio aucklandica	Polychaete	I	10.8	45.6
Helice crassa	Crab	PP	8.6	54.2
Cossura sp.	Polychaete	S	8.1	62.3
Embayment intertidal				
Macomona liliana	Bivalve	S	13.0	13.0
Aquilaspio aucklandica	Polychaete	I	10.6	23.6
Austrovenus stutchburyi	Bivalve	S	9.5	33.1
Nucula hartvigiana	Bivalve	S	9.3	42.4
Colurostylis lemurum	Cumacean	S	6.0	48.4
Embayment channel				
Nucula hartvigiana	Bivalve	S	13.3	13.3
Heteromastus filiformis	Polychaete	I	11.7	25.0
Glycerid	Polychaete	I	10.3	35.3
Boccardia syrtis	Polychaete	S	10.0	45.3
Oligochaeta	Oligochaete	PP	8.4	53.7
Embayment shallow				
Waipirophoxus waipiro	Amphipod	S	41.0	41.0
Aricidea sp.	Polychaete	S	11.4	52.4
Tanaid	Crustacean	S	9.6	62.0
Exogonid	Polychaete	na	9.1	71.1
Cossura sp.	Polychaete	S	4.2	75.3
Embayment deep				
Theora lubrica	Bivalve	P	20.0	20,0
Cossura sp.	Polychaete	S	13.4	33.4
Lumbrinereid	Polychaete	P	12.8	46.2
Waipirophoxus waipiro	Amphipod	S	10.7	56.9
Sigalionidae	Polychaete	na	9.2	66.1
Mangrove				
Scolecolepides sp.	Polychaete	PP	17.4	17.4
Nereid	Polychaete	P	14.0	31.4
Helice crassa	Crab	PP	11.2	43.6
Oligochaeta	Oligochaete	PP	9.0	52.6
Heteromastus filiformis	Polychaete	I	7.9	60.5

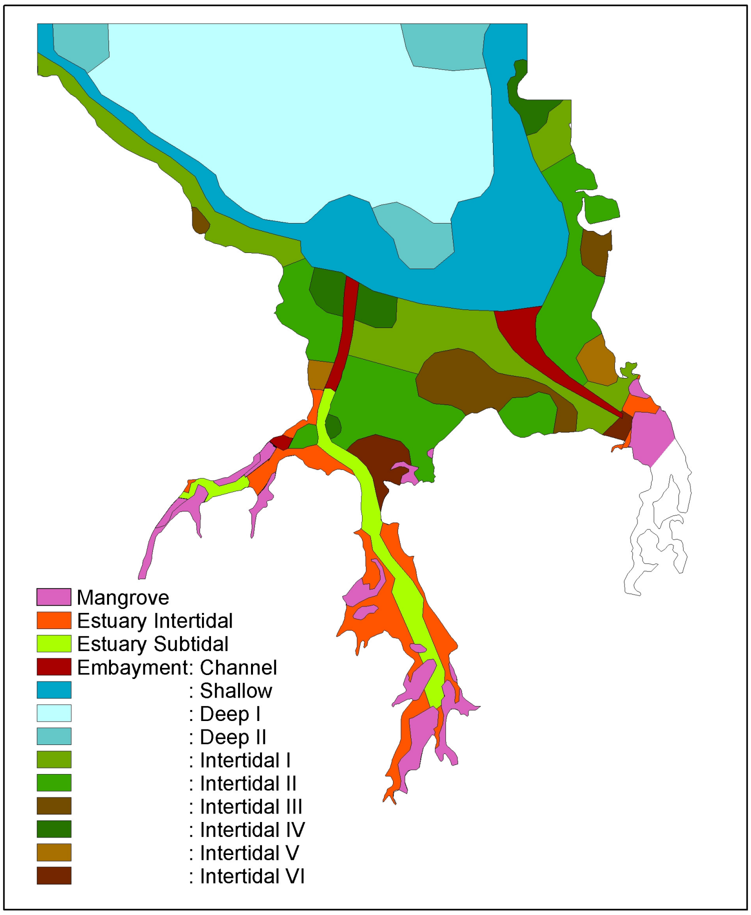
An analytical classification procedure (SIMPER: Clarke and Gorley 2001) was used to determine the taxa that were most important in defining the macrobenthic community composition in each habitat type. These taxa normally include the most numerically dominant members of their respective habitat. In the "Estuary intertidal" habitat the five top-ranked taxa defined 73% of within-habitat similarity in community composition (Table 5.2). This high explanatory power of only 5 taxa demonstrates the low macrobenthic diversity of these mud-enriched habitats. The amphipod Paracorophium excavatum and the mud crab Helice crassa together defined nearly 50%, and the spionid polychaete Aquilaspio aucklandica, nereid polychaetes and the capitellid polychaete Heteromastus filiformis accounted for another 23% of within-habitat similarity (Table 5.2). Some taxa are obviously widespread throughout different habitat types and, for example, Aquilaspio, is also a dominant in the "Estuary subtidal" as well as "Embayment intertidal" sandflats. Norkko et al. (2001) reports on the sensitivity of individual macrofaunal taxa to fine sediments. They found a wide variety of relationships between abundance and sediment mud content for individual species. Importantly, only a few taxa favored sediments containing high mud content. These are animals commonly found in habitats with high mud content of the sediment such as "Mangrove", "Inner estuary intertidal" and "Inner estuary subtidal" habitats. In contrast the "Embayment intertidal" and the "Embayment shallow" habitats are dominated by more sensitive species (Table 5.2). Comparisons between habitats and their associated animal communities is useful as it allows us to make predictions on possible trajectories of communities subject to increasing sedimentation and habitat change. The analytical procedure that determines the taxa most important in defining a habitat also gives an indication of how similar to one another the communities within the habitat type are (see Cumulative percentage similarity in Table 5.2). Whereas communities in the "Estuary intertidal" habitat are very similar to one another, the other habitats (particularly the "Embayment intertidal sandflats") contain more diverse communities. For example, the wedge shell Macomona liliana, Aquilaspio, the cockle Austrovenus stutchburyi, the nutshell Nucula hartvigiana and the crustacean Colurostylis lemurum dominate the intertidal sandflats (Table 5.2). The lower explanatory power of the five most dominant taxa (48%) demonstrate the comparatively high macrobenthic diversity of these sandflats as many other species/taxa are needed to more accurately explain within site variability. Even taking into account the 10 most dominant taxa, only 69% of this variability was explained. The intertidal sandflats of the "Embayment intertidal" and the mudflats of the "Estuary intertidal" and "Mangrove" habitats serve as two contrasting end-points in a likely range of macrobenthic communities from sediments dominated by sands to sediments dominated by mud.

The more variable habitats can be further split into a number of community types using clustering procedures. A K-means classification was conducted on the community data after a chord transformation, using a Calinski-Harabasz statistic as a stopping procedure (Legendre & Gallagher 2001). There were only sufficient sample sites to carry out this procedure for the "Embayment Intertidal" and "Embayment deep" habitats. For the "Embayment intertidal" a further six sub-habitats (or communities) were found, whereas the "Embayment deep" could be split into two (see Table 5.3; Fig. 5.5). The split of "Embayment intertidal" into a further six categories emphasises the overall diversity of these sandflats.

Table 5.3: Sub-habitats/communities found in the Embayment intertidal and deep habitats. Taxa are given in order of abundance.

Embayment intertidal						Embayment deep	
I	II	III	IV	V	VI	I	II
Aricidea	*Nucula*	*Aonides*	*Austrovenus*	*Orbinia*	*Scoloplos*	*Theora*	Phoxocephalids
Macroclymenella	*Austrovenus*	*Macomona*	*Anthopleura*		*Macomona*	*Cossura*	*Cossura*
Macomona	*Aquilaspio*	*Aquilaspio*				*Lumbrinereis*	*Capitella*
Aquilaspio	*Anthopleura*						*Glycera*
Nemertean							Tanaiids

Figure 5.5: Community map of the Whitford Embayment.

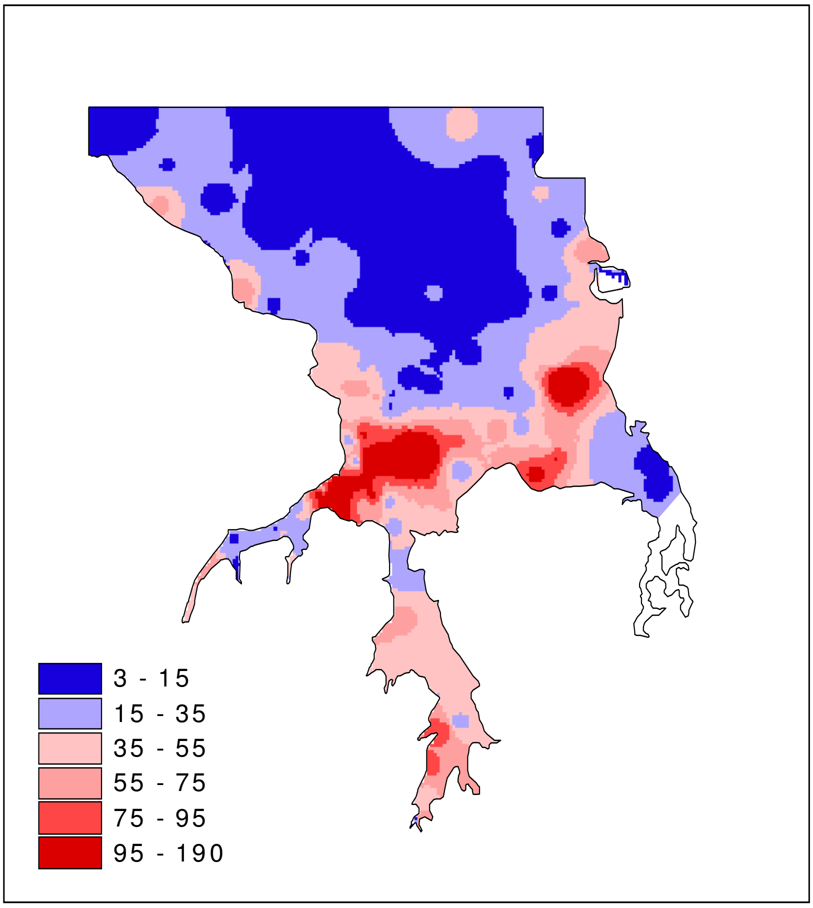


Results from the survey indicate that the Whitford embayment has a diverse range of habitats, ranging from the subtidal bottoms of the main embayment to the extensive intertidal sandflats, and to the inner estuary intertidal mudflats and mangrove communities. Plant and animal communities play important roles in the functioning of estuarine ecosystems. These processes include how nutrients are transported and transformed within the estuary and thus feedback to the productivity of mangroves, seagrass, microphytes and phytoplankton. These organisms provide food and shelter for many of the invertebrates, fish and birds that live and feed in the estuary. Another way that plant and animal communities are important is by influencing the movement and deposition of sediments and pollutants. These and other ecological and environmental processes determine the significant direct and indirect value to humanity of estuarine and coastal ecosystems. The diversity of habitats and communities present in the embayment enhance its overall ecological and recreational value. The main intertidal sandflats, in particular, provide important feeding and resting grounds for many species of birds. These values are indicated by the number of regions within the Whitford embayment designated as Coastal Protection Areas by ARC and more generally as an area of Significant Conservation Value by DOC (see Proposed Auckland Regional Plan: Coastal Schedule 3). This implies that although there have been changes in the embayment probably associated with historic activities in the catchment the embayment is not sufficiently degraded that risk of increased sediment loading poses no threat of further losses of important species and biological diversity. Careful management of catchment inputs and in-embayment activities are likely to maintain and improve populations of sensitive species, as well as habitat and species diversity.

5.4 Areas containing high numbers of taxa, high abundance and many sensitive species

We can visualise the spatial distribution of, for example, "hotspots" of benthic macrofaunal diversity by creating contour maps of numbers of taxa, number of individuals and proportion of sensitive species across the whole Whitford Embayment. This is done using the information from all 95 sample sites. These plots are intended to provide a broad overview of changes in the macrobenthic community around the Whitford Embayment; they are not intended to accurately predict values at specific locations.

Figure 5.6: The distribution of macrobenthic communities based upon numbers of individuals per core in the Whitford embayment.



Communities containing high numbers of individuals are mainly found on intertidal sandflats (Figure 5.6). High densities of animals generally indicate areas of high production. However, communities containing high abundances of animals can still be poor in terms of numbers of species found (see Figure 5.7 inner estuary sites). For example, inner estuary communities are dominated by a handful of species/taxa such as crabs (Helice crassa) and amphipod crustaceans (Paracorophium excavatum) that occur in high densities (Table 5.2; Figure 5.8). Areas with both high numbers of species and individuals, the "hotspots" of species diversity, are mostly found on the intertidal sandflats of the "Embayment intertidal".

Figure 5.7: The distribution of macrobenthic communities based on numbers of taxa per core in the Whitford Embayment.

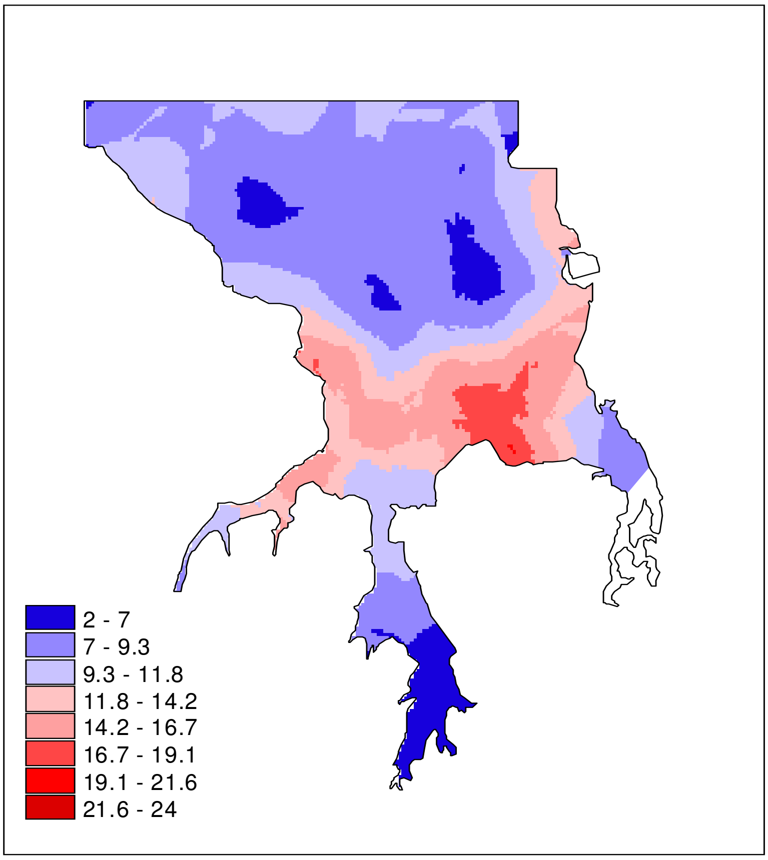
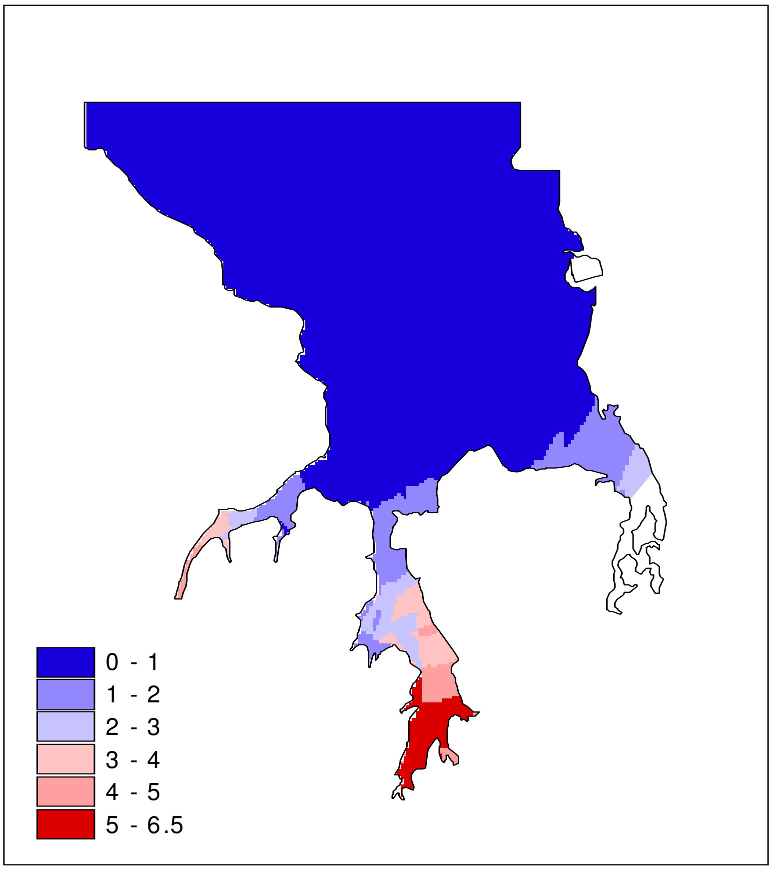
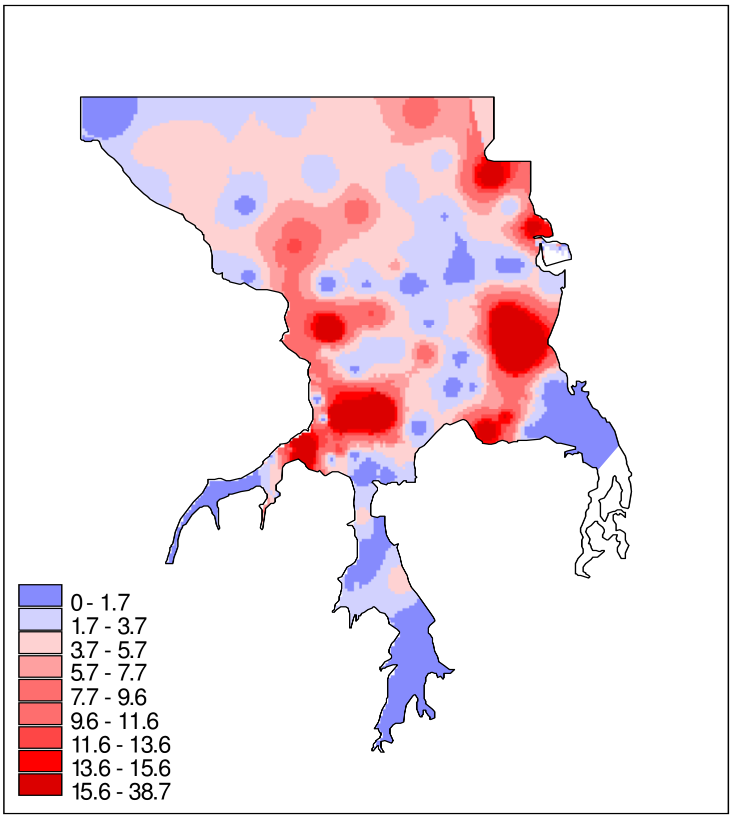


Figure 5.8: The distribution of the mud crab Helice crassa (number per core) in the Whitford Embayment.



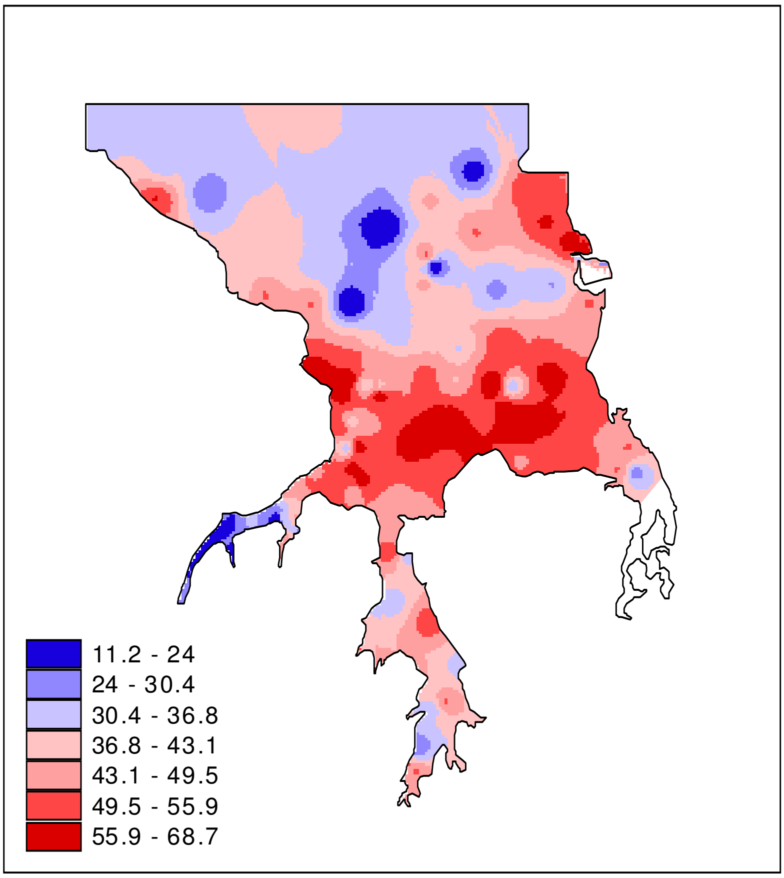
Suspension feeders have an important position in many energy pathways in the estuarine food web. Suspension feeders feed by removing particles from the water, thus, they are likely to be directly impacted by changes to suspended sediment (Hewitt et al. 2001). In estuaries and coastal embayments, such as Whitford, a significant proportion of the benthic macrofauna can be suspension feeders. Furthermore, as most of the shellfish consumed by people are suspension feeders (e.g., oysters, mussels, cockles and pipi), they play a dominant role in the public perception of these environments. They are also important food items for many bird and fish species. In the Whitford embayment, the highest numbers of suspension feeders are found on intertidal sandflats, the main channels and subtidal habitats of the embayment (Figure 5.9). In contrast, the inner estuary habitats and communities only have very low numbers belonging to this group. The highest abundances of suspension feeders coincide spatially with the areas determined as "hotspots" of diversity (compare Figure 5.7.), and in areas in close proximity of more muddy habitats (e.g., Mangemangeroa; Figure 5.9.). These animals might not necessarily be exposed to high levels of sediment deposition, but still experience high levels of suspended sediment with negative effects on their condition and health (Hewitt et al. 2001)

Figure 5.9: The distribution of the suspension feeders (individuals per core) in the Whitford Embayment.



The main intertidal sandflats of the Embayment are the areas with the highest proportion of taxa sensitive to muddy sediments (data derived from Norkko et al. 2001; Figure 5.10). Although some "hotspots" of sensitivity also are found in the Turanga estuary, sensitive taxa are found over a wide expanse on the intertidal sandflats.

Figure 5.10: The proportion of sensitive individuals (expressed as a %) found in the communities throughout in the Whitford embayment (see Norkko et al. 2001 for sensitivity analysis).



5.5 Ecological diversity and responses to increasing sediment deposition

The survey provides a snapshot of the present distribution patterns of habitats and animal communities in the embayment. Our results suggest that there is a close relationship between mud content of sediment and the diversity of animal communities. Previous studies in Okura Estuary have shown a good correlation between the risk of sedimentation events and sediment characteristics (Stroud et al. 1999a, b). Recent studies in the Whitford embayment support these findings with respect to both suspended sediment concentrations (Hewitt et al. 2001) and recently deposited terrigenous sediments (Gibbs et al. 2001). This implies that the community-sediment relationships derived from this study (and elaborated upon in Norkko et al. 2001) can help predict the implications of change in the embayment due to changes in the sedimentation regime on longer-term macrofaunal distributions.

Based on the distribution of animal communities, total abundances and numbers of taxa, we can identify areas of high ecological diversity. These mainly occur on the main intertidal sandflats of the Whitford Embayment. The entrance areas of tributary estuaries Mangemangeroa, Turanga, and Waikopua are dynamic environments and may be viewed as ecological transition zones between different habitat types. They are also areas likely to be particularly sensitive to sediment impacts as these communities have high species/taxa diversity (Figure 5.7) and contain a high proportion of sensitive species (Figure 5.10).

Previous work conducted in the Okura estuary (e.g., Norkko et al. 1999, Nicholls et al. 2000) focused on examining the catastrophic effects of sediment deposition on the ecology of estuaries. This work was instrumental in developing the criteria for acute catastrophic deposition rates (e.g., the 2-cm rule) and has subsequently, through work completed within the framework of our FRST-programme, proved to be a generally applicable rule of thumb as verified from experimental work completed in Coromandel estuaries. However, catchment modelling conducted in Okura estuary (Stroud et al. 1999a, b) demonstrated that catastrophic sedimentation events are infrequent, and that events producing deposition on the order of 2-3 mm were 21 times more common. More recent and ongoing work also suggests that less dramatic sediment depositions could pose a threat to the ecology of estuarine ecosystems. Hence new aspects of our ongoing research, conducted both within our ongoing FRST work as well as through work recently completed in the Whitford embayment under the auspices of ARC (e.g., Hewitt et al. 2001, Berkenbusch et al. 2001, Gibbs et al. 2001) concentrate on the more chronic effects of terrigenous sediments on estuarine ecology.

Berkenbusch et al. (2001) demonstrated that 5 mm deposits of terrigenous sediments had significant negative effects on benthic communities by reducing the abundance of common taxa by around 40% over 10 days. Although some ecological effects also were found for thinner clay layers, rates of recovery were rapid (i.e., 10 days). Therefore unless small sediment depositions (i.e., 2-3 mm) were to occur very frequently or cover large areas, they could be considered to pose less of a risk of further degradation given the present status of the estuary and its sedimentation history. Such events may however, hinder improvements to the ecological status of the embayment. Hence, apart from the 2 cm acute deposition thickness already utilised in the Okura risk assessment work we added a more chronic, 5 mm clay deposition and also 2 and 1 mm thin depositions, to the present assessment. This provides a significant advancement from previous studies conducted in Okura.

To date all our experiments that have generated effects on the benthic community have demonstrated negative impacts. The magnitude of impact depends on the depth of mud deposited, spatial extent of effect, persistence of deposits, the frequency of depositional events and the sensitivity of the impacted community. Potential ecological responses include both structural and functional changes to benthic communities over various time scales. Although responses will be habitat/community dependent, the following generalities are likely to hold true.

- Terrestrial mud deposits >20 mm thick, which persist for more than 5 days, will turn the underlying estuarine sediments anaerobic and kill all resident macrofauna with the exception of mobile crabs and shrimp (Norkko et al. 1999).
- 5 mm thick terrigenous mud deposits, which persist for 10 days will reduce both the number of taxa and abundance within common taxa, and thus change the macrobenthic community structure (Berkenbusch et al. 2001).
- Between the 5 mm and 20 mm, adverse effects will become successively greater with increased depth of sediment deposited.
- Frequent sediment deposition < 5mm can have a long-term cumulative effect, resulting in a change in macrobenthic communities (Berkenbusch et al. 2001).

These last 2 points are particularly important if catchment development were to increase the frequency, depth, and spatial extent of thin deposits of terrigenous sediments on the highly diverse sandflats on the “Embayment intertidal”.

6 Analysis

6.1 Methodology

A risk-based procedure has been developed to condense the large amount of information obtained from the numerical model simulations into a format that is clear, concise and complies with the Description of Services, namely to:

"address the issue of risk to the ecology of the Mangemangeroa, Turanga and Waikopua estuaries and the wider coastal embayment, from sediment runoff from the surrounding catchment during the earthworks phase of potential rural development scenarios."

Risk may be defined as a combination of a) the degree of undesirable consequences and b) the probability of occurrence of these consequences. The undesirable consequences in this instance are measured as the reduction in species diversity due to burial by terrigenous sediment. The level of risk for two development options (Scenario 1 and Scenario 2) is compared with the Existing land use.

The first component of risk, calculating the degree of undesirable consequences, is reported in Section 3. Sediment deposition patterns were predicted for 90 physical conditions, covering the expected range of flood magnitudes, winds and tide ranges. The depth of deposited sediment was then related to the reduction in species diversity (Section 4).

Each of these 90 physical conditions can be assigned a probability of occurrence. Tides are generated by astronomical forcing, and are predictable. At any given instant, the chance that the tide range is near neap is 0.25. Similarly the chance of a near spring tide range is 0.25 and a mean tide has a probability of 0.5.

Meteorological forcing generates both wind and rain (and therefore runoff) and cannot be accurately predicted far into the future, so historical data is required to estimate the probability of future storms. Local experience may indicate that, for example, "the majority of heavy rain comes with a northeast wind", i.e., the wind and rainfall are correlated. This correlation needs to be taken into account when calculating the probabilities of storm events. Using the climate database (http://clidb.niwa.cri.nz:8090/), wind and rainfall data were obtained for the period 1 January 1964 to 1 January 2003. Rain measured at Owairaka and wind measured at Whenuapai, Owairaka and Auckland airports were used in the analysis. Each of the 161 Mangemangeroa events used to determine the flood classes in Section 3.1.2 were compared with the corresponding wind and rainfall data for the period of that event. For each flood event, the wind was identified as either "calm", or from the NE, SE, SW or NW. Table 6.1 shows the joint frequency of runoff and wind. The number of events in each bin was quite low, particularly for the larger events, so smoothing was applied to make the trend monotonic for the larger events. Table 6.1 indicates that most flood events are associated with a northeasterly wind, but it is not a strong correlation. Flood events also occur regularly with southwesterly winds, and can occur under any wind condition, including relatively calm conditions. The historical data shows that 161 events have occurred in 37 years, which is an average of 4.35 events per year. By multiplying the values in Table 6.1 by 4.35, the expected annual frequency of future flood events is obtained for each wind direction. These can then simply be combined with the probability of each tide range to get the expected annual frequency for any combination of flood magnitude, wind and tide range.

It is worth noting that while historical records provide the best information available, they may not be a true representation of the frequency of future meteorological events. In the Pacific region, the climate is known to change slightly due to the Interdecadal Pacific Oscillation2, which has been in a positive phase for the last 20 years but has recently entered a negative phase. Also, despite the large amount of media attention, the effect and magnitude of climate change associated with global warming is still not accurately known. It has been predicted that sea levels will continue to increase, though the response of estuaries, both in physical characteristics and biological impact, is not yet clear. It has also been suggested that the frequency of large storms may increase.

Table 6.1: Joint frequency of runoff and wind, expressed as a percent of the total number of events (161) in the analysis.

Wind / Runoff	Calm	NE	SE	SW	NW
1	5.6	18.6	9.9	14.3	13.7
2	3.1	8.7	3.7	1.9	4.3
3	1.9	3.1	2.0	0.8	2.5
4	0.4	1.2	0.3	0.8	0.4
5	0.1	0.6	0.2	0.7	0.1
6	0.1	0.6	0.0	0.2	0.1

The risk of ecologically damaging sedimentation can be measured as the probability of various levels (thresholds) of sedimentation being exceeded throughout the embayment. Instead of applying this measure of risk to every 50 × 50 m cell within the Whitford embayment, we can apply the analysis to regions selected with regard to the spatial variation in the number of taxa and the hydrodynamics. To achieve this, four Bands of Common Vulnerability (BCV) were defined (Figure 5.1). Also investigated were two Regions of Special Vulnerability (RSV) (Figure 5.2). The BCV's provide a framework for assessing risk in areas of

[2] See www.niwa.cri.nz/ncc/icu/2002-06/article for more information on the Interdecadal Pacific Oscillation.

different ecological diversity, the rationale being that increased risk of sedimentation in areas containing higher numbers of taxa is of more concern than sedimentation in areas with fewer taxa. The RSV's were chosen to target the area of highest diversity and a habitat transition area with high densities of suspension-feeding shellfish.

The area of each region is:

BCV 1 1.83 km2

BCV 2 1.76 km2

BCV 3 4.77 km2

BCV 4 5.97 km2

RSV 1 0.20 km2

RSV 2 0.50 km2

Figure 6.1: Bands of Common Vulnerability (BCV) within the Whitford estuaries and embayment. Four bands are identified, indexed by increasing distance from the sediment source. The bands were chosen by considering the number of taxa in each region (Figure 5.7) and the physical characteristics of the sub-environment (upper/middle/lower estuary and sub or intertidal).

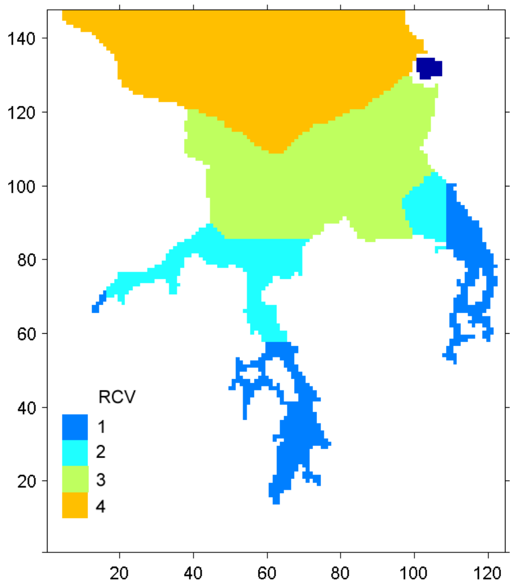
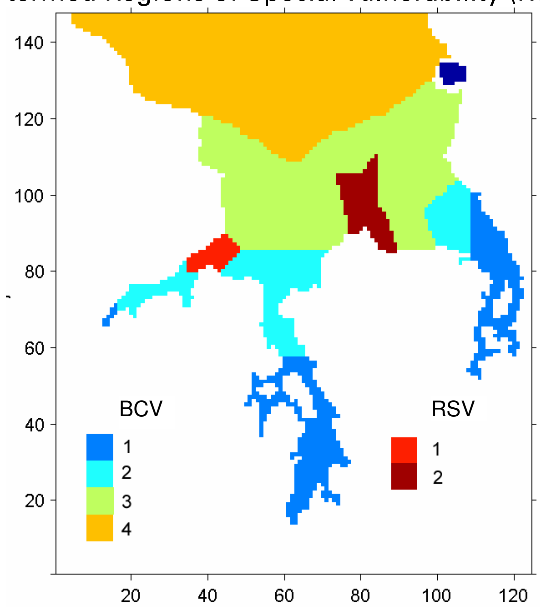


Figure 6.2: In addition to the 4 BCV's, 2 additional regions were identified as warranting more focus due to locally increased number of taxa. These regions are therefore areas of potentially higher vulnerability. These two areas (shown above) are termed Regions of Special Vulnerability (RSV).



For each region (BCV or RSV), the sediment thickness from each of the 90 simulations was compared against 5 threshold levels: 1, 2, 5, 10 and 20 mm. If the threshold was exceeded in any of the 50 × 50 m cells within a region, then the whole of that region was classed as "damaged". This was repeated using the criterion that 1, 2, 5, 10 and 20% of the area of each region must exceed the sediment thickness threshold before the region was classed as damaged.

Each combination of runoff, tide range and wind that results in a sediment threshold being exceeded is termed a "damaging physical condition". For each region (4 BCV's and 2 RSV's), each threshold (1, 2, 5, 10, 20 mm) and each criterion (any 50 × 50 m cell, and 1, 2, 5, 10, 20% of the region area), all the damaging physical conditions were identified, and the corresponding probabilities of occurrence added together. This gives the expected annual frequency of damaging sedimentation for each region. The analysis is performed for the Existing land use, and the two development options, Scenario 1 and 2. The results are presented in Table 6.2.

Table 6.2a: Expected annual frequency that threshold deposition is exceeded in any 50 × 50 m area.

	Threshold levels of deposition (mm)				
	1	**2**	**5**	**10**	**20**
Existing					
BCV 1	4.330	3.825	1.028	0.343	0.123
BCV 2	4.330	4.330	1.903	0.785	0.285
BCV 3	0.305	0.223	0.123	0.040	0.000
BCV 4	0.493	0.285	0.078	0.023	0.000
RSV 1	1.533	1.188	0.468	0.173	0.075
RSV 2	0.078	0.048	0.000	0.000	0.000
Scenario 1					
BCV 1	4.330	4.175	1.383	0.398	0.130
BCV 2	4.330	4.330	3.013	0.895	0.350
BCV 3	0.318	0.245	0.123	0.043	0.000
BCV 4	0.493	0.353	0.088	0.030	0.000
RSV 1	1.553	1.188	0.483	0.213	0.075
RSV 2	0.100	0.048	0.000	0.000	0.000
Scenario 2					
BCV 1	4.330	4.330	2.345	0.645	0.148
BCV 2	4.330	4.330	3.658	1.415	0.420
BCV 3	0.458	0.245	0.138	0.080	0.000
BCV 4	1.173	0.373	0.108	0.033	0.000
RSV 1	2.438	1.413	0.613	0.213	0.093
RSV 2	0.110	0.055	0.000	0.000	0.000

Table 6.2b: Expected annual frequency that threshold deposition is exceeded in 1% or greater of the region area.

	Threshold levels of deposition (mm)				
	1	**2**	**5**	**10**	**20**
Existing					
BCV 1	3.865	1.620	0.423	0.123	0.003
BCV 2	1.700	0.978	0.370	0.150	0.068
BCV 3	0.063	0.033	0.000	0.000	0.000
BCV 4	0.100	0.020	0.000	0.000	0.000
RSV 1	1.533	1.188	0.468	0.173	0.075
RSV 2	0.070	0.025	0.000	0.000	0.000
Scenario 1					
BCV 1	4.330	1.620	0.523	0.188	0.015
BCV 2	2.035	1.078	0.378	0.195	0.075
BCV 3	0.070	0.040	0.000	0.000	0.000
BCV 4	0.100	0.020	0.000	0.000	0.000
RSV 1	1.553	1.188	0.483	0.213	0.075
RSV 2	0.070	0.040	0.000	0.000	0.000
Scenario 2					
BCV 1	4.330	3.253	0.683	0.228	0.068
BCV 2	2.680	1.533	0.523	0.203	0.085
BCV 3	0.075	0.040	0.003	0.000	0.000
BCV 4	0.100	0.020	0.000	0.000	0.000
RSV 1	2.438	1.413	0.613	0.213	0.093
RSV 2	0.085	0.040	0.000	0.000	0.000

Table 6.2c: Expected annual frequency that threshold deposition is exceeded in 2% or greater of the region area.

	Threshold levels of deposition (mm)				
	1	**2**	**5**	**10**	**20**
Existing					
BCV 1	2.525	0.710	0.233	0.078	0.000
BCV 2	0.938	0.528	0.185	0.080	0.000
BCV 3	0.040	0.008	0.000	0.000	0.000
BCV 4	0.060	0.010	0.000	0.000	0.000
RSV 1	1.398	0.688	0.263	0.103	0.000
RSV 2	0.048	0.000	0.000	0.000	0.000
Scenario 1					
BCV 1	3.650	1.098	0.240	0.108	0.000
BCV 2	1.168	0.620	0.200	0.080	0.000
BCV 3	0.040	0.008	0.000	0.000	0.000
BCV 4	0.080	0.015	0.000	0.000	0.000
RSV 1	1.438	0.868	0.270	0.103	0.000
RSV 2	0.055	0.000	0.000	0.000	0.000
Scenario 2					
BCV 1	4.175	1.620	0.310	0.118	0.000
BCV 2	1.820	0.815	0.230	0.113	0.008
BCV 3	0.040	0.033	0.000	0.000	0.000
BCV 4	0.100	0.020	0.000	0.000	0.000
RSV 1	1.753	0.998	0.323	0.128	0.030
RSV 2	0.070	0.013	0.000	0.000	0.000

Table 6.2d: Expected annual frequency that threshold deposition is exceeded in 5% or greater of the region area.

	Threshold levels of deposition (mm)				
	1	**2**	**5**	**10**	**20**
Existing					
BCV 1	1.115	0.315	0.045	0.000	0.000
BCV 2	0.350	0.153	0.010	0.000	0.000
BCV 3	0.000	0.000	0.000	0.000	0.000
BCV 4	0.000	0.000	0.000	0.000	0.000
RSV 1	0.703	0.450	0.148	0.015	0.000
RSV 2	0.000	0.000	0.000	0.000	0.000
Scenario 1					
BCV 1	1.345	0.480	0.048	0.000	0.000
BCV 2	0.458	0.203	0.010	0.000	0.000
BCV 3	0.000	0.000	0.000	0.000	0.000
BCV 4	0.015	0.000	0.000	0.000	0.000
RSV 1	0.738	0.450	0.148	0.048	0.000
RSV 2	0.008	0.000	0.000	0.000	0.000
Scenario 2					
BCV 1	1.760	0.588	0.090	0.000	0.000
BCV 2	0.678	0.255	0.025	0.000	0.000
BCV 3	0.000	0.000	0.000	0.000	0.000
BCV 4	0.020	0.000	0.000	0.000	0.000
RSV 1	0.963	0.535	0.175	0.075	0.000
RSV 2	0.010	0.000	0.000	0.000	0.000

Table 6.2e: Expected annual frequency that threshold deposition is exceeded in 10% or greater of the region area.

	Threshold levels of deposition (mm)				
	1	**2**	**5**	**10**	**20**
Existing					
BCV 1	0.370	0.080	0.000	0.000	0.000
BCV 2	0.140	0.003	0.000	0.000	0.000
BCV 3	0.000	0.000	0.000	0.000	0.000
BCV 4	0.000	0.000	0.000	0.000	0.000
RSV 1	0.365	0.163	0.015	0.000	0.000
RSV 2	0.000	0.000	0.000	0.000	0.000
Scenario 1					
BCV 1	0.370	0.093	0.000	0.000	0.000
BCV 2	0.160	0.003	0.000	0.000	0.000
BCV 3	0.000	0.000	0.000	0.000	0.000
BCV 4	0.000	0.000	0.000	0.000	0.000
RSV 1	0.380	0.175	0.015	0.000	0.000
RSV 2	0.000	0.000	0.000	0.000	0.000
Scenario 2					
BCV 1	0.640	0.138	0.000	0.000	0.000
BCV 2	0.195	0.030	0.000	0.000	0.000
BCV 3	0.000	0.000	0.000	0.000	0.000
BCV 4	0.000	0.000	0.000	0.000	0.000
RSV 1	0.415	0.208	0.023	0.000	0.000
RSV 2	0.000	0.000	0.000	0.000	0.000

Table 6.2f: Expected annual frequency that threshold deposition is exceeded in 20% or greater of the region area.

	Threshold levels of deposition (mm)				
	1	**2**	**5**	**10**	**20**
Existing					
BCV 1	0.005	0.000	0.000	0.000	0.000
BCV 2	0.000	0.000	0.000	0.000	0.000
BCV 3	0.000	0.000	0.000	0.000	0.000
BCV 4	0.000	0.000	0.000	0.000	0.000
RSV 1	0.100	0.010	0.000	0.000	0.000
RSV 2	0.000	0.000	0.000	0.000	0.000
Scenario 1					
BCV 1	0.023	0.000	0.000	0.000	0.000
BCV 2	0.000	0.000	0.000	0.000	0.000
BCV 3	0.000	0.000	0.000	0.000	0.000
BCV 4	0.000	0.000	0.000	0.000	0.000
RSV 1	0.133	0.010	0.000	0.000	0.000
RSV 2	0.000	0.000	0.000	0.000	0.000
Scenario 2					
BCV 1	0.060	0.000	0.000	0.000	0.000
BCV 2	0.000	0.000	0.000	0.000	0.000
BCV 3	0.000	0.000	0.000	0.000	0.000
BCV 4	0.000	0.000	0.000	0.000	0.000
RSV 1	0.153	0.035	0.000	0.000	0.000
RSV 2	0.000	0.000	0.000	0.000	0.000

To estimate the reduction in species diversity corresponding to each deposition thickness, the manipulative experiments described in Berkenbusch et al. (2001) were used. These experiments were located in BCVs 2 – 4 (see Table 6.3) and deal with the effect of 0 mm to 7 mm of sediment deposition on benthic fauna. For sediment deposition between 0 mm to 7 mm, linear relationships (one for each possible region) were derived from this data, thus providing the relationship between the deposition of terrigenous sediment and the reduction in diversity. A different linear relationship was used over the sediment deposition range 7 to 20 mm, with no surviving taxa for sediment thickness greater then 20 mm. Linear relationships were selected for use, these being the most reasonable first-order approximation based on the available information. A more complex relationship might exist, but without more evidence it could not be used with confidence.

There are a number of points to consider when using the relationships calculated for the 0 to 7 mm sediment deposition thicknesses. Throughout we have taken a conservative approach to predicting effects. (1) The relationships used for determining ecological damage in BCVs 2 and 3 are the same for both BCVs. This is because there was no significant difference for any of the experimental sites between the slope of the linear relationship at a particular site and that estimated from all sites together. While appropriate statistically, this may result in an averaging of effect across these BCVs. (2) Three experiments were carried out in RSV2, two in November and one in January. The November experiments resulted in relationships very similar to each other, but with a markedly stronger response to sediment deposition than found in the January experiment. The relationship for RSV2 was obtained by averaging the slopes from the three experiments. (3) We did get very different results for experiments carried out at different times of the year, implying seasonal variation in sensitivity to terrestrial sediment deposition. The only area for which we have an estimate that is based on more than one time is RSV2. Relationship estimates for all other areas come from the January experiments and thus the effect of the sediment deposition may be less than would be obtained in November. (4). We have no results for BCV1 or RSV1. However, one of the experimental sites was located along the channel margin running out from Mangemangeroa. This site had similar fauna to the RSV1 area: abundant large *Austrovenus, Anthopleura, Nucula and Chamaesipho*. Thus, we used the results from this site for estimating ecological risk to RSV1.

We have focused our description of ecological damage on the effect on species diversity, as measured by the number of taxa. This variable was chosen because we are able to use information derived from field experiments in Whitford to model the strength of the community response to sediment deposition of various thicknesses. It is important to note that our predictions of effects are based solely on the immediate disturbance associated with terrestrial sediments smothering the surface of marine sediments in the embayment (see section 5.4 for cautionary notes on interpretation of risk).

The results of the relationships between sediment deposition and ecological damage were then converted to sediment deposition thicknesses that resulted in mortality of 100, 75, 50, 25 and 10% of all taxa. To place these changes in perspective with natural spatial variability, we attempted to quantify natural variability in the number of taxa. We randomly selected times for which we had data from sites in Mahurangi, Manukau and Waitemata harbours that have essentially similar habitats to those found in Whitford. For each of these sites and times, we estimated changes in the number of taxa between contiguous sets of four samples. This work suggested that a "natural" median variability in number of taxa might be around 6% (with an upper quartile of 8% and a 95th percentile of 15%). Thus changes in number of taxa of less than 10% are within our level of uncertainty in the risk assessment.

Finally, the risk of ecological damage due to burial by terrigenous sediment was assessed by plotting the results given in Table 6.2 and superimposing the expected change in biodiversity for each of the sediment threshold levels. Figure 6.3 shows simplified plots for all six regions on a single page and to the same scale for ease of comparison. Results shown in this plot are for sediment covering more than 1% of each region. Figures 6.4 to 6.9 show the same plots in a larger format, with the added detail of the results for all the sediment area criteria. The grey boxes indicate the degree of ecological damage to the estuary (measured by percent change in biodiversity) and the graph lines indicate how often this damage is likely to occur for a given proportion of each region.

Table 6.3: Empirical evidence for predicted changes in benthic communities in BCV's and RSV's, based on experiments detailed in Berkenbusch (2001). The range given in this table is that derived from the survey carried out in October 2000. The average number of taxa found in the control sites during the January 2001 experiments frequently differs from this range, due to seasonal variability in the number of taxa. The caveats are described in Section 5.4.

BCV	**Average number of taxa (core^{-1})**	**General comments on sensitivity of region**	**Information derived from field experiments on ecological effects of thin (0.5 - 5 mm) deposits**	**Caveats to assessment of ecological damage**
1	2 - 7	Faunal communities dominated by taxa favoured by fine sediments		
4	7 – 9.3	Faunal communities have taxa favoured by fine sediments. Few juveniles or suspension feeders	Subtidal experiment: Decreases in Ostracods, *Theora* and Cossura Loss of 2.5 taxa with depths around 5mm	1 – 4 hold but 3 may be less important in this region
2	9.3 – 11.8	Faunal communities include some juveniles and suspension feeders	Intertidal experiment – mud site: Decreases in *Austrovenus*, *Arthritica* Loss of 2.9 taxa with depths around 5 mm	1 – 6 hold but 5 and 6 may be less important in this region
2 RSV1	11.8 – 14.2	Large numbers of suspension feeders, some juveniles.	Intertidal experiment – low site: Decreases in *Austrovenus*, *Notoacmea* Loss of 2.9 taxa with depths around 5 mm	1 – 6 hold. 2 and 6 are particularly important in this region
3	14.2 – 16.7	Large numbers of juveniles, suspension feeders and animals characteristic of sandy sediments	Intertidal experiment – diatom site: Decreases in *Austrovenus*, *Aonides*, *Trochodota* Loss of 2.9 taxa with depths around 5 mm	1 – 6 hold. 2, 5 and 6 are particularly important
3 RSV2	16.7 – 24.0	Large numbers of juveniles and many different types of suspension feeders	Intertidal experiments – Worm/cockle site: Decreases in *Aquilaspio*, *Austrovenus*, *Macomona*, *Nucula*, *Aonides*, Orbinids and *Paracalliope*. Loss of 5.55 taxa with depths around 5 mm	1 – 6 hold. 5 and 6 are particularly important

Figure 6.3: Expected annual frequency of deposition thickness (from Table 6.2) and expected change in biodiversity in each region (BCV and RSV). Shown are the Existing, Scenario 1 and Scenario 2 results with sediment covering greater than 1% of each region. The grey boxes (data not available for BCV1) indicate the degree of ecological damage to the estuary (measured by percent change in biodiversity) and the graph lines indicate how often this damage is likely to occur for a given proportion of each region.

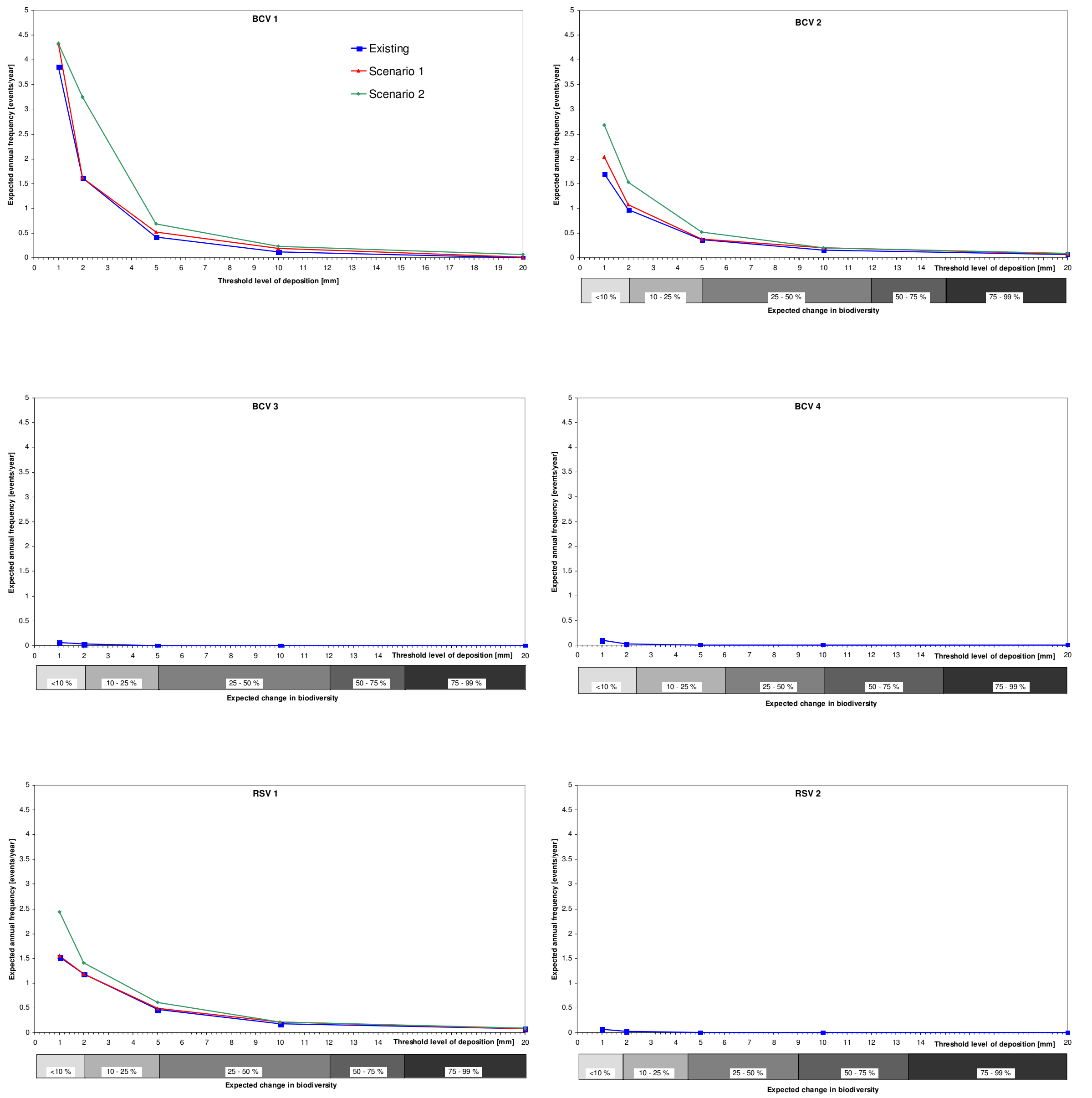


Figure 6.4: Expected annual frequency of deposition thickness in BCV 1.

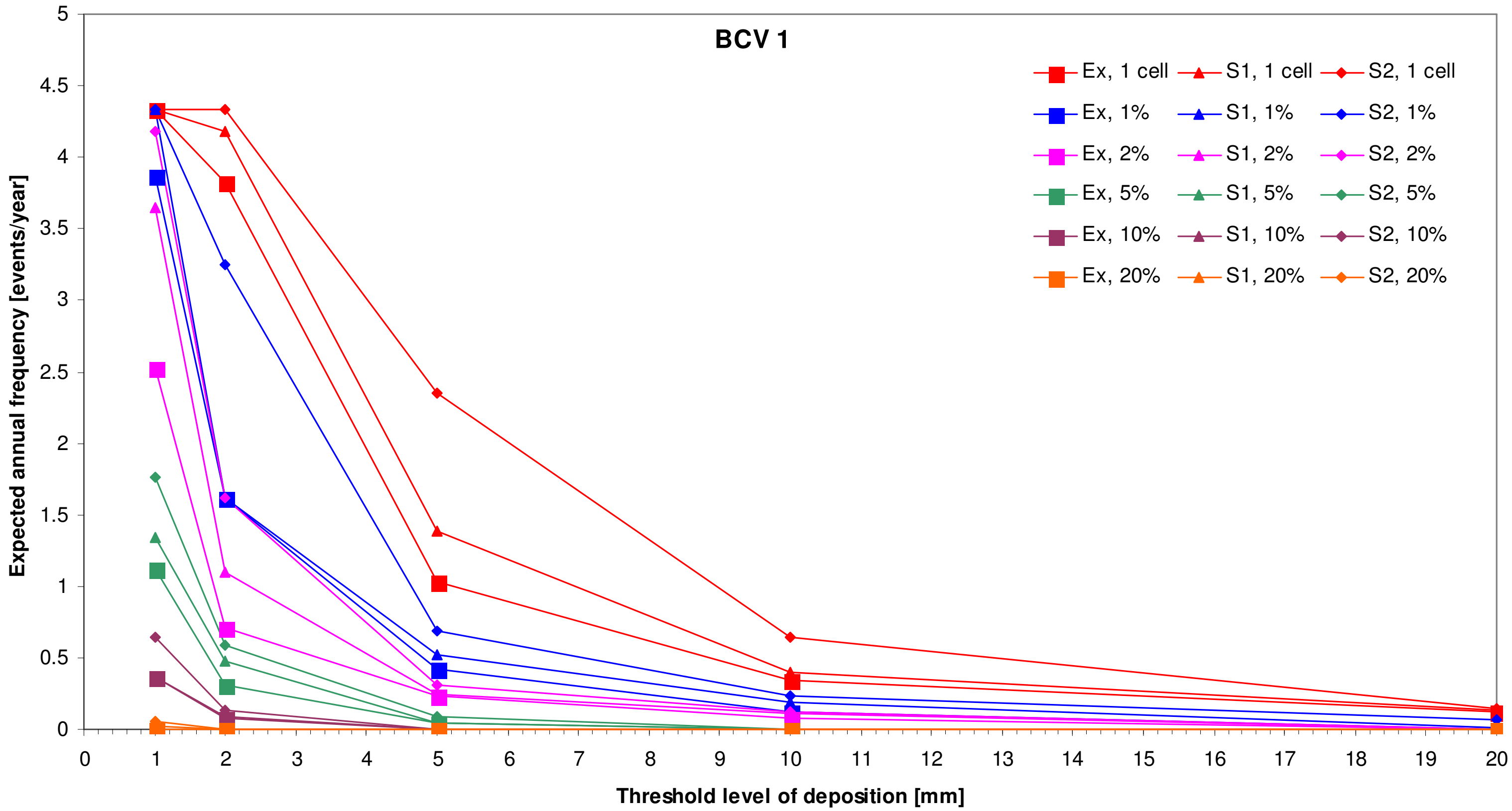


Figure 6.5: Expected annual frequency of deposition thickness and expected change in biodiversity in BCV 2.

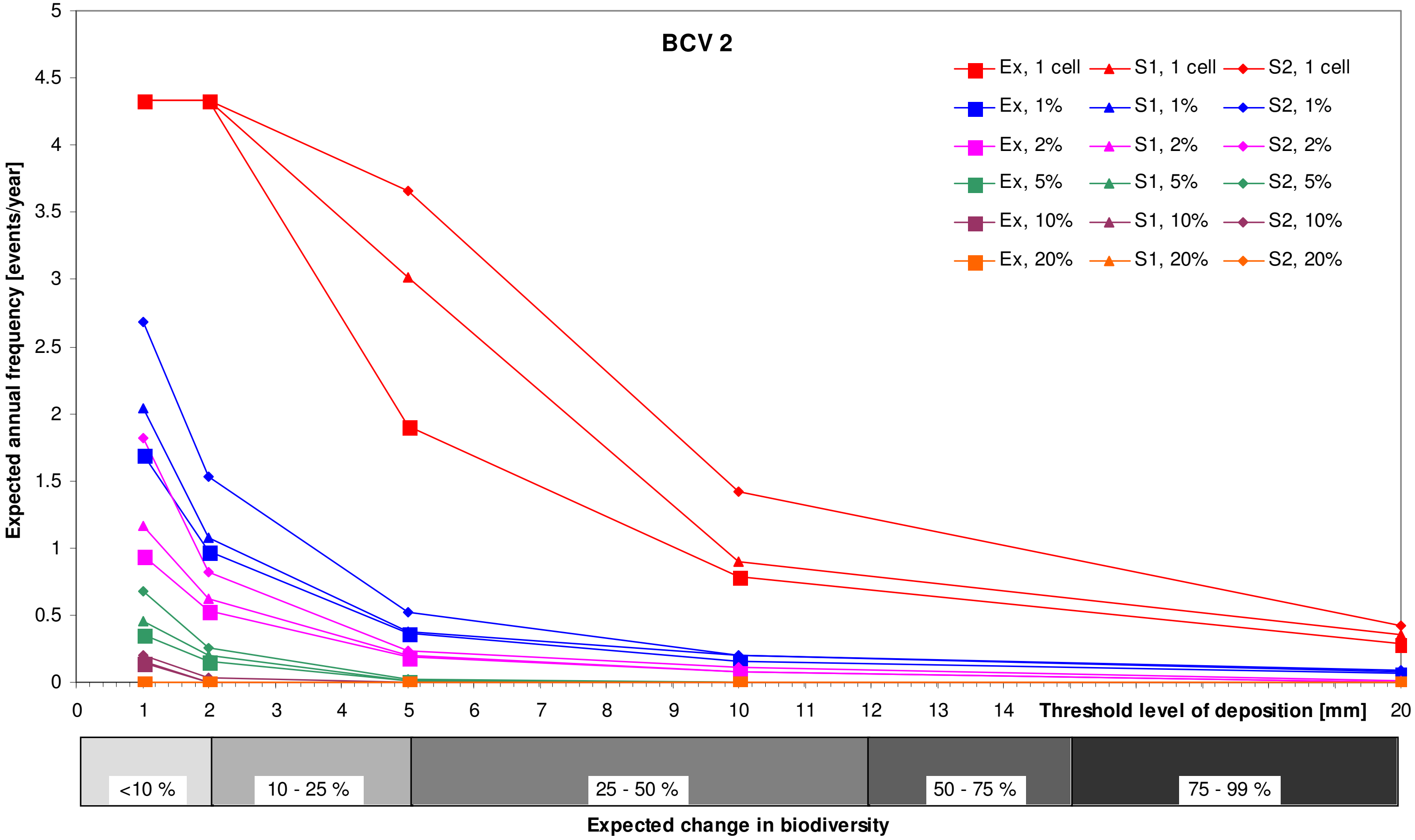


Figure 6.6: Expected annual frequency of deposition thickness and expected change in biodiversity in BCV 3.

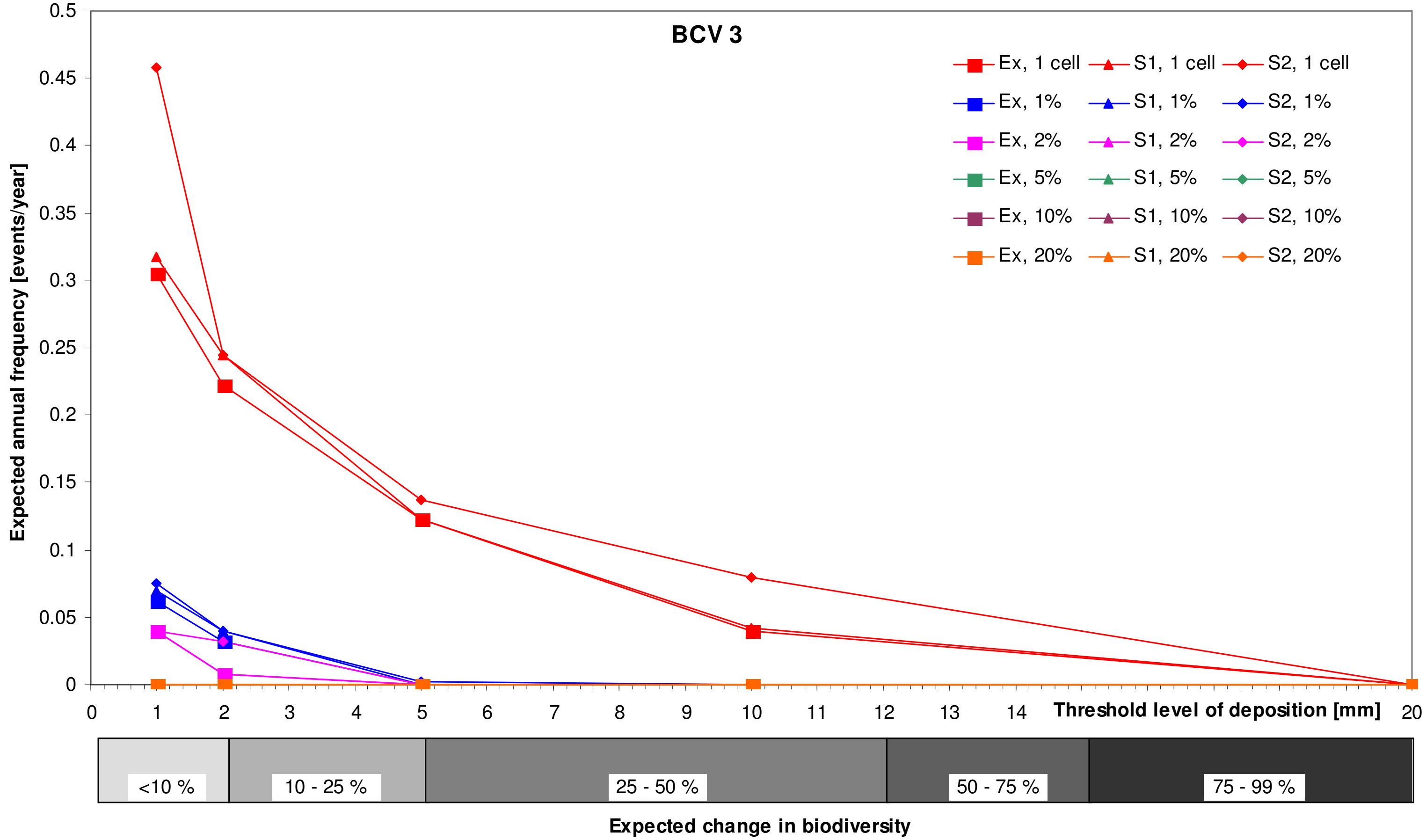


Figure 6.7: Expected annual frequency of deposition thickness and expected change in biodiversity in BCV 4.

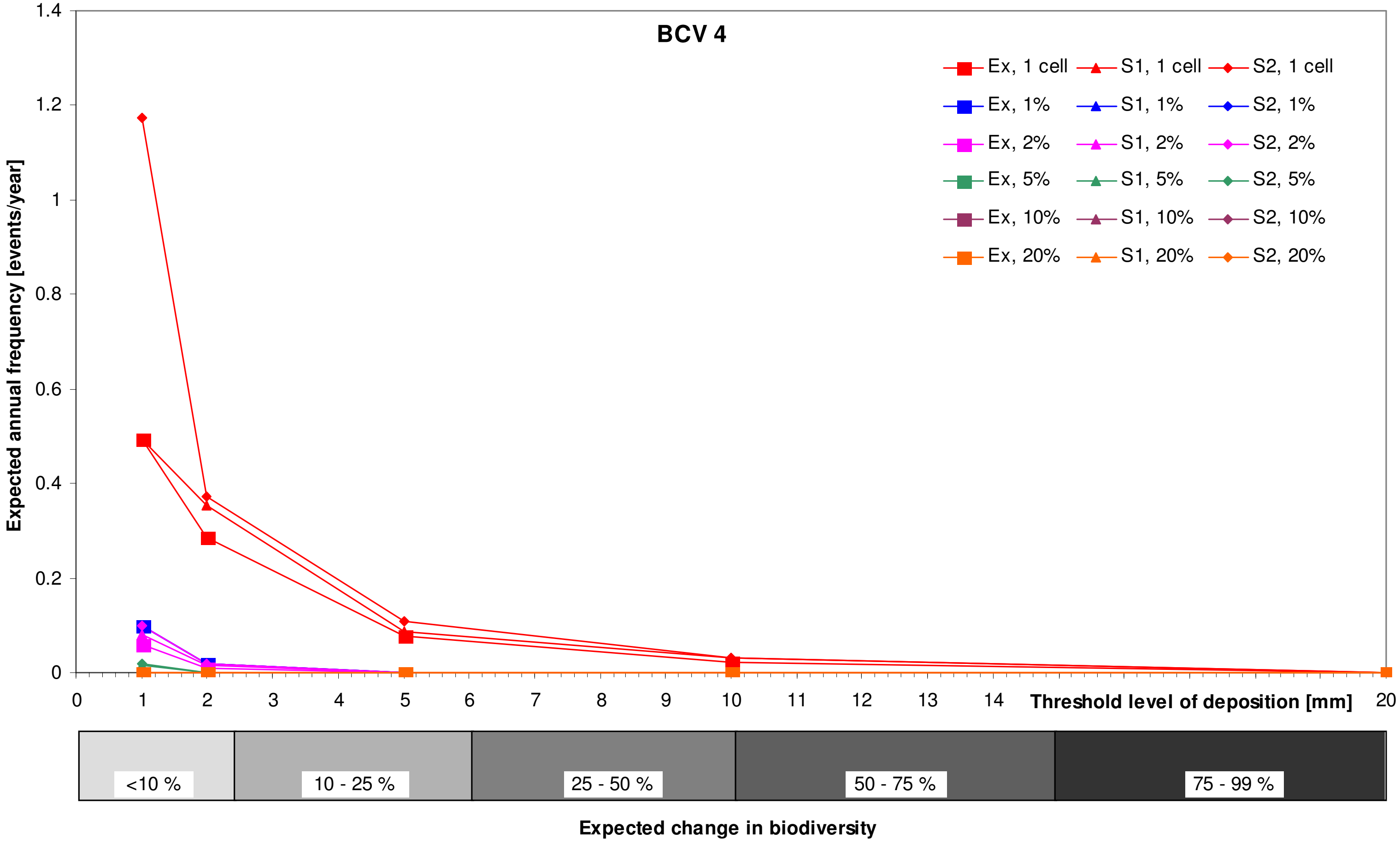


Figure 6.8: Expected annual frequency of deposition thickness and expected change in biodiversity in RSV1.

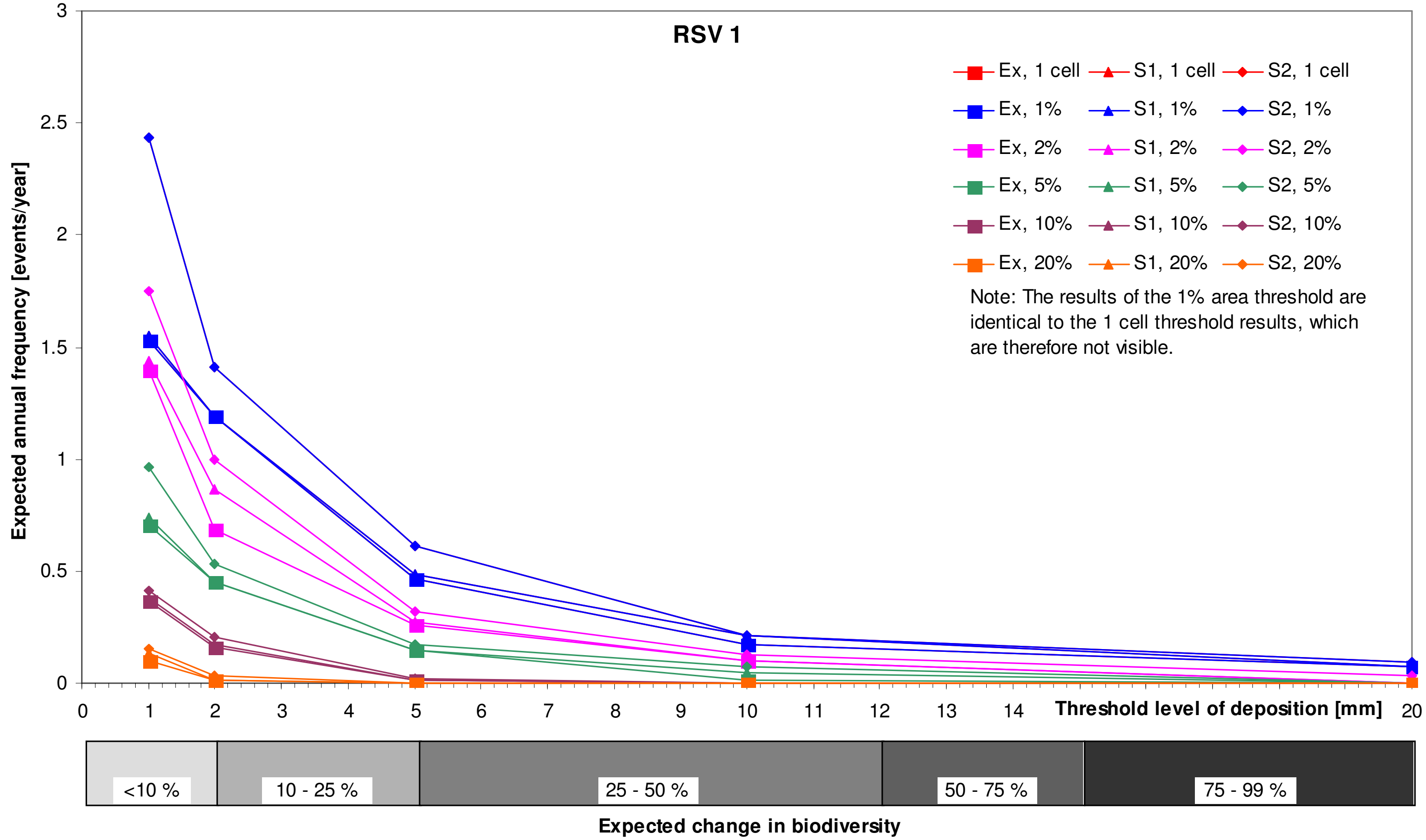
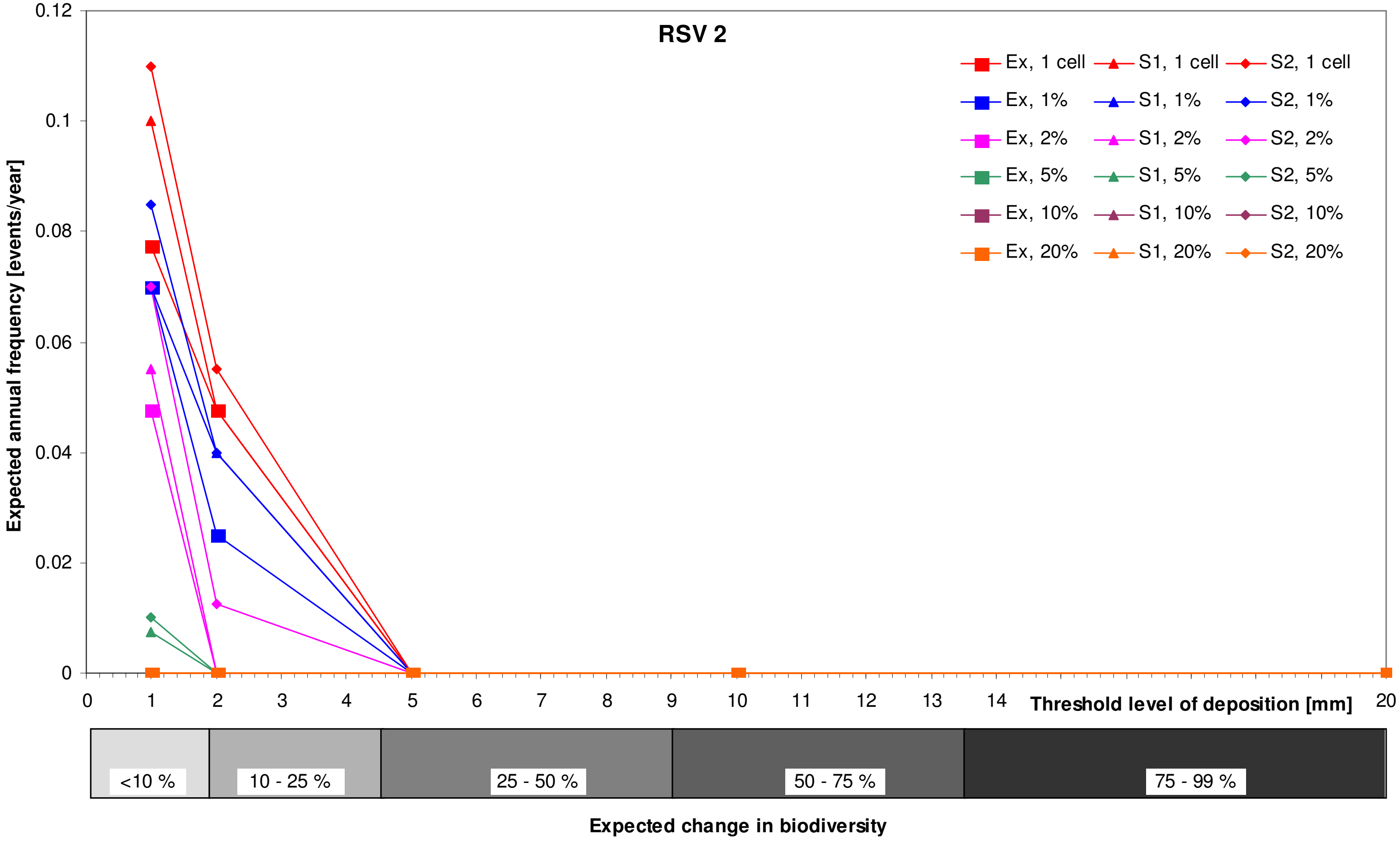


Figure 6.9: Expected annual frequency of deposition thickness and expected change in biodiversity in RSV 2.



6.2 Discussion of results

6.2.1 Expected annual frequency of sediment thresholds

The results show that all threshold levels of deposition will most frequently be exceeded near the source of sediment inflow, i.e., where the streams enter the tributary estuaries of the Whitford embayment (BCV1, Figure 6.4). All of the simulated physical conditions resulted in sediment deposition of over 1 mm in at least one 50 × 50 m cell within BCV1, under all land use scenarios. The criterion that over 1% of the area of BCV1 is buried by at least 1 mm of sediment is also fulfilled by every simulated physical condition under Scenario 1 and 2 (though not under the existing land use).

Due to the way the analysis is set up, the predicted sediment-threshold expected annual frequency cannot exceed 4.35 events per year (which can be seen in Figure 6.4). For high thresholds, the expected frequency of occurrence does not approach this figure, but low thresholds, including the lowest threshold considered in this analysis (1 mm), may, in reality, be exceeded more often than 4.35 times per year. To more accurately estimate the expected frequency of low thresholds, lower magnitude runoff events would need to be included in the model simulations. The 4.35-events-per-year "cap" should be taken into account when interpreting Figure 6.4 and related figures: low thresholds may, in fact, occur more frequently than 4.35 times per year. Furthermore, the lower the threshold, the more frequently it will occur.

The same limit is also reached in BCV2. All physical conditions, under all land use scenarios result in at least one 50 x 50 m cell in BCV2 being buried by at least 1 mm of sediment (Figure 6.5). However, significantly fewer conditions result in 1% of the area of BCV2 (corresponding to seven 50 × 50 m cells) being buried by at least 1 mm of sediment. As both BCV1 and 2 cover areas of similar size (Section 6.1), this would indicate that BCV2 has one or two cells that, due to the local bathymetry, are very susceptible to deposition and are not representative of the region. The same is likely to happen in other regions, e.g., BCV4.

As the deposition thickness criterion increases, the number of occasions per year for which the threshold is exceeded reduces rapidly. For BCV1 under the Existing land use, 1% of the area is covered by 1 mm of sediment approximately 4 times per year. This reduces to approximately 1.6 times per year for a layer of sediment 2 mm thick, and once every 2 years for a sediment layer 5 mm thick. A layer of 10 mm occurs approximately once every five years.

For a given deposition thickness, larger proportions of each region are buried less frequently. For example, 5 mm deposition covering over 5% of BCV1 occurs approximately once every 22 years, compared with once every 2 years for 1% of the area. Further from the sediment source (BCV3 and 4, Figure 6.6 and 6.7), ecologically damaging sediment deposition will occur much more infrequently. For example, in BCV3, 5 mm deposition over 1% of the area is predicted to occur approximately once every 400 years.

Both the Scenario 1 and Scenario 2 proposed land use options deliver more sediment to the embayment than the Existing land use (Existing < Scenario 1 < Scenario 2). It therefore follows that each sediment threshold is exceeded least often under the Existing land use, more often under Scenario 1 and most often under Scenario 2. For example, in BCV2, 10 mm deposition over 1% of the area occurs every 6.6 years under the Existing land use, every 5.1 years under Scenario 1 and every 4.9 years under Scenario 2.

It is very difficult to quantifiably verify the model simulations and risk assessment against direct observations. Recent photographs (Figure 6.10) of mud deposits following a flood event, however, do confirm that the intertidal areas of the Whitford embayment do accumulate thin smears of terrestrial mud, which supports the findings above. The photographs presented here show how a "stream" of terrigenous mud has deposited in a depression in the existing estuary bed. Sediment cores (Oldman and Swales 1999) also confirm that sedimentation in the upper reaches of the tributary estuaries has been rapid in recent decades.

Figure 6.10: Mud deposits overlying an intertidal estuary bed following a recent flood event show that the Whitford embayment does accumulate thin smears of terrestrial mud.

6.2.2 Risk of ecological damage

The predicted loss in biodiversity (determined by percentage change in number of taxa), for the various thresholds of deposition thickness, is shown by the grey scale bars in Figure 6.3 and Figures 6.4 to 6.9, for each BCV and RSV and for each land use (Existing, Scenario 1 and Scenario 2). The predicted loss in biodiversity, together with the annual frequencies for which the various deposition thicknesses are exceeded, provide a measure of the risk to the benthic macrofauna and how that risk changes with the land use scenarios. This is discussed for each region below:

BCV1. This is a region of low biodiversity and consequently was not targeted for an ecological experiment. The likely ecological damage cannot, therefore, be quantitatively estimated in this area. The sediment dispersion modelling, however, does predict frequent sediment deposition in this region. Also, previous laboratory experiments (Nicholls et al. 2000, Norkko et al. 2001) indicate that many common estuarine mud species, expected to be found in these upper reaches of the Whitford tributary estuaries, are adversely affected by sediment deposition. Ecological damage in this region is expected to be most comparable with BCV2.

BCV2. Under all land use scenarios, this region is the most likely to experience significant loss of taxa. This is due to high sediment thresholds being exceeded more frequently than in other regions (except BCV1). For example, an event causing a >10% reduction in biological diversity over 1% of the area is predicted to occur just less than once per year under the Existing land use. That same level of damage is expected to increase under Scenario 1 and Scenario 2, occurring just over once a year under Scenario 1 and 1.5 times a year under Scenario 2 (which is, approximately, a 50% increase over both the Existing land use and Scenario 1).

Higher levels of ecological damage occur more infrequently, with >50% reduction in biological diversity over 1% of the area predicted to occur approximately 0.15 times per year (~ once every 6½ years) under Existing land use, 0.195 times per year under Scenario 1 and 0.203 times per year under Scenario 2 (approximately once every 5 years).

RSV1. Generally, this region has a slightly lower risk of ecological damage than BCV2. However, when comparing the risk of ecological damage over a 50 × 50 m area, the risk is substantially lower in RSV1 compared to BCV2. An event causing a >10% reduction in biological diversity over 1% of the area is predicted to occur 1.188 times per year (approximately every 10 months) under the Existing land use. Scenario 1 is not predicted to give any increase over this frequency, however, under Scenario 2 this damage is predicted to occur 1.413 times per year, or once every 8½ months (which is an increase of 23% over both the Existing land use and Scenario 1). Note that high densities of suspension feeders were observed in this region. These suspension feeders are likely to be adversely affected by increased turbidity (Hewitt et al. 2001), which has not been accounted for in this analysis. The risk of ecological damage is therefore likely to be higher than that predicted based solely on sediment deposition.

BCV3. This region, representing the shallow part of the embayment, experiences significant ecological damage less frequently than the regions closer to the source of the sediment (BCV1, BCV2 and RSV1). An event causing a >10% reduction in biological diversity over 1% of the area is predicted to occur 0.033 times per year (once every 30 years) under the Existing land use and 0.04 times per year under both Scenario 1 and 2 (once every 25 years). Although not apparent for this particular level of damage, Figure 6.6 does show that the risk of ecological damage is generally higher under Scenario 2, compared to under Scenario 1. In BCV3, high densities of suspension feeders and juveniles were observed (especially along channel margins), both of which are likely to be adversely affected by increased turbidity.

RSV2. This area is a sub-set of BCV3 and the risk of ecological damage is somewhat similar to BCV3. However, when compared to BCV3, the ecological response is stronger; i.e., less sediment thickness is required to give the same change in biodiversity. The expected annual frequency of sediment thresholds are however lower, resulting in a similar measure of risk. A >10% reduction in biological diversity over 1% of the area is predicted to occur approximately 0.032 times per year (once every 31 years) under the Existing land use and approximately 0.046 times per year under both Scenario 1 and 2 (once every 22 years). This is a highly diverse area within the embayment with high densities of juveniles and a variety of suspension feeders.

BCV4. The outer embayment also experiences significant ecological damage less frequently than the tributary estuaries. With the exception of a few 50 × 50 m cells, the expected annual frequency of sediment thresholds is predicted to be slightly lower than BCV3. The ecological response to sediment deposition is also likely to be weaker and the resulting risk of ecological damage is therefore the lowest within the Whitford Embayment. A >10% reduction in biological diversity over 1% of the area is predicted to occur approximately 0.018 times per year (once every 55 years) under all land uses. The expected increase in frequency for Scenario 1 and 2 is again not resolved at these low annual frequencies, but is evident when considering sediment thickness over a 50 × 50 m area (see Figure 6.7). There is little likelihood of events resulting in a change of greater than 10% of the diversity over >1% of the area.

It should be noted that ecological observations (see Figure 5.7) suggest the biodiversity in this region is more comparable to areas that are subject to higher frequencies of sediment deposition. This discrepancy may be due to processes that are not taken into account in this analysis. Long-term predictions of changes in biodiversity will depend on the actual disturbance regime, the communities present and the dynamics of their recovery potential. Within BCV4, sediment is expected to be mobile, with potential for numerous cycles of deposition and resuspension, which may increase near-bed turbidity and adversely affect suspension feeders and other members of the benthic community. Due to difficulties in modelling turbidity dynamics and the complexity of biological response, such effects are not quantitatively included in this risk assessment. A full list of caveats to be considered in the interpretation of risk is presented in the next section.

6.3 Ecological effects of sediment deposition: emerging results and cautionary points to consider in risk assessment

In the present study of the Whitford Embayment, increases in the thickness and aerial extent of deposition due to the proposed land use scenarios are predicted to be small, except in BCV1 and 2, and the associated effects on the biota minimal. However, given our evolving knowledge of the effects of thinner clay deposits, and given the potential for long-term habitat change, it is important to consider some cautionary points when interpreting the quantitative predictions of risk and making decisions on the merits of different land-use scenarios with respect to management of the Whitford embayment.

1. Ecological risks are based on the predictions of the effects of smothering. Increased sedimentation may well have other effects that result from associated changes in the physical and chemical environment. These effects have not been considered in the report and may be subtler, cumulative and occur over longer time scales.

2. Model grid size. The model grid size determines the smallest area that deposition is modelled over, in this case 50 × 50 m2, or approximately 1 acre. Sediment is assumed to be deposited evenly within this area. However, 1 mm evenly spread in the model could equally well be, in reality, 5 mm in one fifth of the area. For example, sediment might be deposited in a depression, or channel margin, rather than evenly spread.

3. Event size. All of the physical conditions used in the simulations resulted in sediment deposition of over 1 mm in at least one 50 × 50 m cell within BCV1, under all development options. If smaller, more frequently occurring events were included in the analysis, it is likely that the frequency of 1 mm sedimentation occurring in BCV1 would be higher that predicted here.

4. Climate change. The frequency of future storm events and sea level may change due to the Interdecadal Pacific Oscillation and global warming. The effect and

magnitude of these is, however, not accurately known and is not included in this analysis.

5. As previously discussed with regards to Okura, responses detected in experimental plots may not be the perfect mimic for larger scales of disturbance. For example, ecological recovery theory suggests that as the spatial extent of disturbance increases the potential for colonisation is increasingly restricted. Certainly, sand (bedload transport) and animals are considerably less likely to move across a model cell (50 x 50 m2 area) than across the experimental plots of 2.5 m diameter.

6. Recent experiments on the intertidal flats of the Whitford Embayment demonstrate that frequent deposition of thin clay layers (3 mm deposits) occurring monthly for months, can have cumulative ecological effects on the biota (Berkenbusch et al. 2001). However, this ecological assessment of effects is event based.

7. Further analysis of the experiments carried out in Whitford has revealed that the effect of sediment deposition on juveniles is greater than that on adults. In fact, no effect may be observed on adults, yet juveniles show a marked decrease in density. Decreased survival of juveniles over a couple of years could have long-term effects on populations.

8. All the impacts we have discussed so far relate to sedimentation. Increased resuspension due to the increased amount of fine particles will lead to increased turbidity. Increased turbidity can, above some levels, affect the feeding and survival of suspension feeders such as cockles and pipis (Hewitt et al. 2001). The results from Hewitt et al. (2001) demonstrate species-dependent sensitivity and show non-linear relationships with turbidity. For example, increases in condition of suspension-feeders can occur in a non-linear fashion up to a specific level, beyond which negative effects prevail.

6.4 Risk Assessment: Summary and Conclusions

The main points arising from the risk analysis are:

- The analysis is designed to assess risk over the discrete period of the earthworks phase of potential development. The risk of sediment damage to the ecological diversity is compared between the existing land use and two proposed development scenarios. The analysis was performed on six regions within the Whitford embayment and the tributary estuaries, selected with regard to biological and physical characteristics.

- For each region, a graph is presented showing the expected annual frequency (number of times per year) that various thicknesses of sediment deposition will be exceeded. Also shown on these graphs is the corresponding expected change in biodiversity.
- Scenario 1 and Scenario 2 proposed land use options deliver more sediment to the embayment than the Existing land use (Existing < Scenario 1 < Scenario 2). All sediment thresholds are therefore exceeded more frequently under Scenario 1 and Scenario 2 than under the Existing land use. In some cases, the predicted percentage increase in risk associated with changing the land use from Existing to Scenario 1 or Scenario 2 can be quite high.
- All of the deposition thresholds will be exceeded most frequently near the source of sediment inflow, i.e., where the streams enter the tributary estuaries of the Whitford embayment, and within the tributary estuaries themselves. Under Existing land use, approximately 4 times each year, sediment deposition in these upper reaches is expected to exceed 1 mm for over 1% of the area of the region, in the aftermath of a storm.
- Most likely to experience significant loss of taxa are the shallow intertidal regions of the embayment and the entrances to the tributary estuaries (BCV2). For example, an event causing ≥10% reduction in biological diversity over 1% of the area is predicted to occur just less than once per year under the Existing land use, just more than once a year under Scenario 1 and 1.5 times a year under Scenario 2 (approximately a 50% increase over both the Existing land use and Scenario 1).
- The outer embayment presents the least risk of ecological damage.

The risk analysis and summary points above indicate that ecologically damaging sediment deposition events are already occurring quite frequently in the Whitford tributary estuaries and inner embayment. Sediment cores (Oldman and Swales 1999) confirm that sedimentation in the upper reaches of the tributary estuaries has been rapid in recent decades. Although there is no corresponding historical ecological data, it is likely that the estuary and embayment ecology has been degraded since early European times.

Compared to the Existing land use, the frequency (and therefore risk) of an ecologically damaging sedimentation event occurring during the earthworks phase of potential rural development is expected to increase under Scenario 1, and increase further still under Scenario 2.

Sediment controls were not applied to the housing development sites for either of the two development scenarios in this study. It is likely that the implementation of such land management measures may reduce sediment run-off and, therefore, may lead to a decrease in the deposition of sediment in the tributary estuaries and embayment. These measures may be implemented in the short term, being applicable to the earthworks phase of development, or, applied in the longer term once development is complete. Potential on-site mitigation measures for the earthworks phase of development include restricting the amount of bare-earth exposed, use of hay bales and silt fences, and seasonal restrictions upon earthworks with earthworks stabilisation in the off-season. Longer-term catchment-wide measures include tree planting upon erosion prone slopes, stock exclusion, and riparian retirement. A previous modelling study at Okura (Stroud and Cooper, 1999) predicted that short term on-site measures would reduce sediment input to the estuary, during the earthworks phase of development, by 19 to 63%, depending upon the combination of measures adopted. However, the efficiency of control measures was shown to be highly dependent upon the size of rainfall event. During very large events, which deliver much of the sediment load to the estuary, efficiency was relatively low. It is not possible to extrapolate results from the Okura study and thereby predict the reduction in ecological risk that may result from using on-site controls within the Whitford catchment. This is because the efficiency of control measures is strongly dependent upon soil type and slope angle, which differ between the Okura and Whitford catchments. The hydrodynamics of the Okura and Whitford estuaries are also fundamentally different, particularly in terms of the wave and current patterns that disperse sediments throughout the estuaries.

Finally, it is important to remember that the risk analysis used in this study requires significant simplification and loss of information. A number of important cautionary points are presented in Section 5.3.

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