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Prediction of Contaminant Accumulation in the Upper Waitemata Harbour – Methods

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Prediction of Contaminant Accumulation in the Upper Waitemata Harbour – Methods

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Prepared for
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Contents

Executive Summary

This report describes the methods used to predict contaminant accumulation within the estuarine sediments of the Upper Waitemata Harbour (UWH). Other reports in this series describe results, as follows:

Contaminant	Report
Zinc	NIWA Client Report HAM2003-087/2
Copper	NIWA Client Report HAM2003-087/3
PAHs	NIWA Client Report HAM2003-087/4
Organochlorines	NIWA Client Report HAM2003-087/5

The goal has been to predict the temporal development and spatial patterns of contaminant accumulation associated with (1) the existing pattern of landuse in the catchment, and (2) two proposed patterns/sequences of development. The proposed developments encompass, among other things, different lot sizes, development timing, best management practices, source controls and other practicable landuse management tools. The contaminants of concern are shown in the table above. For each combination of contaminant and scenario, two timeframes are addressed: (1) 50 years, (2) 100 years. The level of spatial resolution of the predictions is the "subestuary". For this study, the UWH has been subdivided into 10 subestuaries (seven "arms" or tidal creeks that branch off the "main body" of the UWH estuary, and three subdivisions of the main body itself). In addition to predicting the accumulation of contaminants in each subestuary, the origin of sediments and contaminants is traced back to the seven subcatchments into which the UWH catchment has been divided for this study. Also, the time history of sediment/contaminant movements and accumulations is tracked so that the effects of certain stagings of management options may be investigated.

The prediction scheme initially conceived in a previous project (Green et al., 2001; Green et al., 2003) and fully realised and implemented in this study, combines key pieces of information at a semi-quantitative level in order to predict contaminant accumulation in estuarine sediments. In essence, a number of "satellite modules" feed information to a "central module" which combines the information and makes the predictions. The satellite modules include (1) estuary hydrodynamics/sediment-dispersal modelling, (2) sediment distribution and baseline estuarine-sediment contaminant concentrations, (3) estuarine sedimentation rates, (4) estuarine bioturbation, (5) sediment input from catchment, (6) contaminant input from catchment. The output from the central module is essentially a mass-balance equation for each subestuary, which describes how sedimentation in a subestuary is constituted on an event basis, where an event is a rainstorm and its immediate aftermath. Once established, the set of mass-balance equations for the entire harbour can be combined with other information (including typical number of rainstorms in a year, the various sediment and catchment loads derived from the catchment, and bioturbation rates), and freely manipulated to estimate changes in contaminant accumulation associated with different possible management strategies, which may cause changes in sediment and/or contaminant loads. Complete details of the methodology are given in this report.

The principal outputs are predictions of:

1. concentration of contaminants in the sediments of each subestuary, and how this changes over time as the development proceeds;

2. sediment-deposition rate in each subestuary averaged over the simulation period, which provides the primary validation of the model predictions;

3. origin of sediments/contaminants that deposit in each subestuary (expressed as a mass or as a percentage of the total amount of sediment/contaminant deposited in the subestuary), which shows where sediments/contaminants deposited in each subestuary come from;

4. fate of sediments/contaminants that originate in each subcatchment (expressed as a mass or as a percentage of the total amount of sediment/contaminant originating in the subcatchment), which shows where sediments/contaminants originating in each subcatchment go to.

Information that is common to all simulations (i.e., combinations of contaminant and scenario) is presented in this report: (1) the subdivision of the UWH into subestuaries; (2) the subdivision of each subestuary into channels (where sedimentation is not permitted) and banks / intertidal flats (where sedimentation is permitted); (3) the subdivision of the UWH catchment into subcatchments; (4) the specification of rainstorm events (frequency of occurrence, freshwater discharge); (5) the division of sediments into particle sizes; (6) the term (*R*) that describes the pattern of sediment/contaminant dispersal and deposition throughout the estuary during the event; (7) the term (*R3*) that describes the pattern of sediment/contaminant redispersal and redeposition throughout the estuary between events; (8) the way estuarine sediments are bioturbated.

The reader is referred to the relevant report (see Table above) to view results of the simulations.

A number of approaches have been taken to model verification. The "core" catchment and estuary models have been calibrated and verified in standard ways, which are reported in Appendices herein. Certain tests have been applied to establish confidence in the contaminant-accumulation predictions, which combine information from the various core models as well as information from other sources. These include comparing predicted and observed annual-average estuarine sedimentation rates, and comparing predicted and observed contaminant-concentration profiles in bed sediments. The latter represents quite a severe test of the model, since concentration profiles in reality develop from the entire suite of interacting processes simulated by the model. The verification tests of the contaminant-accumulation predictions are reported in Appendices herein.

1. Introduction

This report describes the methods used to predict contaminant accumulation in the Upper Waitemata Harbour. Other reports in this series describe results:

Contaminant	Report
Zinc	NIWA Client Report HAM2003-087/2
Copper	NIWA Client Report HAM2003-087/3
PAHs	NIWA Client Report HAM2003-087/4
Organochlorines	NIWA Client Report HAM2003-087/5

1.1 Strategic Fit

Central to most resource management issues that the Auckland Regional Council and the Territorial Local Authorities face in the Auckland Region is the management of growth and development. In the Auckland Regional Policy Statement and in the District Plans, the imperative of ensuring the Region has the capacity to meet the demands of population and economic growth is placed alongside the necessity of protecting the Region's resources. This project supports these strategic requirements by providing information that will be used in assessing the effects that future growth in the Upper Waitemata Harbour (UWH) catchment will have on the natural environmental resources of the Upper Waitemata Harbour estuary. From a strategic standpoint, this project aims to support the decision-making required to enable growth to continue in the UWH catchment whilst providing for the long-term sustainability of the environmental values of the UWH estuary.

1.2 Study Development

Over the past few years, the ARC and TLA's have collaborated in undertaking studies of catchments that have sensitive receiving environments and that have been identified as likely candidates for landuse intensification in the near future. The study areas include Mahurangi, Okura and Whitford. This study of the Upper Waitemata Harbour fits into the same context. The Regional Growth Forum clearly identified additional development in the UWH catchment, and for this reason this project also fits into the context of the Regional Growth Forum validation process, which, amongst other things, requires a verification of environmental-impact predictions.

In late 2000, the ARC convened a meeting of representatives of North Shore City Council, Rodney District Council and Waitakere City Council. Various potential impacts of development on the sensitive receiving environment of the UWH were identified, and the meeting attendees resolved to investigate the relative significance of these with a view to reaching agreement on a comprehensive, catchment-wide, environmental risk-assessment approach. The following potential effects were considered:

- Nutrient enrichment and microorganism increase and resulting public health implications. For both of these potential effects, the proposed development in the UWH catchment is expected to result in no significant increase in inputs, and potentially a net reduction, over those deriving from present landuses.

- Stream values. Proposed development presents opportunities for enhancement by fencing, riparian planting, etc.

- Increased sediment input during development. This was identified as an issue of concern, which needed to be dealt with in a separate modelling study.

- Contaminant accumulation. The potential for the accumulation in UWH estuarine sediments of contaminants associated with urbanisation resulting in levels above which lethal or sublethal effects on aquatic biota can be expected to occur was identified as a major area of concern. This issue is the focus of this study.

1.3 Project Aim

The accumulation of contaminants in the Upper Waitemata Harbour sediments from mature urban areas has been identified as a major issue associated with the development of the Upper Waitemata catchment.

The aim of this project is to predict the temporal development and spatial patterns of contaminant accumulation in UWH estuarine sediments associated with

1. the existing pattern of landuse in the catchment, and

2. two proposed patterns/sequences of development.

The proposed developments encompass, among other things, different lot sizes, development timing, best management practices (BMPs), source controls and other practicable landuse management tools.

- The contaminants of concern are (1) zinc/copper, (2) polyaromatic hydrocarbons (PAHs) and (3) organochlorines (pesticides/herbicides).

- The aim is to predict contaminant accumulation over (1) 50 years and (2) 100 years[1].

[1] In fact, these numbers are approximate. The prediction timeframes are actually 54 years and 108 years (for esoteric technical reasons).

- The level of spatial resolution of the predictions is the "subestuary". For this study, the UWH has been subdivided into 10 subestuaries (seven "arms" or tidal creeks that branch off the "main body" of the UWH estuary, and three subdivisions of the main body itself).

- In addition to predicting the accumulation of contaminants in each subestuary, the origin of sediments and contaminants will be traced back to the seven subcatchments into which the UWH catchment has been divided for this study.

- Also, the time history of sediment/contaminant movements and accumulations will be tracked so that the effects of certain stagings of management options may be investigated.

The results may subsequently be compared to relevant environmental guidelines, which will provide one basis for determining the capacity of the Upper Waitemata Harbour to sustain future urban and countryside living. Relevant environmental guidelines in the form of allowable limits of contaminant concentration in estuarine sediments have been provided by the Working Party[2] for display in this report. The determination of capacity to sustain human activities is outside the scope of this project. Overall, the Working Party aims to use the information generated in this project, together with other relevant information, to identify the level of development and controls necessary to secure the long-term protection of the environmental values of the Upper Waitemata Harbour estuary.

1.4 Study Approach

Many processes have a bearing on contaminant accumulation, including: sediment and contaminant supply from the catchment; sediment dispersal and sedimentation in the harbour; and bioturbation of estuarine sediments.

The prediction scheme initially conceived in a previous project (Green et al., 2001) and fully realised and implemented in this study, combines key pieces of information at a semi-quantitative level in order to predict contaminant accumulation in estuarine sediments. To appreciate what this means, we note firstly:

- Using numerical models of estuarine hydrodynamics and sediment transport/sedimentation it is possible to predict the dispersal of water and sediments that enter the estuarine/coastal environment from point sources such as streams and stormwater overflows during and immediately after rainstorms. This is

[2] Representatives of the Auckland Regional Council, North Shore City Council, Rodney District Council and Waitakere City Council.

most readily done for a given set of environmental conditions (i.e., tide, waves, winds, freshwater inflows and stormwater overflows) on the event (rainstorm) timescale (i.e., days). Assuming that contaminants travel principally by (1) being adsorbed to sediment particles and/or (2) in solution, then contaminant dispersal can also be predicted on this timescale. For the first case, contaminants are treated by the model as a type of sediment. For the second case, contaminants are treated like water. It is possible to build contaminant chemistry into the model, which could account for some of the specific behaviour of contaminants (i.e., treat contaminants as more than just equivalent to water or a type of sediment), and some of this has indeed been done. Such "event-deterministic" numerical estuary models can be applied directly to short-timescale problems such as dispersal of runoff and associated contaminants in estuarine and coastal waters following a rainstorm.

- Determining contaminant accumulation (which can be thought of as the result of many injections and dispersals, combined with other processes such as bioturbation, physical mixing) over longer timescales (months, years and more) is difficult because this is determined by the future sequence of environmental conditions (winds, rain, tides, freshwater discharges), which is unknown. In addition, it would take too long to run this length of simulation anyway, and the prediction errors would compound, thus reducing the confidence of any predictions. Thus, it is not possible to use an event-deterministic numerical estuary model directly to predict contaminant accumulation over these longer timescales.

A way forward was developed by Green et al. (2001) in a predecessor project. In essence, a method of extrapolating "core calculations" over the long-term was developed, where the core calculations can be derived by the use of an event-deterministic numerical estuary model. The actual method of extrapolating over the long term depends on having an understanding of how Auckland estuaries work and varies depending on location in the estuary, timescale for the extrapolation, and the particular question being addressed. This was called a "semi-quantitative conceptual approach" in the report, as it combines elements of numerical modelling and conceptual understanding. With this approach we can:

- Identify areas in estuaries prone to contaminant accumulation over the long term.

- Predict the long-term accumulation of contaminants in estuarine sediments associated with landuse intensification/change in the surrounding catchment.

The prediction process as implemented for this study is illustrated as follows. A number of "satellite modules" feed information to a "central module" which combines the information and makes the predictions (Figure 1.1).

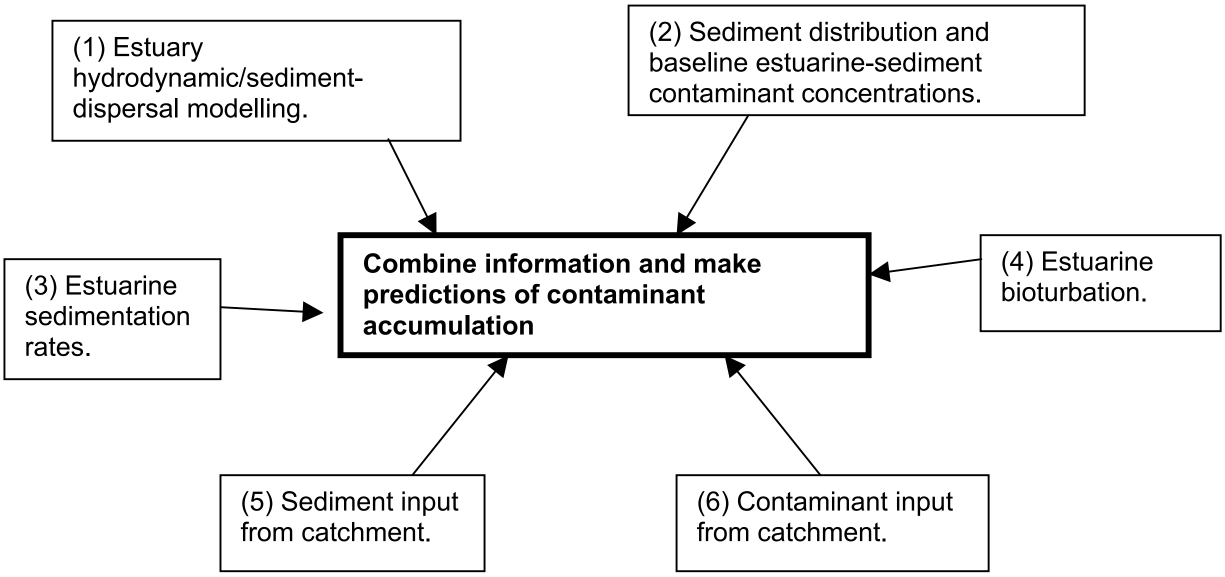

Figure 1.1 Organisation of the study.

The output from the central module is essentially a mass-balance equation for each subestuary. Each mass-balance equation describes how sedimentation in that subestuary is constituted on an event basis, where an event is a rainstorm and its immediate aftermath. For instance, on a particular intertidal flat, 50% of sediment depositing in an event of a particular size may come from catchment A, 20% from catchment B and 30% from catchment C. (The "decomposition" of sedimentation in each subestuary in this way is based on an understanding of physical processes in estuaries and draws on several different types of information, including estuarine hydrodynamics and sediment dispersal.) Then, knowing sediment and contaminant loads from each subcatchment and the numbers and sizes of events that occur in a typical year, it is possible to apply the mass-balance equation for each subestuary to estimate contaminant accumulation in terms of mass on an annual average basis. Knowing bioturbation rate in each subestuary, each mass can then be converted into change in contaminant concentration in the bed sediments. Once established, the set of mass-balance equations for the entire harbour can be freely manipulated to estimate changes in contaminant accumulation associated with different possible management strategies, which may cause reductions in sediment and/or contaminant loads. Any number of "what if" games can be played without needing to rebuild the mass-balance equations each time. The reason is that the mass-balance equations derive fundamentally from the estuarine dispersal and sedimentation *processes*, which are, to first order, independent of catchment sediment/contaminant loads.

The satellite modules in this study are as follows:

- Satellite Module 1 Estuary hydrodynamic/sediment-dispersal modelling.
    - o Aim: Establish patterns of sediment dispersal in the Upper Waitemata Harbour (UWH) under a range of weather/oceanographic scenarios.
    - o Tools: DHI model Mike 21.

- Satellite Module 2 Baseline estuarine-sediment contaminant concentrations.
    - o Aim: Establish existing levels of contaminant concentrations.
    - o Tools: Sediment sampling, particle size determination, particle size fractionation, analyses.

- Satellite Module 3 Estuarine sediment distribution and sedimentation rates.
    - o Aim: Establish sediment distribution throughout the UWH and sedimentation rates in key locations.
    - o Tools: Existing literature, coring, bed-sediment survey and analysis (in conjunction with module 2).

- Satellite Module 4 Bioturbation.
    - o Aim: Establish bioturbation rates and vertical profiles in key sub-environments.
    - o Tools: Literature review (Green et al., 2001), concentration profile-fitting of cores (from module 3), rapid sediment profiling techniques.

- Satellite Module 5 Sediment input from catchment.
    - o Aim: Establish annual sediment inputs from the surrounding catchments, including under future development scenarios.
    - o Tools: Existing literature and data, previous catchment modelling, use of model outputs from the companion Riverlea-Totara-Waiarohia study, further model runs, knowledge of in-stream processes.

- <u>Satellite Module 6</u> Contaminant input from catchment.
    - o Aim: Establish annual contaminant inputs from the catchment, and relationships with sediment inputs, including under future development scenarios.
    - o Tools: Development proposals, literature and research source loads, sediment loads (module 5), present estuary sediment contaminant concentrations (module 2).

2. Overview – Hydrology of the Upper Waitemata Harbour

2.1 General

The Upper Waitemata Harbour (UWH) is at the head of a complex, deeply indented and infilled drowned-river-valley estuary. Seven shallow tidal creeks (Hellyers, Lucas, Paremoremo, Rangitopuni, Brighams, Rarawaru, Waiarohia) drain into the main body of the UWH, which in turn connects with the relatively broad and open Middle Waitemata Harbour (MWH). The MWH connects to the Commercial Harbour (Auckland Harbour), before opening into the Rangitoto and Motukorea Channels and beyond to the Hauraki Gulf. For the purposes of this study, the Upper Waitemata Harbour is defined as the tidal area upstream of the constriction formed by Beach Haven Wharf at the entrance of Hellyers Creek (latitude 36° 47.5'), which covers an area of 9.8×10^6 m^2 (Figure 2.1).

The basement rock of the UWH, over which modern sediments have been deposited, is uneven and irregular. Sediments in the upper reaches of the 7 tidal creeks tend to be thinly draped, but in the lower reaches of the creeks, mudbanks exceed 10-m thickness in parts, and tend to be stabilised by mangroves along the landward margins.

The creeks are largely intertidal, with narrow central channels. In the smaller creeks (Brighams, Rarawaru), these are maintained at low tide only by catchment drainage. A distinct channel cleaves the main body of the UWH and connects with each tidal creek, however, at low tide, the channel is less than 1 m deep in places and is barely navigable. The channel picks its way between rock outcrops, sandbanks in the lower parts (where it connects with the Middle Waitemata Harbour), bare mudbanks, and mudbanks stabilised by mangroves. Approximately 50% of the UWH is intertidal, and the seven tidal creeks account for approximately 50% of the area of the UWH.

At high tide, water depth over the intertidal areas is 1–2 m. Tidal currents are typically not strong enough over the intertidal flats to entrain bed sediments. The estuary sits within a valley that is aligned east–west, which crosses the dominant wind directions (southwest and northeast). Hence, it is relatively sheltered, and waves are typically small.

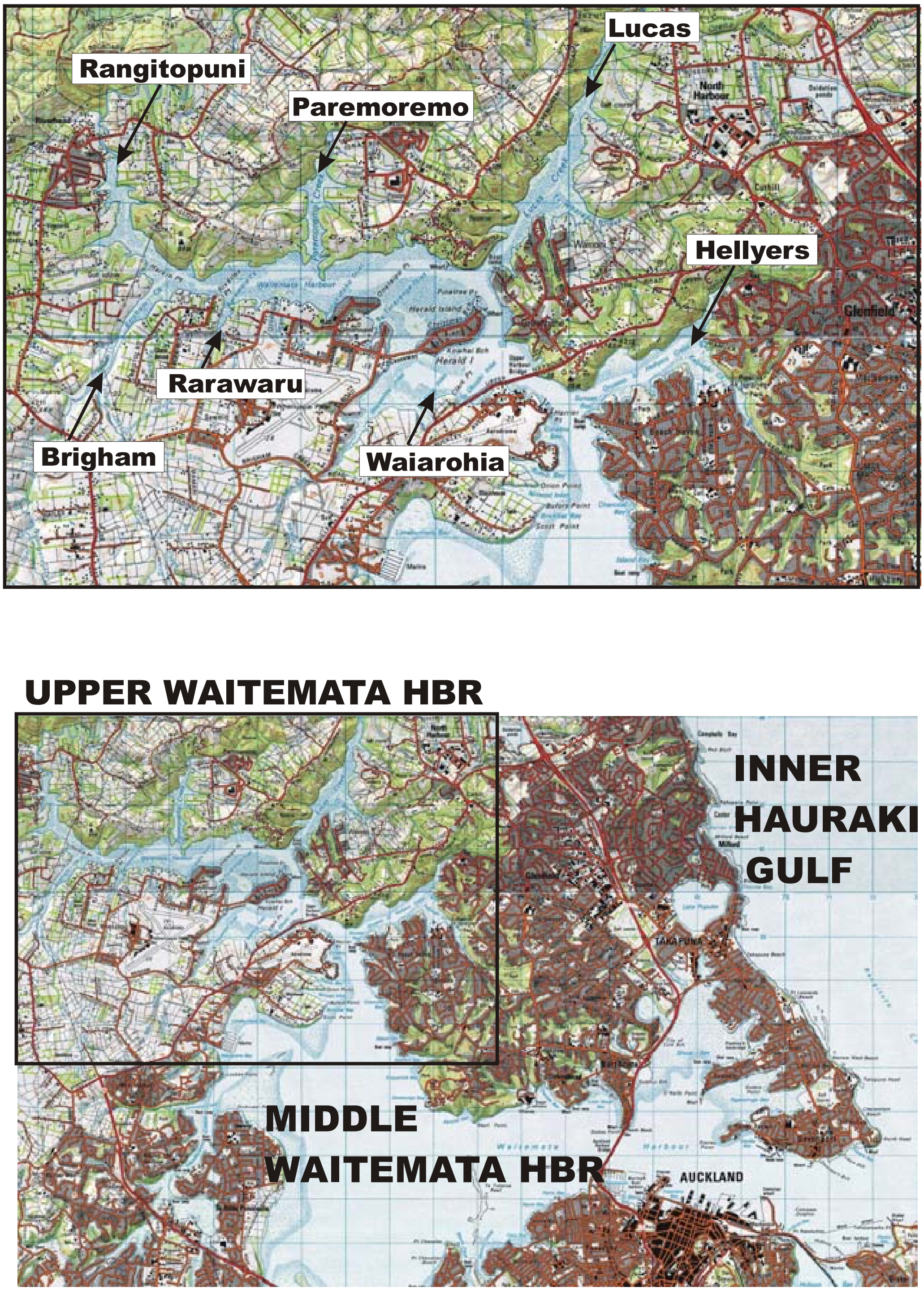

Figure 2.1 Location map: Upper Waitemata Harbour, and its relationship to the Middle Waitemata Harbour.

2.2 Bathymetry

Figure 2.2 shows the estuary bathymetry. The main channel opposite Rarawaru is 1–2 m below Chart Datum (CD). A flat ridge extends across the harbour landward of Paremoremo Creek; and the main channel deepens to ~4 m below CD at the entrance of Lucas Creek. Depths of 12–18 m are found seaward of Lucas Creek. The tidal creeks are largely intertidal, with a single channel remaining at low tide. An unusual feature of the UWH is the rock sills within the intertidal zone of the Rangitopuni and Lucas Creeks. During much of the tidal cycle, these rock sills prevent upstream intrusion of estuarine water.

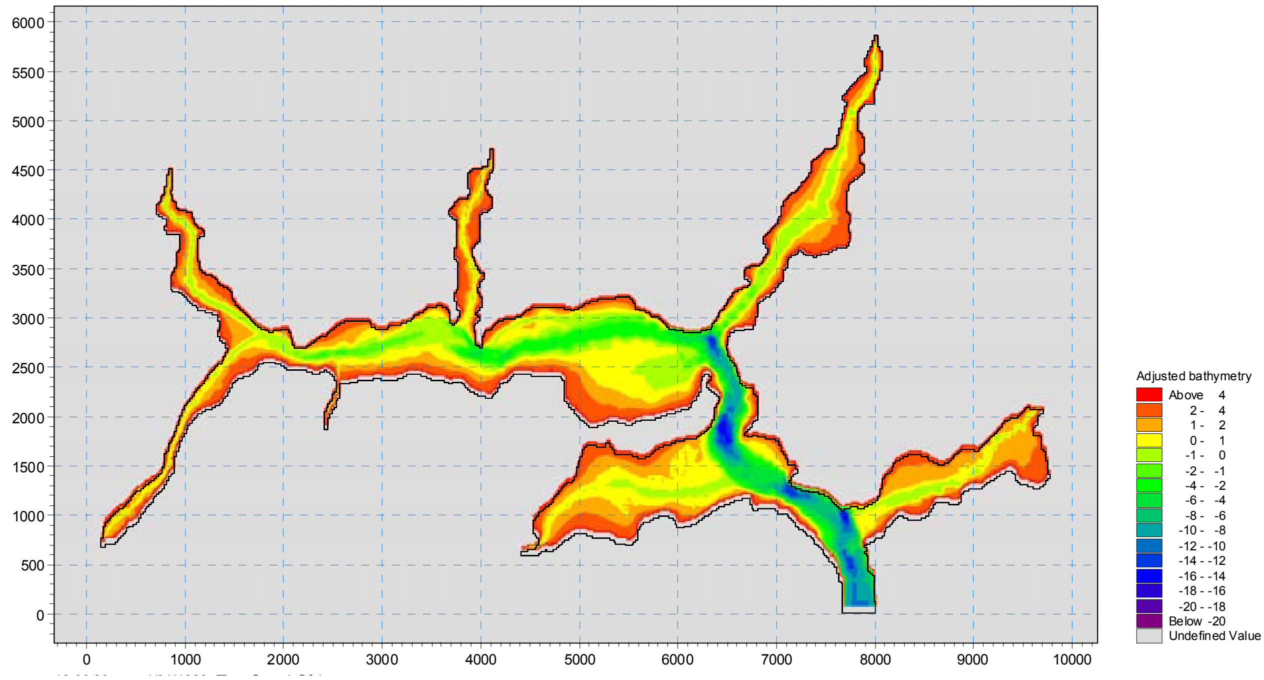

Figure 2.2 Estuary bathymetry, relative to Chart Datum.

2.3 Tide

The tide follows a typical spring/neap tidal cycle, with spring range of 3.7 m and neap range of 2 m. Comparing the six-month tide record at the Salthouse jetty (Williams and Rutherford, 1983) with tides in the Commercial Harbour (Queens Wharf), shows that high tide occurs simultaneously at the two locations but is 0.15 m higher in the UWH. Low tide is generally 0.12 m lower in the UWH, and the time of low water is variable compared to Queens Wharf (+/- 20 minutes). Water slopes within the UWH are very small. The tidal prism (volume of the estuary at high water minus volume at low water) is 1.86×10^7 m^3 during spring tides and 1.00×10^7 m^3 during neap tides.

2.4 Currents

Williams and Rutherford (1983) measured mid-channel tidal currents up to 0.7 m/s during peak ebb tide in the lower reaches of Lucas Creek. Measurements made during this study at the side of the main channel off Paremoremo Creek in the middle of the UWH showed peak ebb velocities of 0.5 m/s. Currents reduce significantly out of the channels. Currents within the main body of the UWH are driven principally by the tide and current patterns are governed mainly by local bathymetry (channels, mudbanks, headlands, bays). It is only during large freshwater floods, and even then only in the tidal creeks, that freshwater momentum is a significant factor driving currents. Because the estuary is sheltered, wind typically does not generate strong currents (either as shear-driven surface movements or orbital motions associated with wind waves). However, wind-driven motions may become important under strong winds that blow down the long axis of the estuary.

2.5 Sediments

Sediments entering the UWH are mainly sourced from soil and rock erosion within the UWH catchment and carried to the estuary by streamflow, mainly during floods. Additional sources are erosion of stream channels and suspended-sediment entering from the Middle Waitemata Harbour on flood tides, but both of these are relatively insignificant.

Sediment thickness throughout the harbour can be measured against the depth to the underlying Pleistocene basement rock, and can vary from zero at stream headwaters to over 10 m. Much of this sediment can probably be attributed to the impact of man from about 1070 years BP (before present), with a major increase in the rate of sedimentation that coincided with the start of European settlement 100 years BP (Auckland Regional Water Board, 1983). In recent times, human activity has resulted in increased sedimentation south of Herald Island, probably due to the construction of the Herald Island causeway, and also along the southern shores of Hellyers Creek, due to urbanisation of the Hellyers catchment.

Estuarine sediment dispersal and sedimentation are determined by the characteristics of the source material (size, shape, density, mineralogy and organic content) and the dynamics of the estuarine receiving waters. Water motions (principally tidal currents and associated turbulence) mix, disperse and, in places, resuspend sediment particles. Gravity causes sediment to settle and deposit onto the estuary bed, but opposing this are the random movements of turbulent eddies, which increase in strength as current speed increases. The tidal creeks are the focus of freshwater–saltwater mixing, which promotes flocculation of freshwater-borne suspended sediments. This, in turn, increases particulate settling speed thereby promoting deposition of suspended particulate matter. Hence, deposition of terrigenous sediments and associated contaminants is favoured in tidal creeks.

Sediment is generally sorted throughout the estuary by the ability of finer particles to be more easily transported by weaker currents. As a result, the finer particles are more likely to settle in very sheltered areas, such as the upper reaches of the tidal creeks and mangroves. Once deposited, fine sediment may dehydrate and consolidate, which makes it more resistant to subsequent erosion. Coarser particles, which can be moved only by the stronger currents that typically occur in channels, are more likely to remain within those channels. However, coarser particles are also found at the entrances to the creeks, where they have been deposited in the aftermath of large floods and where tidal currents are not energetic enough to resuspend and redisperse them.

3. Overview – Catchment of the Upper Waitemata Harbour

The following brief description of the UWH catchment is drawn from field visits and technical reports (Auckland Regional Water Board, 1983; Smith, 1983; Cowcroft and Bowden, 2002).

The UWH catchment encompasses 185 km^2 and drains to a relatively small estuary with a restricted outlet, rendering the harbour potentially susceptible to pollutants washed from the land. Pastoral land predominates in the catchment, with native bush and pine (Riverhead Forest in the Rangitopuni catchment) also present. In addition, both established and ongoing (Lucas Creek) urban development is found. Most of the catchment is flat to rolling land, but steeper slopes are found in the Riverhead Forest, and in parts of the Lucas Creek and Paremoremo subcatchments. These are susceptible to mass movements. Most land lies between 30 m and 80 m above sea level, although in the northwest and the margins of the catchment, land rises up to 155 m above sea level.

Rainfall varies between 1600 mm in Riverhead Forest (northwest of the catchment), to 1300 mm in the southeast (Hellyers Creek). Heavy rainfall occurs most often in summer, which is also when earthwork activities are greatest. This raises implications for the effectiveness of earthworks restrictions that are typically applied over the winter months. Long-term records indicate an increase in annual rainfall and the frequency of heavy rain. This trend is predicted to continue in the future.

Sandstones and siltstones of the Waitemata Group underlie much of the catchment, but these are overlain by extensive thin alluvial material in flatter areas, particularly in those subcatchments to the south of the estuary (Brighams, Rarawaru and Waiarohia). Siltstones of the Onerahi formation and a pocket of Mahurangi limestone (underlying the Dairy Flat region) are found in the northern part of the Rangitopuni subcatchment. Both these formations and the alluvium have a low water storage capacity. As a consequence, streams in the north of the Rangitopuni and south of the estuary respond rapidly to rainfall and have low or no flow during the summer months. The poor drainage of pastoral land in the north of the Rangitopuni renders it susceptible to pugging in winter, and high stock numbers can cause appreciable erosion. Those areas of the catchment draining the Waitemata sandstones respond more slowly to rainfall and have more sustained low flows.

Water abstraction occurs to supply horticulture, irrigation and stock needs. Most abstraction is taken from dams, reflecting the general unreliability of summer low flows.

Incised alluvial channels drain the catchment and these have fairly stable banks. Stream headwaters are characterised by sand and shingle pool and riffle sequences, whilst in the lower reaches the channel floor is characterised by deep pools and rock bars. On the southern side of the harbour the stream channels are not so deeply incised and are characterised by ponds or swamp areas in their middle reaches.

4. Explanation of the Prediction Scheme

4.1 Introduction

Full details of the prediction scheme are in Appendix A.

The main processes that affect contaminant accumulation in estuarine sediments are listed in Table 4.1, classified by whether they occur within an event or between events. Here, an event is a rainstorm and its immediate aftermath.

Table 4.1 **Main processes that affect contaminant accumulation in estuarine sediments.**

Within event	Between events
Sediment erosion from land	Resuspension, dispersal and redeposition of settled sediments and associated contaminants by waves and currents
Attachment of contaminants to suspended sediments in freshwater runoff	Bioturbation
Passage of sediments / contaminants through controls	Overturn / mixing of settled sediments and associated contaminants by waves and currents
Delivery of sediments with attached contaminants to estuarine headwaters	
Flocculation of suspended sediments / contaminants	
Dispersal throughout estuary of suspended sediments / contaminants	
Deposition of suspended sediments / contaminants	

The prediction scheme is based on the within-event/between-events dichotomy:

- Delivery to the estuary of contaminants and sediments is summed over all the events that occur in the simulation period.
- Bioturbation and redispersal throughout the estuary by waves and currents of sediments and contaminants is tracked between events.

The prediction scheme is essentially a book-keeping exercise:

- At each in a set of locations in the estuary, the sediments and contaminants depositing during each event, being redispersed between events, and being mixed down into the pre-existing sediments by bioturbation are kept in a ledger.

- The origin of sediments and contaminants arriving at each location in the estuary is kept track of, so that contaminant accumulation can be related back to specific locations in the catchment where sediments and contaminants are generated.

- The time history of sediment/contaminant accumulations and movements is kept track of so that contaminant accumulation can be related back to times certain events occurred, times certain management actions were taken (e.g., implementation or removal of a particular control), or phases of a development scenario.

The locations where contaminant accumulation will be calculated are the subestuaries into which the Upper Waitemata Harbour has been divided for this study (Figure 4.1).

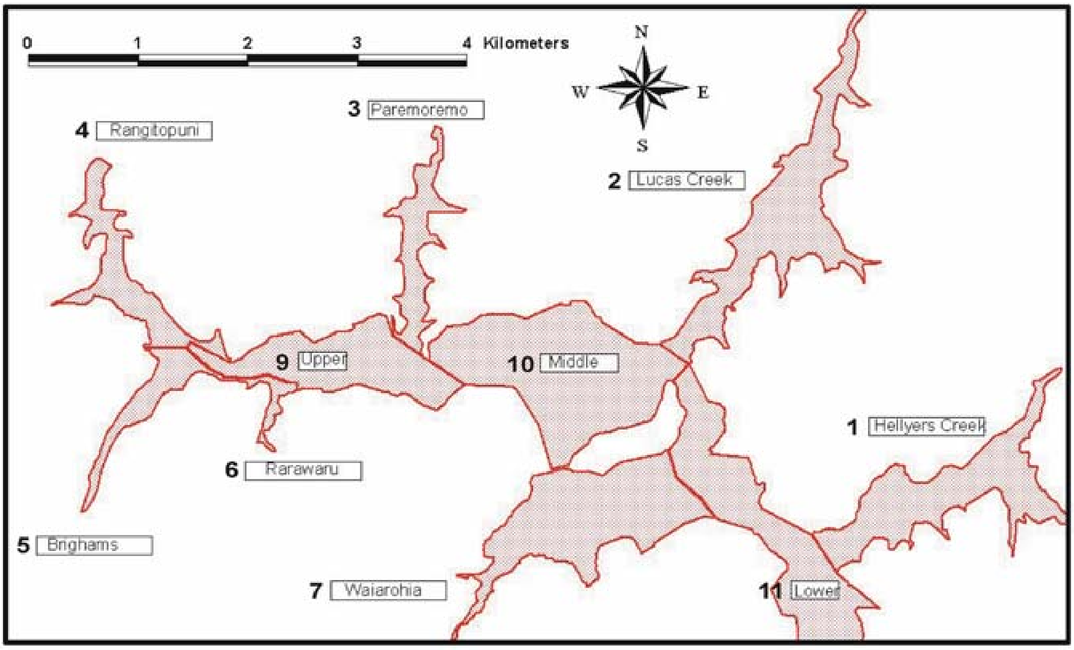

Figure 4.1 Subestuaries into which the Upper Waitemata Harbour has been divided for this study.

Subestuaries 1–7 are arms (tidal creeks) that branch off the main body of the Upper Waitemata Harbour. Arms link main points of freshwater discharge with the main body of the upper estuary. Arms are sheltered, primarily intertidal, and the focus of freshwater–saltwater mixing, which promotes flocculation of freshwater-borne suspended sediments.

Hence, deposition of terrigenous sediments and associated contaminants is favoured in arms. The main body of the upper estuary is divided into three zones (subestuaries 9–11). Compared to arms, the main body is exposed, has more energetic tidal currents, and a smaller proportion of the area comprises intertidal flats. Hence, compared to arms, deposition is less favoured in the main body. Subestuary #8 is the Middle Waitemata Harbour.

Each subestuary has been further subdivided into channels and banks / intertidal flats (Figure 4.2).

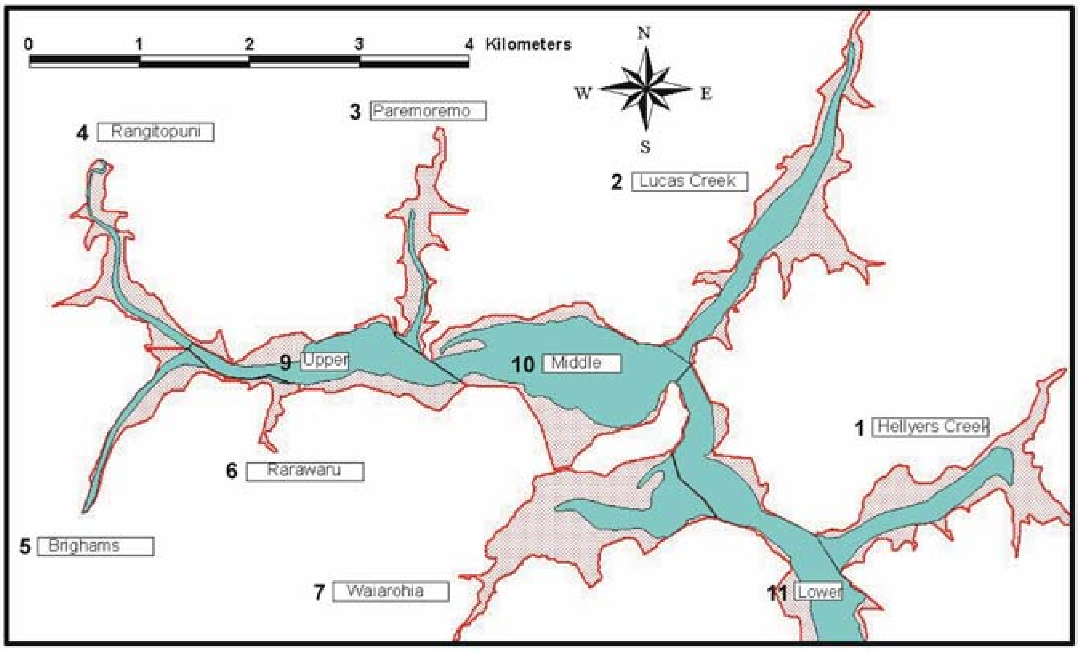

Figure 4.2 **Subdivision of each subestuary into channel (blue) and banks / intertidal flats (pink).**

Within the modelling framework, deposition of sediments and contaminants is not allowed in channels, since water depth is greater and currents are stronger (compared to on banks and intertidal flats), which hinders settlement and accumulation of suspended sediments and attached contaminants. Deposition of sediments and contaminants may occur only on banks and intertidal flats. Contaminant accumulation will be presented as an average value over all of the banks and intertidal flats in each subestuary, except for the Middle Waitemata Harbour (subestuary #8), to which sediments and contaminants are simply "lost". Sediments and contaminants may not be returned to the Upper harbour from the Middle harbour.

Subestuary areas are given in Table 4.2, together with the areas of channels and banks / intertidal flats within each subestuary.

Table 4.2 Total area of each subestuary, and area of channel and banks / intertidal flats in each subestuary.

	Area (square m)		
Subestuary	Channel	Banks / Intertidal Flats	Total
1 = Hellyers	407,443	787,302	1,194,745
2 = Lucas	576,477	807,990	1,384,467
3 = Paremoremo	80,280	376,442	456,722
4 = Rangitopuni	110,987	468,592	579,579
5 = Brighams	124,142	201,756	325,898
6 = Rarawaru	5,016	92,291	97,307
7 = Waiarohia	408,886	1,056,106	1,464,992
8 = Middle Waitemata Harbour	nominal	nominal	nominal
9 = Upper main body of the UWH	646,808	363,356	1,010,164
10 = Middle main body of the UWH	1,409,347	546,772	1,956,119
11 = Lower main body of the UWH	1,016,595	344,751	1,361,346

To match the subdivision of the estuary, the catchment of the Upper Waitemata Harbour has also been divided into subcatchments (Figure 4.3).

Figure 4.3 Subdivision of the catchment.

4.2 Principal Outputs of the Prediction Scheme

The principal outputs are predictions of:

Concentration of contaminants in estuarine sediments

- $\beta_{surface,kest}$ plotted against time.

This is the contaminant concentration in the surface sediment of subestuary *kest*. Plots of $\beta_{surface,kest}$ against time show how contaminant concentrations change as development proceeds.

Sediment-deposition rate

- $\delta_{ANNUALAVG,54years,kest}$ (one number for the 54-year simulation period). This is the annual sediment-deposition rate averaged over 54 years in subestuary *kest*.
- Similarly, $\delta_{ANNUALAVG,108years,kest}$ (one number for the 108-year simulation period) is the annual sediment-deposition rate averaged over 108 years in subestuary *kest*.

These terms will provide primary validation of the model predictions.

Origin of sediments and contaminants that deposit in each subestuary

- $\eta_{jcatch,54years,kest}$, which is the total amount of sediment over the 54-year simulation period deposited in subestuary *kest* that comes from subcatchment *jcatch*.
- Similarly, $\eta_{jcatch,108years,kest}$ is the total amount of sediment over the 108-year simulation period deposited in subestuary *kest* that comes from subcatchment *jcatch*.

Both of these show where sediments deposited in each subestuary come from. They can be expressed as a mass or as a percentage of the total amount of sediment (i.e., from all subcatchments) deposited in the subestuary.

- $\eta_{jcatch,CUM,kest}$, which varies through time, is the cumulative amount of sediment deposited in subestuary *kest* that comes from subcatchment *jcatch*.

This is plotted against time, which shows how origin of sediments in any particular subestuary changes as development proceeds. This can be expressed as a mass or as a percentage of the cumulative total (i.e., from all subcatchments) sediment deposited in the subestuary.

The analogous terms for describing where contaminants come from are:

- $\lambda_{jcatch,54years,kest}$, which is the total amount of contaminant over the 54-year simulation period deposited in subestuary *kest* that comes from subcatchment *jcatch*
- $\lambda_{jcatch,108years,kest}$ is the analogous term for the 108-year simulation period.
- $\lambda_{jcatch,CUM,kest}$, which varies through time, is the cumulative amount of contaminant deposited in subestuary *kest* that originates from subcatchment *jcatch*.

All of these can be expressed as a mass or as a percentage of the total amount of contaminants (i.e., from all subcatchments) deposited in the subestuary.

<u>Fate of sediments and contaminants that originate in each subcatchment</u>

These show where sediment from each subcatchment goes to over the simulation period:

- $\varepsilon_{kest,54years,jcatch}$, which is the amount of sediment originating in subcatchment *jcatch* that is deposited in subestuary *kest* over the 54-year simulation period.
- $\varepsilon_{kest,108years,jcatch}$, which is the analogous term for the 108-year simulation period.

Both of these can be expressed as a mass or as a percentage of the total amount of sediment that originates from subcatchment *jcatch* <u>and that passes through any controls and enters the estuary</u>.

- $\varepsilon_{kest,CUM,jcatch}$, which varies through time, is the cumulative amount of sediment that originates in subcatchment *jcatch* and that is deposited in subestuary *kest*.

This is plotted against time, which shows how fate of sediments from any particular subcatchment changes as development proceeds. $\varepsilon_{kest,CUM,jcatch}$ can be expressed as a mass or as a percentage of the total, cumulative amount of sediment that originates from subcatchment *jcatch* <u>and that passes through any controls and enters the estuary</u>.

The analogous terms for describing where contaminants from each subcatchment go to are:

- $\phi_{kest,54years,jcatch}$, which is the amount of contaminant originating in subcatchment *jcatch* that is deposited in subestuary *kest* over the 54-year simulation period.

- $\phi_{kest,108years,jcatch}$, which is the analogous term for the 108-year simulation period.
- $\phi_{kest,CUM,jcatch}$, which varies through time, is the cumulative amount of contaminant that originates in subcatchment *jcatch* and that is deposited in subestuary *kest*.

All of these can be expressed as a mass or as a percentage of the total amount of contaminant that originates from subcatchment *jcatch* <u>and that passes through any controls and enters the estuary</u>.

A summary of the principal outputs of the prediction scheme is given in Appendix G.

4.3 General Constitution of the Model

The prediction scheme is based on the within-event/between-events dichotomy: delivery to the estuary of contaminants and sediments is summed over all the events that occur in the simulation period; bioturbation and redispersal throughout the estuary of sediments and contaminants by waves and currents is tracked between events. The origin of sediments and contaminants arriving at each location in the estuary is kept track of, so that contaminant accumulation can be related back to locations of initial generation within each subcatchment. The history of sediment/contaminant transport and accumulations is recorded, so that contaminant accumulation can be related back to times certain events occurred, times certain management actions were taken (e.g., implementation or removal of a particular control), or phases of a development scenario.

4.3.1 "Core" models

4.3.1.1 Catchment model

Catchment sediment loads were derived using GLEAMS (Knisel, 1993), which is a field-scale computer model that predicts hydrological and sediment losses on a daily basis. GLEAMS calculates a daily water balance, proportioning rainfall between surface runoff, storage in the soil profile, evapotranspiration, and percolation below the root zone. Predictions of surface runoff are coupled with soil, vegetation and slope properties to calculate particle detachment and hillslope sediment transport and deposition. Processes of sheetwash and rill erosion are represented in the model but soil loss from mass movement (e.g., landslips) is not. Model simulations were conducted for the dominant combinations of soil, slope and landuse within each subcatchment. This includes incorporating the spatial and temporal pattern of proposed earthworks within the model.

For each scenario (existing, development #1, development #2), GLEAMS was run under a long-term (27-year) rainfall record[3] for the entire UWH catchment and with the landuse appropriately specified. Use of the 27-year rainfall record allows for interannual rainfall variability to be incorporated into the simulations. Each simulation (existing, development #1 and development #2 scenarios) results in 27-year daily water-discharge and sediment-runoff time series at each subcatchment outlet. Further details on the use of GLEAMS under each scenario are given in the relevant reports describing the results.

The daily outputs from GLEAMS were converted into event-based outputs as follows.

The 27-yr daily water-discharge time series at the Rangitopuni subcatchment outlet generated under the "existing" scenario was analysed to determine four representative events of increasing magnitude (*E1*, *E2*, *E3*, *E4*). This was achieved as follows. First, the 27-year time series of daily water discharge was converted into a time series of events by summing discharges over periods (which may be longer than one day) when a baseline discharge was exceeded. Next, a number of runoff events covering a range of event-total discharges were selected as being representative of the whole series. The chosen events were selected to be representative of a group of similar-sized events, occurring at a similar frequency, such that if the 27-yr time series of actual events were replaced by the representative events, the total volume of freshwater discharged over the 27-yr period would be approximately the same. Table 4.3 shows the average number of occurrences of each representative event over the 27-yr period, and also extrapolated over 54 and 108 years. Finally, the freshwater discharged from each subcatchment for each magnitude event was obtained by scaling the discharge from Rangitopuni (Table 4.4). Each scale factor was calculated by comparing the representative events within the Rangitopuni subcatchment model with the Paremoremo, Lucas, Hellyers, Waiarohia, Rarawaru, and Brighams subcatchment models.

Table 4.3 Average occurrences for each magnitude event.

	Number of occurrences		
Event Magnitude	**27 years**	**54 years**	**108 years**
E1	500	1000	2000
E2	84	168	336
E3	22	44	88
E4	5	10	20

Table 4.4 Average freshwater discharge for each magnitude event.

	Freshwater discharge (cubic metres)

[3] (Daily rainfall was obtained from NIWA's climate database for the Whenuapai airbase site)

Subcatchment	*E1*	*E2*	*E3*	*E4*
1 = Hellyers	2.16E+05	1.06E+06	2.00E+06	3.78E+06
2 = Lucas	5.13E+05	2.52E+06	4.75E+06	8.97E+06
3 = Paremoremo	1.76E+05	8.62E+05	1.63E+06	3.07E+06
4 = Rangitopuni	1.35E+06	6.63E+06	1.25E+07	2.36E+07
5 = Brighams	2.97E+05	1.46E+06	2.75E+06	5.19E+06
6 = Rarawaru	5.40E+04	2.65E+05	5.00E+05	9.44E+05
7 = Waiarohia	1.21E+05	5.97E+05	1.12E+06	2.12E+06

To complete the conversion between daily outputs and event-based outputs, for each simulation (existing, development #1 and development #2 scenarios) the 27-year daily water-discharge and sediment-runoff time series at each subcatchment outlet were interrogated to assign a sediment yield to each magnitude event for each subcatchment. These are reported in the relevant reports describing the results.

Note that sediment yield associated with each magnitude event can vary with subcatchment, to account for differences in landuse, geology and so on. Note also that sediment yield associated with each magnitude event can vary through time, to account for staging of proposed development.

The sediment load was partitioned across particle sizes based on the GLEAMS output. Two particle sizes are chosen to represent the partitioning:

- size fraction 1: <63 m particle diameter (silt),
- size fraction 2: 63–500 m particle diameter (sand).

Partitioning is accomplished as a function of the particle size of the in-situ undisturbed soil, and subsequent deposition and entrainment of the eroded sediment upon the hillside. Note that size fractions 1 and 2 always carry, between them, all of the sediment. Note also that size partitioning can vary with subcatchment, to account for differences in landuse, geology and so on, and it can also vary through time, to account for staging of proposed development.

Finally, note that sediment controls that apply during development are built directly into the GLEAMS model, and hence come into play when GLEAMS is being run to generate sediment loads. These sediment controls are distinct from controls that may be applied post-development to stormwater to remove contaminants adsorbed to particulate sediments. These are described below when generation of contaminants is described.

4.3.1.2 Estuary model

Sediment dispersal and sedimentation in the estuary were quantified with a coupled hydrodynamic and particle-tracking computer model (DHI Mike 21). The movement of water within the estuary was driven by tidally varying water levels (under an average tidal range) and the discharge of the 7 streams entering the UWH. These simulations of water movement were then used as input to the particle-tracking scheme, to predict where sediment discharged from each subcatchment would settle after a rainstorm.

4.3.1.3 Generation of contaminants.

- Metals. During dry periods, metals accumulate on impervious surfaces such as roads, parking lots and building roofs. The main metals originating from normal human activities are zinc and copper; zinc mostly from vehicle tyres, galvanised iron roofs and paints, and copper from vehicle brake linings and building materials. When it rains these metals are washed into the stormwater network, initially in solution, but increasingly attached to suspended sediment. By the time the stormwater reaches the receiving estuary, there is very little metal left in solution. For each catchment and each year, the metal loads are specified as a function of the number of dwellings and vehicle movements (which is the number of vehicles times the number of kilometres they travel). These loads change each year because of increased development. In addition to the metal loads generated by the "urban environment" (dwellings and vehicles), there is a natural or "background" load that derives from metals naturally present in the catchment soils. The derivation of the dwelling, vehicle and natural loads for zinc are described in Appendix F and the derivations for the other contaminants are described in the relevant reports. Metals generally attach preferentially to the silt fraction of both soils (catchment) and sediments (estuary). Here, the measured ratio of the metal concentration in silt to the metal concentration in sand in the harbour sediments is assumed to apply also to the catchment soils. The metals from dwellings and vehicles are attached to the catchment soils in the same ratio. Note that silt (size fraction 1) and sand (size fraction 2) always carry, between them, all of the metals. Stormwater treatment controls are applied after all the metals have attached to the sediment. For example, if treatment retains 30% of the silt it also retains 30% of the metals attached to the silt. Although this is not strictly correct in the real world, it is easier to model and makes no material difference to the results. The sediment retention efficiencies of the controls, which are different for silt and sand and which can be different for each subcatchment and for each year, determine the sediment and metal loads reaching the subestuaries. These efficiencies are specified as part of each development scenario being investigated.

- Organic contaminants. Two groups of organic contaminants known to cause severe adverse effects in aquatic animals were considered: polycyclic aromatic hydrocarbons (PAHs) and organochlorine compounds (OCs). PAHs are formed by the incomplete combustion of material containing carbon, such as wood and fossil fuels. For the mostly residential landuse proposed for future development of the Upper Waitemata Harbour, vehicle exhaust emissions and leaking engine sump oil will be the main sources of PAHs. In older developed parts of the catchments, coal tar was used many years ago for making roads. As these roads erode or when they are renovated, some of the coal tar could be mobilised into the downstream estuary. Most of the OCs in catchment soils are pesticides applied up until about the middle 1980s to farm and horticultural land. DDT is the best known of these and it, as well as its potentially-toxic degradation products, are still present in catchment soils. Both PAHs and OCs attach preferentially to organic-rich sediment. Since this type of sediment has a very low settling rate in water (the critical value for modelling the behaviour of sediment in the harbour), we consider that all PAHs and OCs are attached to silt, which also has a low settling rate. The derivation of the "urban" loads for PAHs is described in NIWA Client Report HAM2003-087/8 – Results: PAHs, Existing Scenario. The amounts of OCs in the sub-catchments are fixed by the historic application of these compounds and since the use of almost all of these compounds is now banned, these amounts will not increase in future. Since OCs are attached to the catchment soils, the OC loads moving from the catchments are given by the sediment loads multiplied by the average OC concentration in the catchment soils assuming that all the OC is attached to silt as explained above. The average OC concentration in the catchment soils is determined from the results of past studies as described in NIWA Client Report HAM2003-087/11 – Results: Organochlorines, Existing Scenario.

4.3.2 Prediction during a single event

4.3.2.1 Delivery

The way sediments and contaminants were delivered to the estuary from each subcatchment during any event of a given size is shown in Figure 4.4. Note that size fractions 1 and 2 always carry, between them, all of the sediment and all of the contaminant.

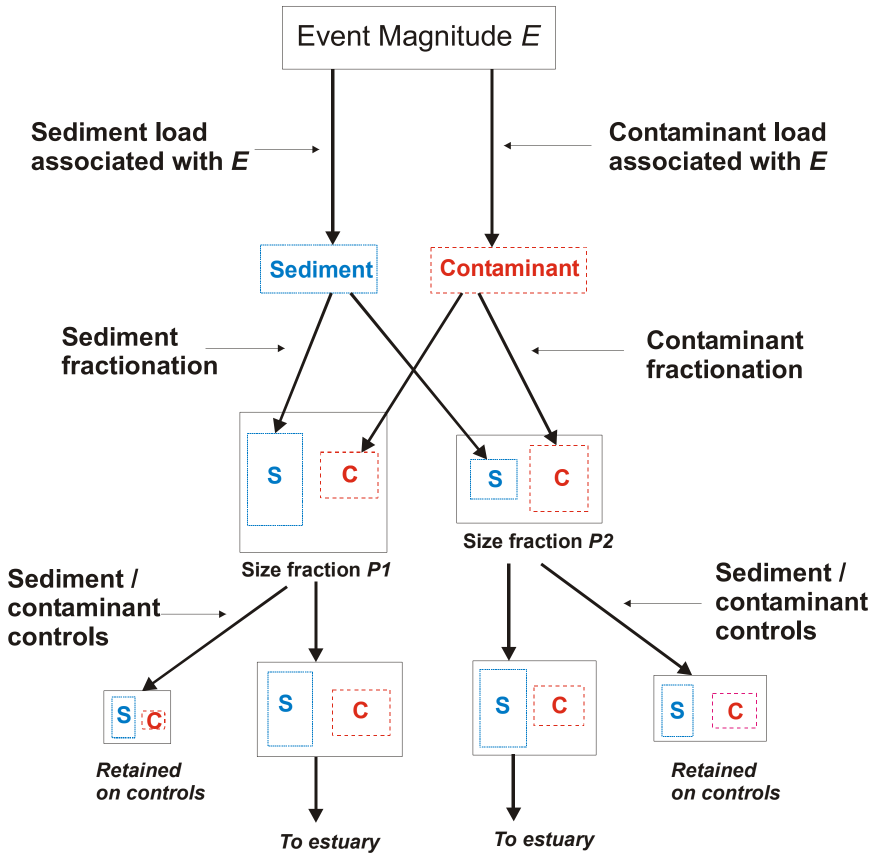

Figure 4.4 Sediment / contaminant generation and delivery to the estuary during a single event from a given subcatchment.

4.3.2.2 Dispersal

The way sediments and contaminants were dispersed amongst the subestuaries is shown schematically in Figure 4.5.

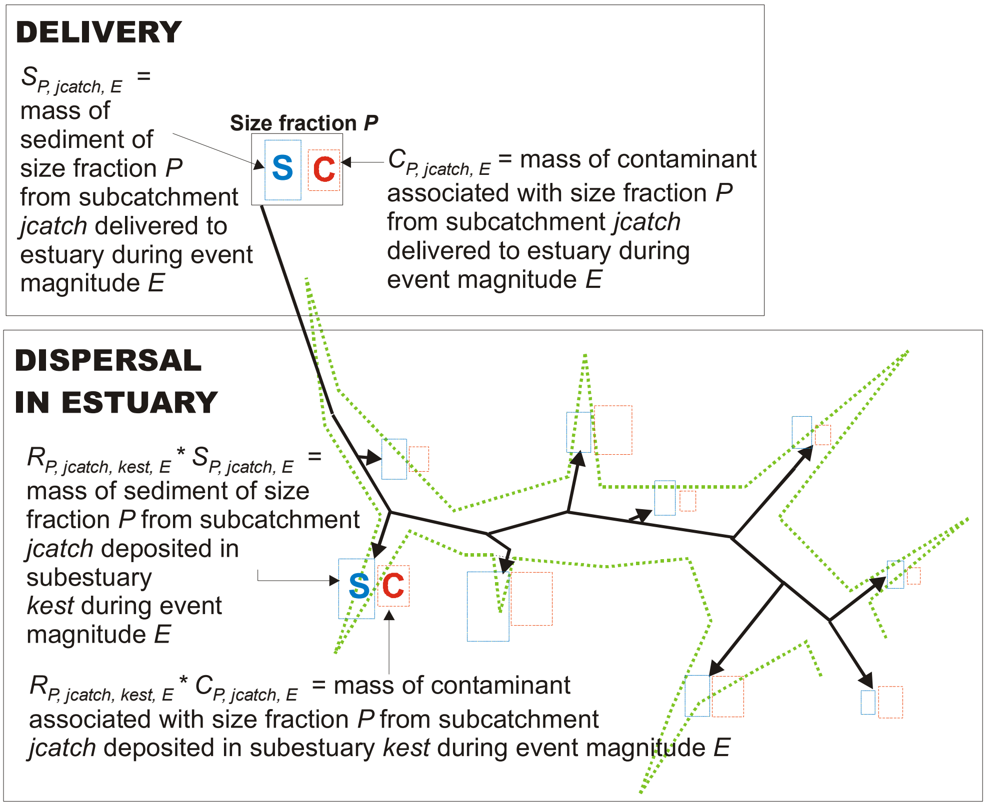

Figure 4.5 Dispersal around the estuary of sediments and contaminants generated in a single subcatchment during a single event.

The mass of sediment of size fraction *P* from subcatchment *jcatch* depositing in subestuary *kest* during event magnitude *E* is given by $S_{P,jcatch,E} \times R_{P,jcatch,kest,E}$ where $S_{P,jcatch,E}$ is the mass of sediment of size fraction *P* from subcatchment *jcatch* that is passed through any controls and that is subsequently delivered to the estuary during event magnitude *E*. $R_{P,jcatch,kest,E}$ is the fraction of the sediment load discharged from subcatchment *jcatch* (after going through any controls) that is deposited in subestuary *kest*, which is determined from the estuary modelling. In effect, the term *R* describes the pattern of sediment dispersal and deposition throughout the estuary during the event. Note that *R* varies with event magnitude *E*, since estuarine circulation and mixing, which are first-order controls on sediment dispersal and deposition, vary with the amount of freshwater discharge, which in turn varies with event magnitude. *R* also varies with size fraction *P* since particle settling speed, which also controls sediment dispersal and deposition, varies with size fraction.

R was estimated by employing the coupled hydrodynamic and particle-tracking computer model of the UWH estuary. Four hydrodynamic simulations were performed, one for each magnitude event. Sediment discharge from each of the 7 streams was modelled separately, and the mass of sediment that was deposited onto the estuary bed at the end of the simulation period in each of the 11 subestuaries was calculated. R is simply the fraction of sediment deposited within each of the sub-estuaries, and is a measure of the pattern of sediment transport. Simulations were performed for each magnitude event, discharge from each of the 7 streams and for 2 types of sediment, characterised by the rate at which the sediment falls through the water under the influence of gravity. Fifty-six particle-tracking simulations were therefore performed. Note that for each simulation, the sum of the seven R values obtained is equal to one.

Full details on the computational model methodology, model calibration and the procedure for obtaining R can be found in Appendix B.

Figure 4.6 shows the calculated values for R used in the study. Tables 4.5 and 4.6 show summaries of the information in Figure 4.6. Generally, sand (size fraction #2) deposits in the subestuary adjacent to the respective subcatchment of origin. That is, $R_{P2,jcatch,kest,E}$ typically equals 1, where $jcatch$ = $kest$. That is also approximately true of silt (size fraction #1), but there is more dispersal compared to sand, because of silt's relatively smaller settling speed. Dispersal is also greater for the greater magnitude events, which are more "energetic" and therefore more capable of dispersing sediments.

The mass of contaminant associated with size fraction P from subcatchment $jcatch$ depositing in subestuary $kest$ during event magnitude E is analogously given by $C_{P,jcatch,E} \times R_{P,jcatch,kest,E}$, where $C_{P,jcatch,E}$ is the mass of contaminant associated with size fraction P from subcatchment $jcatch$ that is passed through any controls and that is subsequently delivered to the estuary during event magnitude E. Note that the same value of R used for sediment dispersal and deposition is also used for contaminant dispersal and deposition; in effect, contaminants remain "locked" to sediments (but different particle sizes, with their associated contaminants, can disperse and settle differently).

	Event magnitude			
Subcatchment	1	2	3	4
1	1	1,Upp	1,Upp,Mid,6	1,Upp,Mid
2	2	2	2	2, Mid
3	3	3	3,Lost	3,Lost,Mid
4	4	4	4	4,Lost
5	5	5	5	5
6	6	6,Upp	6,Upp	6,Upp.Mid
7	7	7	7,Upp	7,Upp,Mid

Table 4.5 Summary of silt dispersal patterns during events, as given by *R* values. The larger number in each cell denotes the subestuary where most of the sediment originating from the corresponding subcatchment gets deposited. The smaller numbers in each cell denote subestuaries where some sediment also deposits. "Lost" denotes sediment is lost to the Middle Waitemata Harbour, "Upp" denotes the upper reaches of the main body of the MWH, "Mid" denotes the middle reaches of the main body of the MWH, "Low" denotes the lower reaches of the main body of the MWH.

	Event magnitude			
Subcatchment	1	2	3	4
1	1	1	1	1
2	2	2	2	2
3	3	3	3	3
4	4	4	4	4
5	5	5	5	5
6	6	6	6	6
7	7	7	7	7

Table 4.6 Summary of sand dispersal patterns during events, as given by *R* values. The larger number in each cell denotes the subestuary where most of the sediment originating from the corresponding subcatchment gets deposited. The smaller numbers in each cell denote subestuaries where some sediment also deposits. "Lost" denotes sediment is lost to the Middle Waitemata Harbour, "Upp" denotes the upper reaches of the main body of the MWH, "Mid" denotes the middle reaches of the main body of the MWH, "Low" denotes the lower reaches of the main body of the MWH.

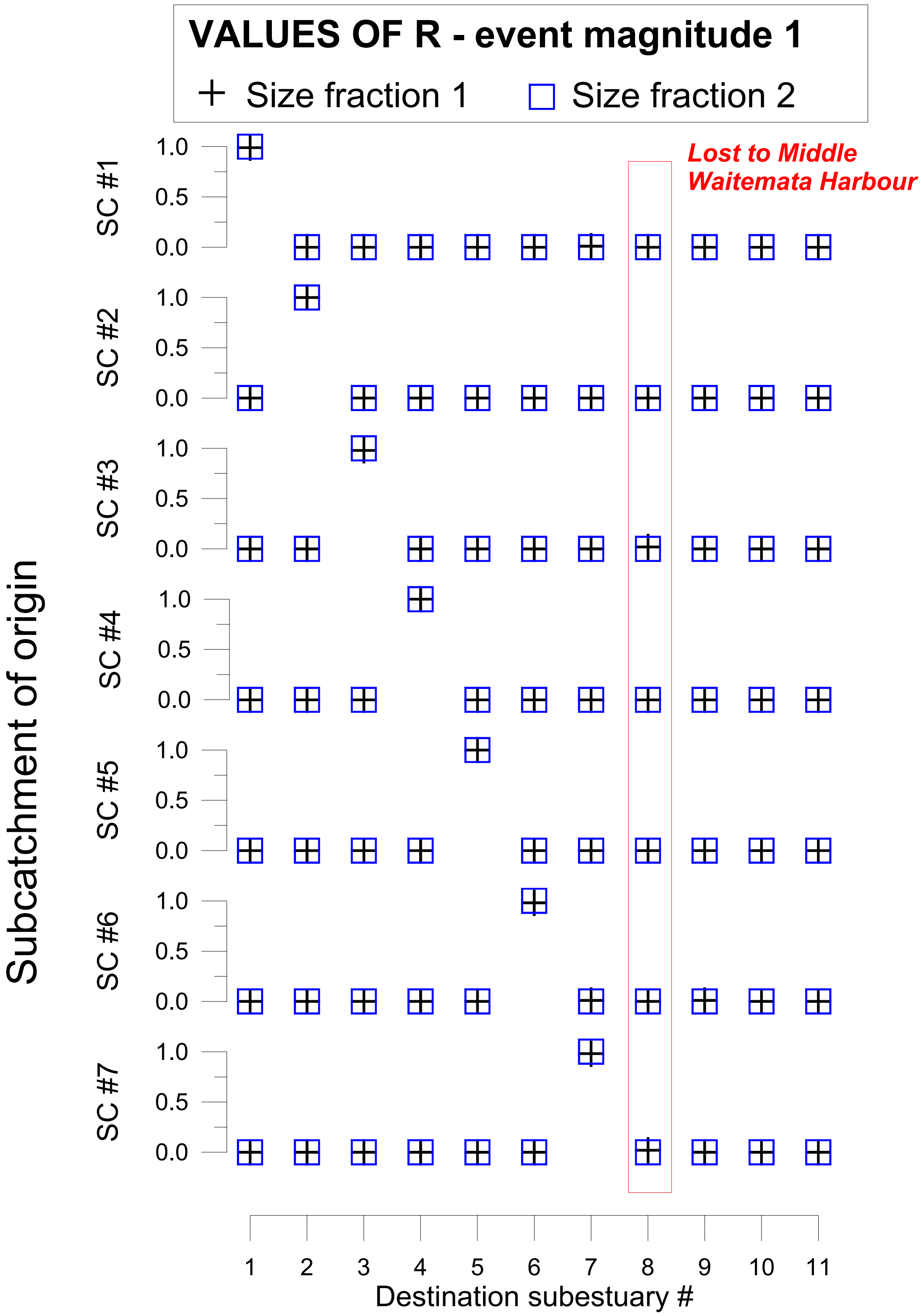

Figure 4.6 Values of *R* used in the study – event magnitude 1.

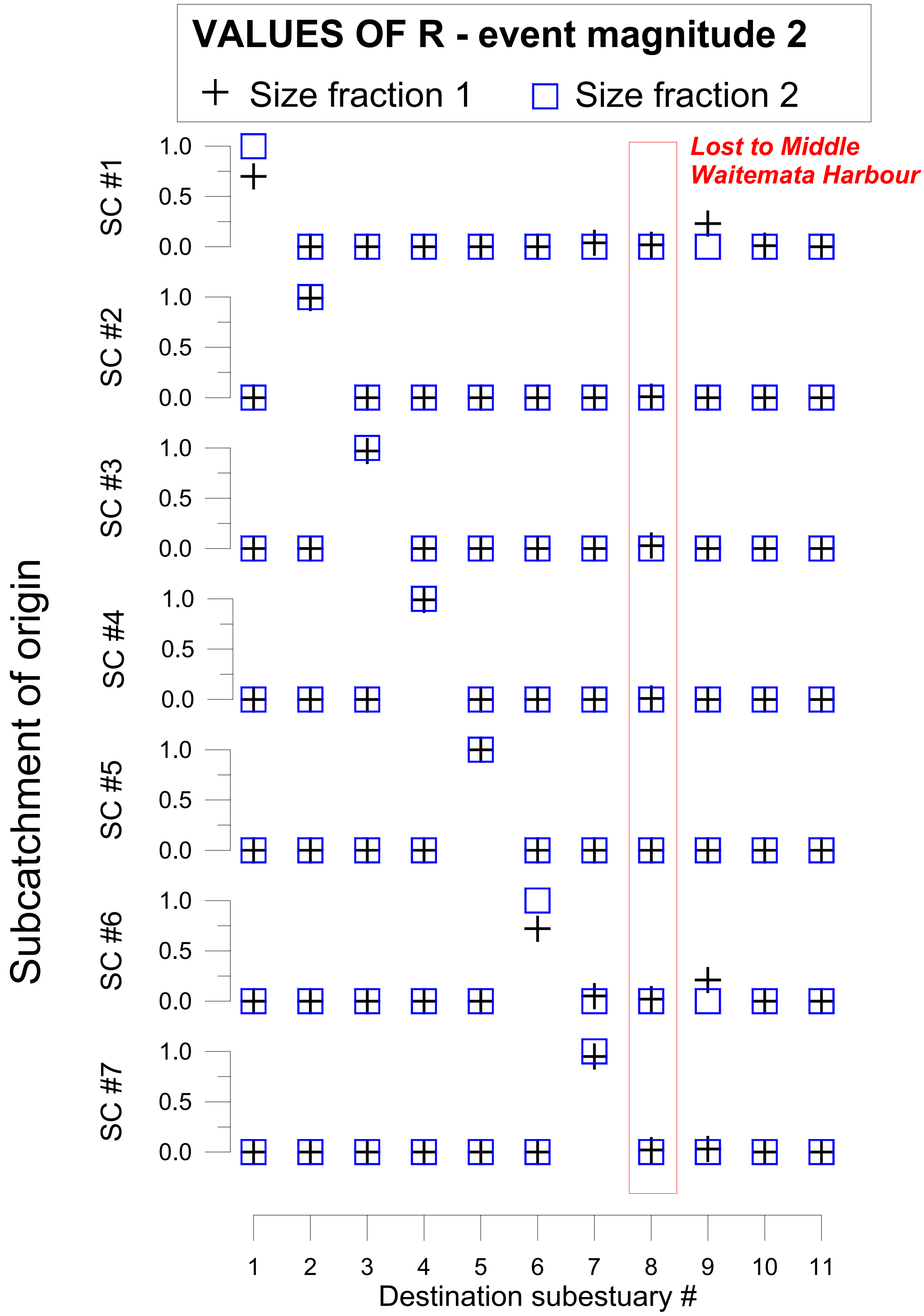

Figure 4.6 (cont.) Values of *R* used in the study – event magnitude 2.

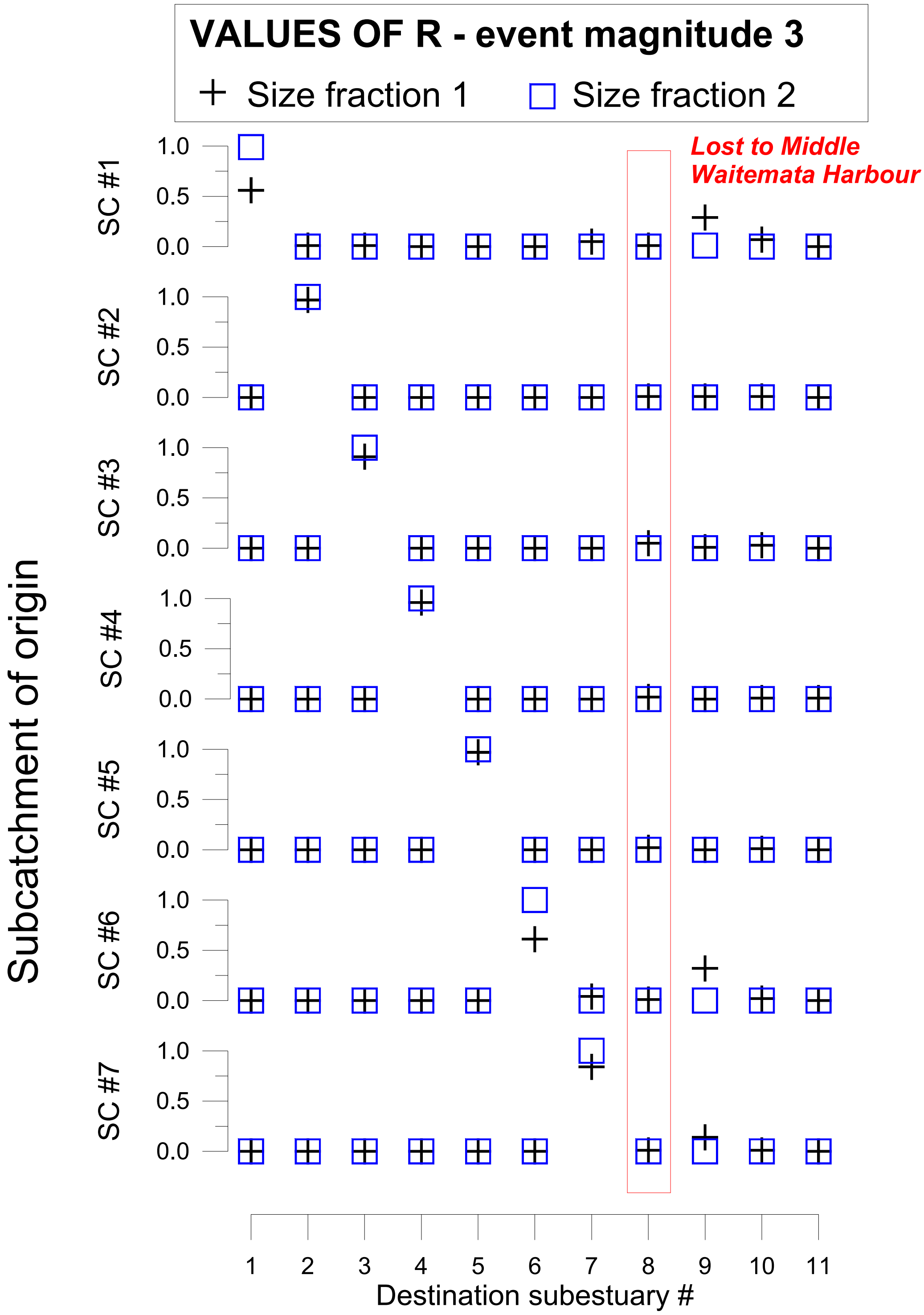

Figure 4.6 (cont.) Values of *R* used in the study – event magnitude 3.

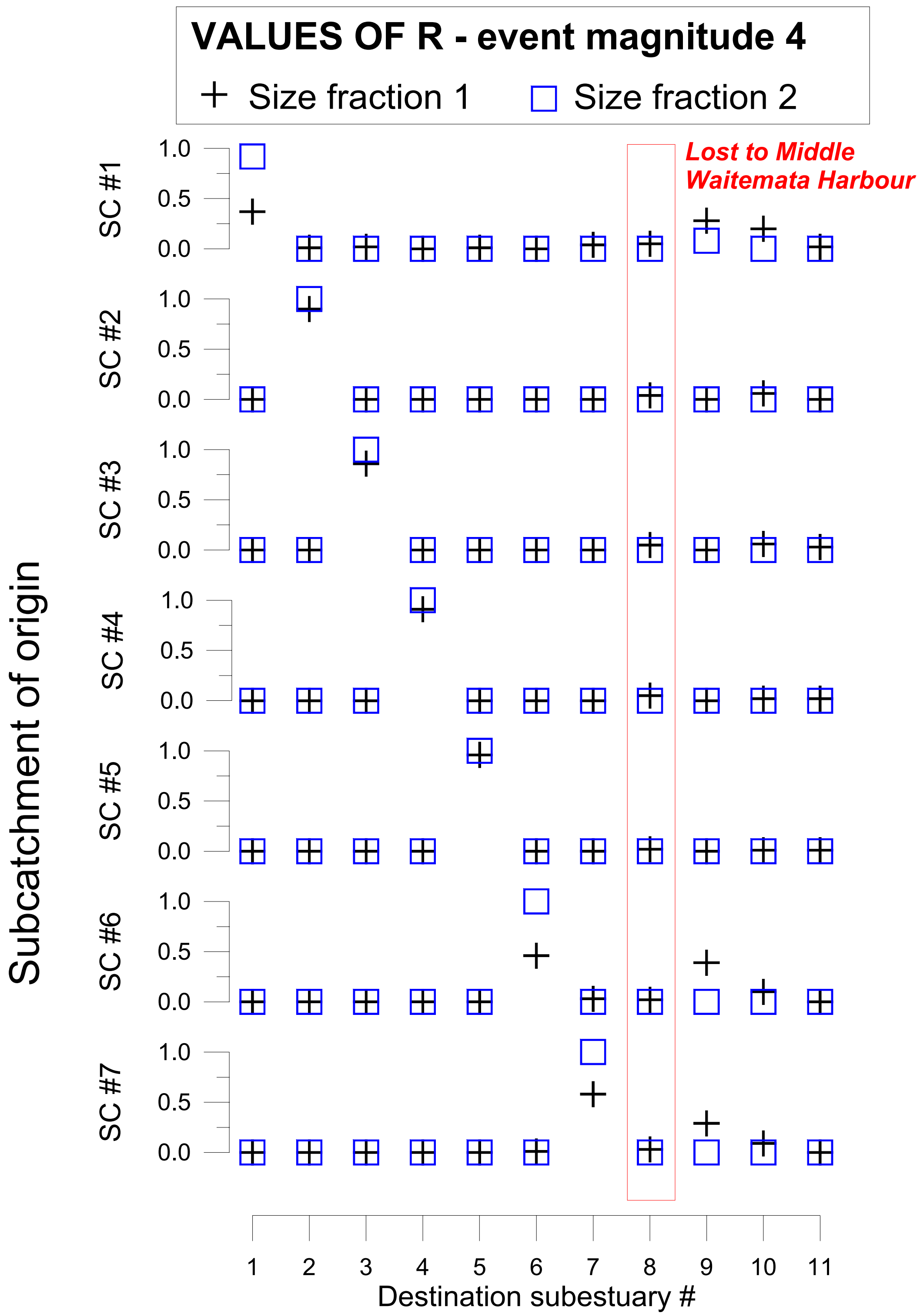

Figure 4.6 (cont.) Values of *R* used in the study – event magnitude 4

4.3.3 Prediction between any two events

4.3.3.1 Redispersal by waves and currents

Between events, sediments and associated contaminants are redispersed throughout the estuary by waves and currents, which can include being "lost" to the Middle Waitemata Harbour. The fraction of sediment of size fraction *P* deposited in an event in subestuary *kest1* that is, on average, resuspended, redispersed and redeposited in subestuary *kest2* before the next event is given by $R3_{P,kest1,kest2}$. Hence, the mass of sediment of size fraction *P* that gets transferred from *kest1* to *kest2* between E_n and E_{n+1} in the time interval $t_n < t < t_{n+1}$ is:

$$R3_{P,kest1,kest2} \times \sum_{jcatch=1}^{ncatch} [S_{P,jcatch,E_n} \times R_{P,jcatch,kest1,E_n}]$$

and contaminants are treated analogously. The term *R3* describes the pattern of sediment and contaminant redispersal and redeposition throughout the estuary between events. Note that the same values of *R3* used for sediment redispersal and redeposition are also used for contaminant redispersal and redeposition. In effect, contaminants remain "locked" to sediments (but, again, different particle sizes, with their associated contaminants, can redisperse and redeposit differently).

R3 was calculated using the same hydrodynamic/particle-tracking computer model of the estuary as used previously to calculate *R*. The same hydrodynamic simulations were utilised, but with the sediment sources as the intertidal flats previously identified as being areas of deposition, rather than where the streams discharge into the tidal-creek headwaters. Particle-tracking simulations were performed with each intertidal flat thus assigned as a source to determine how sediments and contaminants are redispersed following deposition in the immediate aftermath of an event.

Full details on the computational model methodology, model calibration and the procedure for obtaining *R3* can be found in Appendix B. Figure 4.7 shows values of *R3* used in the study, and Table 4.7 summarises the information shown in that figure.

In general, size fraction 2 sediment (sand) is not widely redispersed between events. Sand deposited in most subestuaries within an event does not get transferred to any other subestuary between events. That is, $R3_{P2,kest1,kest2}$ typically equals 1, where *kest1* = *kest2*. That is not the case for size fraction 1 sediment (silt), for which there are some significant transfers amongst subestuaries between events. Note, however, that transfers are generally from the arms to the main body, rather than to other arms. Some silt does get transferred from the main body to the arms (primarily from the upper part of the main body [subestuary #9]). There are also some significant losses to the Middle Waitemata Harbour (subestuary #8).

Table 4.7 Summary of silt and sand redispersal patterns between events, as given by *R3* values. The larger number in each cell denotes the subestuary where most of the sediment originating from the corresponding subestuary gets deposited between events. The smaller numbers in each cell denote subestuaries where some sediment also deposits. "Lost" denotes sediment is lost to the Middle Waitemata Harbour, "Upp" denotes the upper reaches of the main body of the MWH, "Mid" denotes the middle reaches of the main body of the MWH, "Low" denotes the lower reaches of the main body of the MWH.

Subestuary	Silt	Sand
1	1	1
2	2,Upp,Mid,Low	2
3	3,Upp,Mid	3
4	4,5,Upp	4
5	5,Upp	5
6	Upp,Mid,5,6	6,Upp
7	Lost,7,Mid	7
Upp	Upp,Mid,2,4	Upp
Mid	Mid,Lost,2,Upp,Low	Mid
Low	Low,Lost,Mid,2	Low

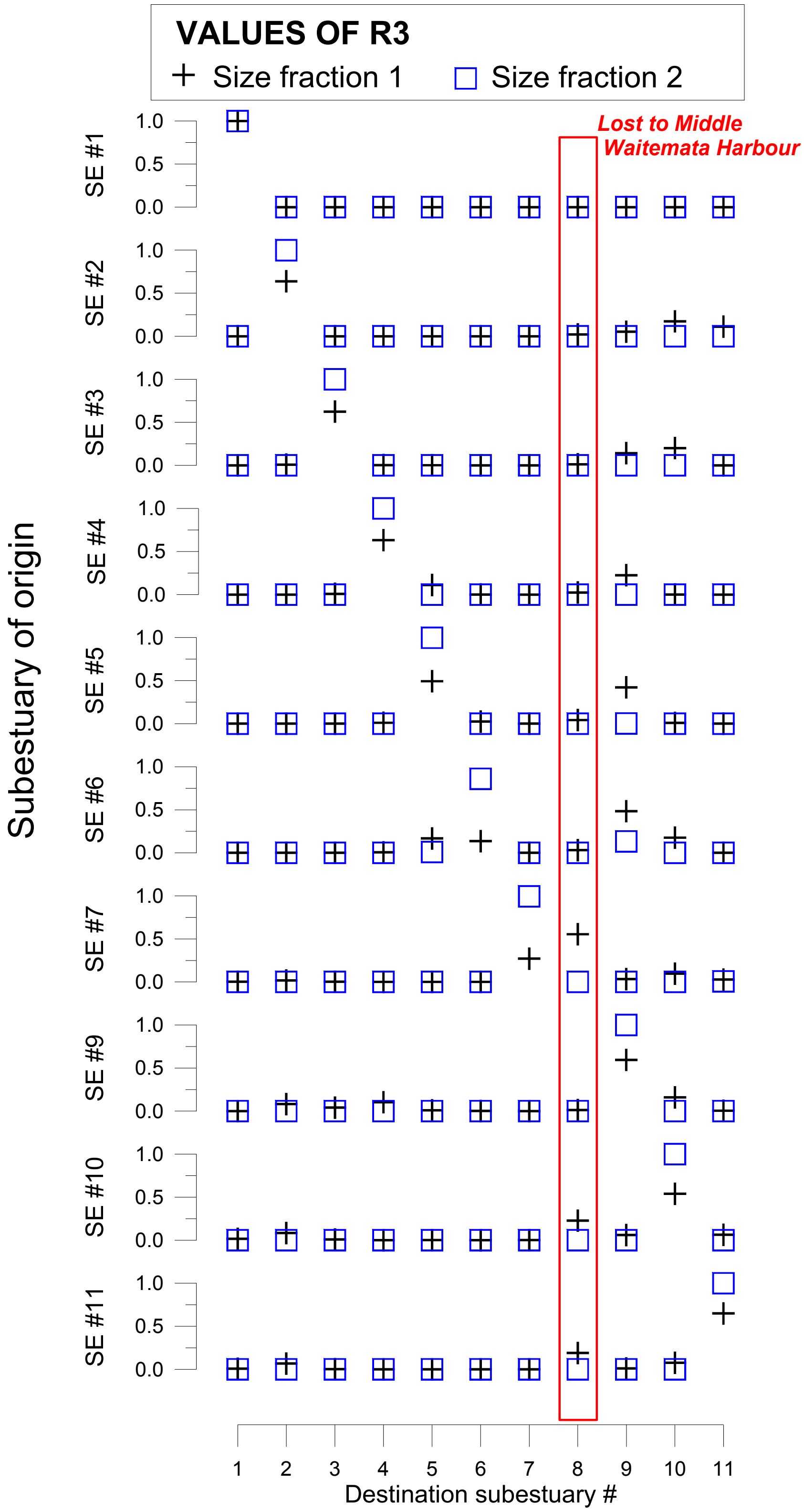

Figure 4.7 Values of *R3* used in the study.

4.3.3.2 Bioturbation

Sediments and associated contaminants are also bioturbated between events, which results in mixing of recently deposited layers with pre-existing bed sediments.

Mud crabs (*Helice crassa*) are probably one of the most important bioturbators in the muddy areas of Auckland estuaries, at least in the intertidal zone, since they are abundant, relatively large, and burrow extensively. Shrimps may be the most important bioturbators in the subtidal zone. Both types of animal excavate burrows by moving sediments lower in the sediment profile up to the surface. Burrows become blocked with surface sediment falling down the burrow, especially when the surface is agitated by wavelets as the tidal front passes over the burrows. This sediment needs to be expelled to maintain the viability of the burrow. In addition, new burrows are formed frequently. Other small animals (worms, etc.) mix sediment between the burrows.

Helice crassa distribution varies seasonally – downshore in summer, up in winter – and activity also varies with temperature and food supply. Furthermore, populations may also be seriously impacted by frequent flood events, which are more likely in winter and spring. Thus it seems likely that bioturbation varies both spatially and temporally, and such variation will be very difficult to model in any simple way.

To demonstrate the importance of mixing, we consider a case with no mixing, in which sediment is laid down, but does not mix with the underlying sediment. The predicted profile is given in Figure 4.8, which shows zinc in Pakuranga estuary (from Green et al., 2001). Very high concentrations would occur with no mixing, much greater than the highest concentration actually observed in Pakuranga estuary of about 230 mg/kg. Furthermore, the depth of contamination would be confined to the top 6 cm, whereas contaminants are actually found at much greater depths.

Any number of bioturbation models are available which can be applied, including diffusion models and simple uniform, or "homogeneous", mixing models. Earlier models (the Urban Stormwater Contaminant Model – USC) assumed homogeneous mixing in the surface 15 cm layer, which was chosen to represent the commonly observed burrow depth for mud crabs, which were assumed to be primarily responsible for much of the mixing. [Morrisey et al. (1999) report mean burrow depths of ~25 cm for *Helice crassa* in mud or muddy sand, which is significantly deeper than 15 cm. However, the choice of 15 cm in the USC model was a compromise for a discontinuous mixing function, representing gradually declining mixing over 10–25 cm depth.] If the mixing depth in the homogeneous model is too small, then predicted concentrations will be too high, with an extreme case being shown in Figure 4.8. Conversely, if the mixing depth is too great, then predicted concentrations will be too low.

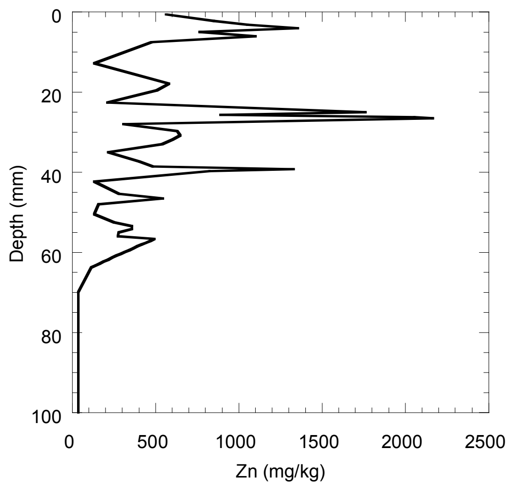

Figure 4.8 **Predicted Zn concentrations in Pakuranga estuary with no bioturbation.**

In 2001, we reviewed and summarised the international literature in the search for a realistic model(s) to describe sediment mixing by bioturbation (Green et al., 2001). There are many models available, most of which could describe a fundamentally heterogeneous mixing process. However, it was impossible to fit local data to these models because measured core profiles were highly variable. A detailed, critical evaluation of local data showed that homogeneous mixing in fact gives a good approximation of contaminant profiles, at least to order of magnitude. It was concluded that any improvements in the mixing model beyond the simple uniform-mixing case would have to await better local data.

To that end, detailed cores were collected and analysed from Lucas Creek, one of the more contaminated estuaries in the Upper Harbour. Multiple cores were collected from 25 by 5-m plots and composited to overcome the high variability due to small-scale heterogeneity in the sedimentary environment. This is appropriate, since we aim to estimate an average mixing rate for an intertidal bank. The methods and results are described in detail in Appendix C.

Figure 4.9 shows Zn, Cu and Pb profiles from one set of cores. The cores, which are sampled from near the ARC Long Term Baseline monitoring site, suggest a mixing depth of 13 cm, with contamination extending to 30 cm. Assuming that most contamination occurred since 1950, this then suggests a deposition rate of 3 mm per year averaged over the period 1950 to present. Most importantly, the profile suggests that homogeneous (uniform) mixing is a reasonable assumption, with a mixing depth of 13 cm indicated for this site.

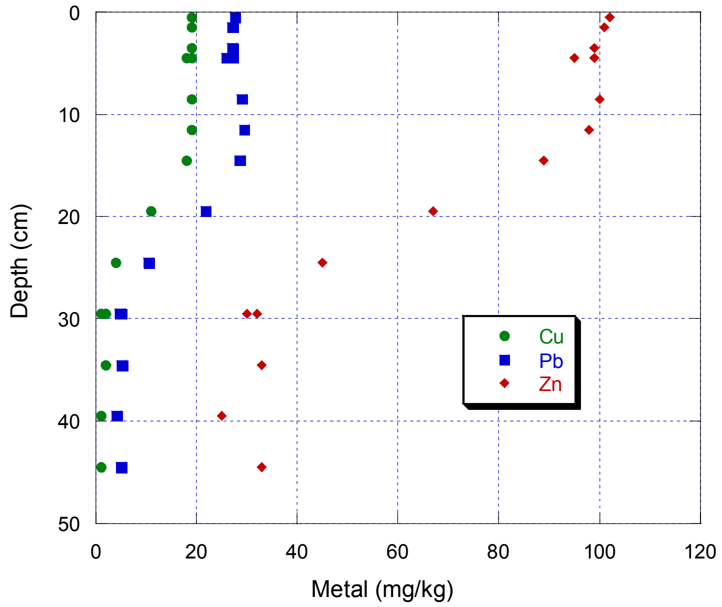

Figure 4.9. Cu, Pb and Zn profiles from a muddy intertidal bank from Lucas Creek.

Simple uniform (homogeneous) bioturbation was assumed for this study. The details of how this was implemented are given in Appendix A. The model requires specification of a mixing depth, as well as initial contaminant concentrations in estuarine sediments. These are presented in the reports in this series dealing with results.

4.3.4 Prediction across many events

The simulation period is broken down into what happens within events and what happens between events. Events are spread throughout the simulation period to yield an event time series. Events may be spread uniformly, randomly, or clustered in ways that are meant to simulate "worst-case" or "best-case" outcomes. For this study, events were spread uniformly throughout the simulation period, to give an "average" outcome.

Within each event, sediments and associated contaminants are generated throughout the catchment, passed through controls, delivered to the estuary, dispersed throughout the estuary, and allowed to settle on banks and intertidal flats. Between events, sediments and associated contaminants are bioturbated and redispersed throughout the estuary by waves and currents, which builds up contaminant concentrations. Origin and fate of sediments and contaminants are tracked through time together with the buildup of contaminants in the sediments of each subestuary. As a reminder, the principal model outputs are:

Contaminant concentration in estuarine sediments	
$\beta_{surface,kest}$	
Sediment-deposition rate	
$\delta_{ANNUALAVG,54years,kest}$, $\delta_{ANNUALAVG,108years,kest}$	
Origin of sediments/contaminants that deposit in each subestuary	
$\eta_{jcatch,54years,kest}$, $\eta_{jcatch,108years,kest}$, $\eta_{jcatch,CUM,kest}$	sediments
$\lambda_{jcatch,54years,kest}$, $\lambda_{jcatch,108years,kest}$, $\lambda_{jcatch,CUM,kest}$	contaminants
Fate of sediments/contaminants that originate in each subcatchment	
$\varepsilon_{kest,54years,jcatch}$, $\varepsilon_{kest,108years,jcatch}$, $\varepsilon_{kest,CUM,jcatch}$	sediments
$\phi_{kest,54years,jcatch}$, $\phi_{kest,108years,jcatch}$, $\phi_{kest,CUM,jcatch}$	contaminants

4.4 Model Verification

The calibration and verification of the DHI estuary hydrodynamic/sediment-transport model, which is one of the core models, is described in Appendix B.

The calibration and verification of the GLEAMS catchment model, which is also one of the core models, is described in Appendix D.

There is no direct way to verify the larger contaminant-accumulation model, which is forward-looking and which combines information from the various core models as well as information from other sources. However, certain tests have been applied to establish confidence in the predictions:

- Annual sedimentation rates in each subestuary predicted by the model and averaged over the simulation period have been compared to measured annual sedimentation rates averaged over the past 50 years or so, which have been established by coring. A favourable comparison between predicted and observed indicates that sediment loads from the catchment, sediment dispersal/deposition patterns, and sediment redispersal/redeposition patterns are being treated correctly in the model. The comparison will not be strictly valid, since the predictions are forward-looking and the observations are backward-looking, however this problem will be minimised by applying the comparison only to predictions under the existing landuse scenario. The results of this test are shown in Appendix E.

- Contaminant concentrations in estuary-sediment cores can be compared to predictions by the model. This is, in fact, quite a severe test of the model, since concentration profiles in reality develop from the entire suite of interacting processes simulated by the model. In particular, this provides a good test of the bioturbation mixing depth, which can be tuned to achieve observed profiles. In order not to exacerbate the forward/backward-looking problem, the comparison is only applied to predictions under the existing landuse scenario. The results of this test are shown in Appendix F.

5. Conclusions

This report describes the methods used to predict contaminant accumulation in bed sediments of the Upper Waitemata Harbour over decadal timescales under various landuse scenarios.

The method is based on extrapolating core calculations, where these in turn are derived from the use of more detailed deterministic models. At the heart of the method is a set of mass-balance equations that describes how estuarine sedimentation is constituted on an event basis, where an event is a rainstorm and its immediate aftermath. Once established, the mass-balance equations can be freely manipulated to estimate changes in contaminant accumulation associated with different possible management strategies, which may cause reductions in sediment and/or contaminant loads. Any number of "what if" games can be played without needing to rebuild the equations each time. The reason is that they derive, fundamentally, from the estuarine dispersal and sedimentation processes, which are essentially independent of catchment sediment/contaminant loads.

With this approach, we can now identify areas in estuaries prone to contamination and predict the long-term accumulation of contaminants in estuarine sediments associated with landuse intensification in the surrounding catchment.

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APPENDIX A. Prediction Scheme Details

A.1 Prediction During a Single Event

Building on the within-event/between-events dichotomy, the first task is to establish a method of predicting sediment and contaminant movements during a single event.

An overview of sediment / contaminant generation and delivery to the estuary during a single event from a given subcatchment is shown in Figure A.1.

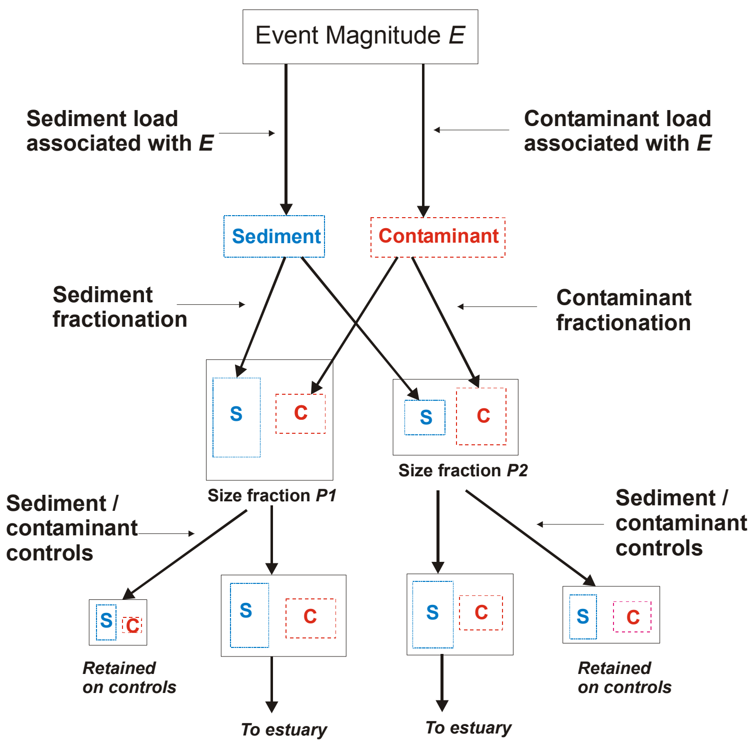


Figure A.1 Sediment / contaminant generation and delivery to the estuary during a single event from a given subcatchment.

The scheme shown in Figure A.1 for sediment / contaminant generation and delivery to the estuary during a single event from a given subcatchment is applied independently to every subcatchment that drains into the Upper Waitemata Harbour.

Sediments generated and delivered to the estuary from a given subcatchment during a particular event are dispersed to the subestuaries as shown schematically in Figure A.2.

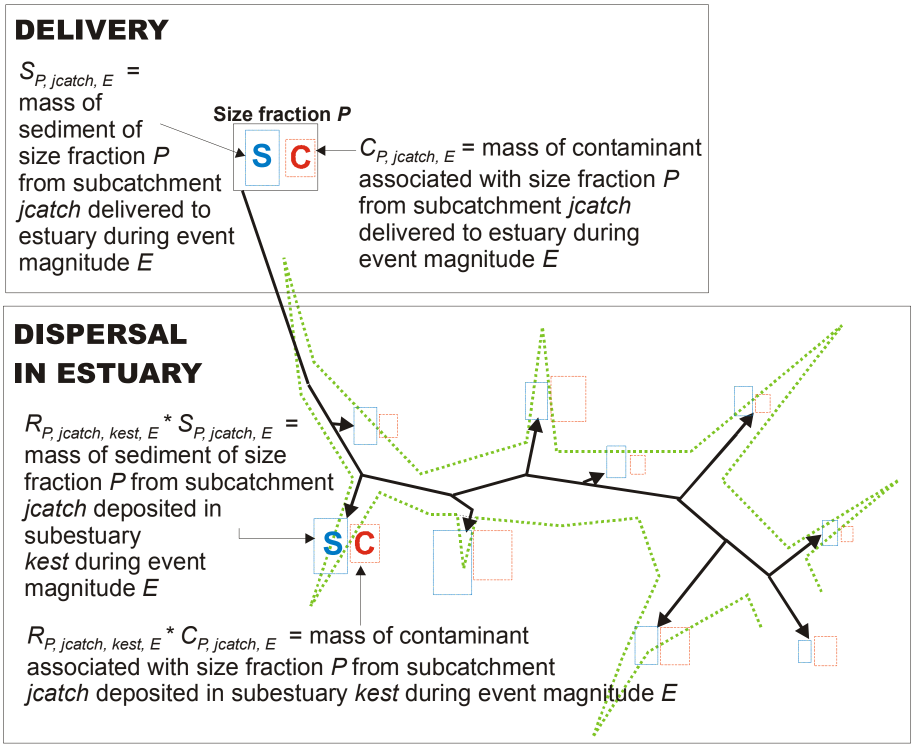


Figure A.2 Dispersal around the estuary of sediments and contaminants generated in a single subcatchment during a single event.

- The mass of sediment of size fraction *P* from subcatchment *jcatch* depositing in subestuary *kest* during event magnitude *E* is given by:

  $$S_{P,jcatch,kest,E} = S_{P,jcatch,E} * R_{P,jcatch,kest,E}$$

  where $S_{P,jcatch,E}$ is the mass of sediment of size fraction *P* from subcatchment *jcatch* that is passed through any controls and that is subsequently delivered to the estuary during event magnitude *E*.

- In effect, the term R describes the pattern of sediment dispersal and deposition throughout the estuary during the event. Literally, RP,jcatch,kest,E is the fraction of the sediment load discharged from subcatchment jcatch (after going through any controls) that is deposited in subestuary kest. Hence,

  $$\sum_{kest=1}^{nest} R_{P,jcatch,kest,E} = 1$$

  where *nest* is the number of subestuaries. Hence, all sediment discharged from the subcatchment is accounted for.

- Sediment that is transported to subestuary 8 (the Middle Waitemata Harbour) is "lost", hence RP,jcatch,8,E is the fraction of sediment from subcatchment jcatch during event magnitude E that is not deposited in the Upper Waitemata Harbour.

- R varies with event magnitude E, since estuarine circulation and mixing, which are first-order controls on sediment dispersal and deposition, vary with the amount of freshwater discharge, which in turn varies with event magnitude.

- R varies with size fraction P since particle settling speed, which is a first-order control on sediment dispersal and deposition, varies with size fraction.

Contaminants generated and delivered to the estuary from a given subcatchment during a particular event are dispersed to the subestuaries as shown schematically in Figure A.2.

- The mass of contaminant associated with size fraction P from subcatchment jcatch depositing in subestuary kest during event magnitude E is given by:

  $$C_{P,jcatch,kest,E} = C_{P,jcatch,E} * R_{P,jcatch,kest,E}$$

  where $C_{P,jcatch,E}$ is the mass of contaminant associated with size fraction *P* from subcatchment *jcatch* that is passed through any controls and that is subsequently delivered to the estuary during event magnitude *E*.

- As before, the term R describes the pattern of contaminant dispersal and deposition throughout the estuary during the event. Note that the same value of R used for sediment dispersal and deposition is also used for contaminant dispersal and deposition. In effect, contaminants remain "locked" to sediments.

The scheme shown in Figure A.2 for dispersal to the subestuaries is applied to sediment and contaminants generated from each subcatchment.

The total mass of sediment of size fraction *P* deposited in subestuary *kest* during event magnitude *E* is given by:

$$\sum_{jcatch=1}^{ncatch} S_{P,jcatch,kest,E}$$

where *ncatch* is number of subcatchments.

The total mass of contaminant associated with size fraction *P* deposited in subestuary *kest* during event magnitude *E* is given by:

$$\sum_{jcatch=1}^{ncatch} C_{P,jcatch,kest,E}$$

The total mass of sediment deposited in subestuary *kest* during event magnitude *E* is given by:

$$SED_{kest,E} = \sum_{P=1}^{nparticle} \sum_{jcatch=1}^{ncatch} S_{P,jcatch,kest,E}$$

where *nparticle* is the number of size fractions.

The total mass of contaminant deposited in subestuary *kest* during event magnitude *E* is given by:

$$CONT_{kest,E} = \sum_{P=1}^{nparticle} \sum_{jcatch=1}^{ncatch} C_{P,jcatch,kest,E}$$

The deposition thickness in subestuary *kest* during event magnitude *E* is given by:

$$DEP_{kest,E} = SED_{kest,E} / (\rho_{\text{settled}} * A_{kest})$$

where ρ_{settled} is the bulk density of sediment (all size fractions) when settled on the bed and A_{kest} is the area within subestuary *kest* that deposition can occur. As explained previously, deposition can only occur on banks / intertidal flats, not channels.

The mass/mass contaminant concentration in the layer of sediment deposited during event magnitude *E* in subestuary *kest* before any bioturbation or mixing between events occurs is:

$$CCONC_{kest,E} = CONT_{kest,E} / SED_{kest,E}$$

A.2 Prediction Between Any Two Events

Between events, sediments and associated contaminants are redispersed throughout the estuary by waves and currents, and sediments are also bioturbated, which results in mixing of recently deposited layers with pre-existing bed sediments. This section describes how between-event processes are treated.

A.2.1 Redispersal

Sediments deposited in a particular subestuary during a particular event may be resuspended, transported and deposited in another subestuary (which includes being "lost" to subestuary 8, the Middle Waitemata Harbour) by waves and currents that occur after that event and before the next event.

Event number *n*, which is designated by E_n, is said to occur at time t_n, and event number $n+1$, which is designated by E_{n+1}, occurs at time t_{n+1}. Hence, redistribution of sediments between E_n and E_{n+1} occurs in the time interval $t_n < t < t_{n+1}$.

The fraction of sediment of size fraction *P* deposited in an event in subestuary *kest1* that is, on average, resuspended, redispersed and redeposited in subestuary *kest2* before the next event is given by $R3_{P,kest1,kest2}$. Hence, the mass of sediment of size fraction *P* that gets transferred from *kest1* to *kest2* between E_n and E_{n+1} in the time interval $t_n < t < t_{n+1}$ is:

$$R3_{P,kest1,kest2} * \sum_{jcatch=1}^{ncatch} S_{P,jcatch,kest1,E_n}$$

Similarly, the mass of contaminant associated with size fraction *P* that gets transferred from *kest1* to *kest2* between E_n and E_{n+1} in the time interval $t_n < t < t_{n+1}$ is:

$$R3_{P,kest1,kest2} * \sum_{jcatch=1}^{ncatch} C_{P,jcatch,kest1,E_n}$$

The combined term *R3* describes the pattern of sediment and contaminant redispersal and redeposition throughout the estuary between events. Note that the same values of *R3* used for sediment redispersal and redeposition are also used for contaminant redispersal and redeposition. In effect, contaminants remain "locked" to sediments.

The total mass of sediment transferred away by waves and currents from subestuary *kest1* between E_n and E_{n+1} in the time interval $t_n < t < t_{n+1}$ is:

$$SEDLOST_{kest1,[E_n - E_{n+1}]} = \sum_{P=1}^{nparticle} \sum_{kest2=1}^{nest} [R3_{P,kest1,kest2} * \sum_{jcatch=1}^{ncatch} S_{P,jcatch,kest1,E_n}]$$

Similarly, the total mass of contaminant transferred away by waves and currents from subestuary *kest1* between E_n and E_{n+1} in the time interval $t_n < t < t_{n+1}$ is:

$$CONTLOST_{kest1,[E_n - E_{n+1}]} = \sum_{P=1}^{nparticle} \sum_{kest2=1}^{nest} [R3_{P,kest1,kest2} * \sum_{jcatch=1}^{ncatch} C_{P,jcatch,kest1,E_n}]$$

On the other hand, the total mass of sediment transferred to subestuary *kest1* by waves and currents between E_n and E_{n+1} in the time interval $t_n < t < t_{n+1}$ is:

$$SEDGAINED_{kest1,[E_n - E_{n+1}]} =$$

$$\sum_{P=1}^{nparticle} \sum_{kest2=1}^{nest} [R3_{P,kest2,kest1} * \sum_{jcatch=1}^{ncatch} S_{P,jcatch,kest2,E}]$$

Similarly, the total mass of contaminant transferred to subestuary *kest1* by waves and currents between E_n and E_{n+1} in the time interval $t_n < t < t_{n+1}$ is:

$$CONTGAINED_{kest1,[E_n - E_{n+1}]} =$$

$$\sum_{P=1}^{nparticle} \sum_{kest2=1}^{nest} [R3_{P,kest2,kest1} * \sum_{jcatch=1}^{ncatch} C_{P,jcatch,kest2,E}]$$

The deposition thickness in any subestuary *kest* in the wake of event magnitude *E* but before the arrival of the next event therefore gets adjusted to:

$$DEPALTERED_{kest}(t_{\rightarrow E_{n+1}}) =$$

$$[SED_{kest,E} + SEDGAINED_{kest[E_n - E_{n+1}]} - SEDLOST_{kest[E_n - E_{n+1}]}]/(\rho_{\text{settled}} * A_{kest})$$

Note that *DEPALTERED* develops immediately before the arrival of event E_{n+1}, which is designated by the time $t = t_{\rightarrow E_{n+1}}$.

Similarly, the mass/mass contaminant concentration in the layer of sediment deposited in any subestuary *kest* during event *E* and modified by waves and currents before the arrival of the next event is given by:

$$CCONCALTERED_{kest}(t_{\rightarrow E_{n+1}}) =$$

$$[CONT_{kest,E} + CONTGAINED_{kest[E_n - E_{n+1}]} - CONTLOST_{kest[E_n - E_{n+1}]}]/$$

$$[SED_{kest,E} + SEDGAINED_{kest[E_n - E_{n+1}]} - SEDLOST_{kest[E_n - E_{n+1}]}]$$

A.2.2 Bioturbation

Bioturbation is assumed to result in uniform mixing of sediments to a depth of *BDEPTH* between events.

The newly bioturbated layer that develops between events E_n and E_{n+1} in the time interval $t_n < t < t_{n+1}$ is said to be fully developed by time $t = t_{\rightarrow E_{n+1}}$, which is immediately before the arrival of event E_{n+1}.

In any given subestuary *kest*, the bioturbated layer that develops by time $t = t_{\rightarrow E_{n+1}}$ is a mixture of two sediment layers. The top layer is sediment deposited in event E_n and subsequently redispersed by waves and currents in the interval $t_n < t < t_{n+1}$. This layer is

$$DEPALTERED_{kest}(t_{\rightarrow E_{n+1}})$$

thick. The bottom layer is pre-existing sediment (which itself has been bioturbated) and which is

$$BDEPTH - DEPALTERED_{kest}(t_{\rightarrow E_{n+1}})$$

thick.

The mass per unit area of contaminant in the top layer is:

$$[CONT_{kest,E_n} + CONTGAINED_{kest[E_n - E_{n+1}]} - CONTLOST_{kest[E_n - E_{n+1}]}] / A_{kest}$$

The mass per unit area of contaminant in the bottom layer is:

$$CCONCBIOTURBATED_{kest}(t_{\to E_n})*$$

$$[BDEPTH - DEPALTERED_{kest}(t_{\to E_{n+1}})] * \rho_{\text{settled}}$$

where

$$CCONCBIOTURBATED_{kest}(t_{\to E_n})$$

is the contaminant concentration in the pre-existing (and previously bioturbated) layer.

Note, for $n = 1$,

$$CCONCBIOTURBATED_{kest}(t_{\to E_n}) = CCONCINITIAL_{kest}$$

which is the initial or "starting" contaminant concentration in the bed sediments.

The contaminant concentration in the newly bioturbated layer that develops by time $t = t_{\to E_{n+1}}$ in subestuary *kest* is therefore:

$$CCONCBIOTURBATED_{kest}(t_{\to E_{n+1}}) =$$

$$\{([CONT_{kest,E_n} + CONTGAINED_{kest[E_n - E_{n+1}]} - CONTLOST_{kest[E_n - E_{n+1}]}] / A_{kest}) +$$

$$(CCONCBIOTURBATED_{kest}(t_{\to E_n})*$$

$$[BDEPTH - DEPALTERED_{kest}(t_{\to E_{n+1}})] * \rho_{\text{settled}})\} /$$

$$(BDEPTH_{kest} * \rho_{\text{settled}}).$$

Finally, note that if

$$DEPALTERED_{kest}(t_{\to E_{n+1}}) \geq BDEPTH$$

then

$$CCONCBIOTURBATED_{kest}(t_{\to E_{n+1}}) = CCONCALTERED_{kest}(t_{\to E_{n+1}})$$

A.3 Prediction Across Many Events

The simulation period is broken down into what happens within events and what happens between events. Within each event, sediments and associated contaminants are generated throughout the catchment, passed through controls, delivered to the estuary, dispersed throughout the estuary, and allowed to settle on banks / intertidal flats. Section A.1 described how within-event processes are treated. Between events, sediments and associated contaminants are bioturbated and redispersed throughout the estuary by waves and currents. Section A.2 described how between-event processes are treated. This section describes how between-event processes are interspersed between the within-event processes in order to predict accumulation of sediments and contaminants across the simulation period.

Events are spread throughout the simulation period to yield an event time series. Events may be spread uniformly, or they may be clustered in ways that are meant to simulate "worst-case" or "best-case" outcomes. More details on this are given where the simulations are described. Figure A.3 shows four different magnitude events spread uniformly throughout simulation periods of 54 and 108 years.

The time series of events is used to drive the simulation. For instance, at time $t = t_{\to E_2}$ (which is after event number 1 has occurred and immediately before event number 2 occurs), the contaminant concentration in the bioturbated layer in subestuary *kest* is:

$$CCONCBIOTURBATED_{kest}(t_{\to E_2}) =$$

$$\{([CONT_{kest,E_1} + CONTGAINED_{kest[E_1-E_2]} - CONTLOST_{kest[E_1-E_2]}]/A_{kest}) +$$

$$(CCONCINITIAL_{kest} *$$

$$[BDEPTH - DEPALTERED_{kest}(t_{\to E_2})] * \rho_{\text{settled}})\}/$$

$$(BDEPTH_{kest} * \rho_{\text{settled}}).$$

Next, at time $t = t_{\to E_3}$ (which is after event number 2 has occurred and immediately before event number 3 occurs), the contaminant concentration in the bioturbated layer in subestuary *kest* changes to:

$$CCONCBIOTURBATED_{kest}(t_{\to E_3}) =$$

$$\{([CONT_{kest,E_2} + CONTGAINED_{kest[E_2-E_3]} - CONTLOST_{kest[E_2-E_3]}]/A_{kest}) +$$

$$(CCONCBIOTURBATED_{kest}(t_{\to E_2}) *$$

$$[BDEPTH - DEPALTERED_{kest}(t_{\to E_3})] * \rho_{\text{settled}})\}/$$

$$(BDEPTH_{kest} * \rho_{\text{settled}}).$$

And so on.

A.3.1 Prediction of contaminant concentration in surface sediment

The mass/mass contaminant concentration in the surface sediment of any subestuary *kest* at any time t_n that is immediately prior to event number n+1 is given by:

$$\beta_{surface,kest}(t_n) = CCONCBIOTURBATED_{kest}(t_{\to E_{n+1}})$$

which is the contaminant concentration in the top *BDEPTH* cm of the sediment column at that time.

> $\beta_{surface,kest}$ plotted against time is a principal output of the study. Such a graph shows how contaminant concentration in the surface sediment develops over time through the simulation period.

A.3.2 Prediction of sediment-deposition rate

The change in height of the sediment surface in any subestuary *kest* between two times t_n and t_m, where t_n is immediately prior to event number n and t_m is immediately prior to event number m+1, where $m > n$, is given by:

$$\sum_{i=n}^{m} DEPALTERED_{kest}(t_{\to E_{i+1}})$$

Hence, the sediment-deposition rate over the period t_n to t_m is:

$$\delta_{[t_n - t_m],kest} = \sum_{i=n}^{m} DEPALTERED_{kest}(t_{\to E_{i+1}})/(t_m - t_n)$$

If n = 1 and m is the last event in the simulation period (54 or 108 years), then t_1 to t_2 encompasses the entire simulation period (54 or 108 years). In that case, $\delta_{[t_n - t_m],kest}$ = $\delta_{ANNUALAVG,54years,kest}$ is the annual deposition rate averaged over 54 years in subestuary *kest*, and $\delta_{[t_n - t_m],kest}$ = $\delta_{ANNUALAVG,108years,kest}$ is the annual deposition rate averaged over 108 years in subestuary *kest*.

$\delta_{ANNUALAVG,54years,kest}$ and $\delta_{ANNUALAVG,108years,kest}$ are principal outputs of the study. Each of these summarises the deposition rate over the entire simulation period.

A.3.3 Origin of sediments and contaminants that deposit in each subestuary

The total mass of sediment deposited in any subestuary *kest* between two times t_n and t_m, where t_n is immediately prior to event number *n* and t_m is immediately prior to event number *m*+1, where *m* > *n*, is given by:

$$TOTALSED_{[t_n - t_m],kest} = \sum_{i=n}^{m} DEPALTERED_{kest}(t_{\rightarrow E_{i+1}}) * \rho_{settled} * A_{kest}$$

Similarly, the total mass of contaminant deposited in any subestuary *kest* between two times t_n and t_m, where t_n is immediately prior to event number *n* and t_m is immediately prior to event number *m*+1, where *m* > *n*, is given by:

$$TOTALCONT_{[t_n - t_m],kest} =$$

$$\sum_{i=n}^{m} [CCONCALTERED_{kest}(t_{\rightarrow E_{i+1}}) * DEPALTERED_{kest}(t_{\rightarrow E_{i+1}})] *$$

$$\rho_{settled} * A_{kest}$$

The movements of sediments and contaminants are tracked in the prediction scheme such that $TOTALSED_{[t_n - t_m],kest}$ and $TOTALCONT_{[t_n - t_m],kest}$ can be decomposed according to the subcatchment of origin of sediment and contaminant, respectively. That is:

$$TOTALSED_{[t_n - t_m],kest} = \sum_{jcatch=1}^{ncatch} SEDFROMCATCHMENT_{jcatch,[t_n - t_m],kest}$$

and:

$$TOTALCONT_{[t_n - t_m],kest} = \sum_{jcatch=1}^{ncatch} CONTFROMCATCHMENT_{jcatch,[t_n - t_m],kest}$$

The total mass of sediment that deposits in subestuary *kest* in the period t_1 to t_2 and that originates from subcatchment *jcatch* is given by:

$$\eta_{jcatch,[t_1 - t_2],kest} = SEDFROMCATCHMENT_{jcatch,[t_n - t_m],kest}$$

where $t_1 = t_{\rightarrow E_n}$ and $t_2 = t_{\rightarrow E_{m+1}}$.

Alternatively, the sediment that deposits in subestuary *kest* in the period t_1 to t_2 and that originates from subcatchment *jcatch*, expressed as a percentage of the total amount of sediment deposited in the subestuary (i.e., from all subcatchments), is given by:

$$\eta_{jcatch,[t_1-t_2],kest} =$$

$$(SEDFROMCATCHMENT_{jcatch,[t_n-t_m],kest} / TOTALSED_{[t_n-t_m],kest})*100$$

where $t_1 = t_{\rightarrow E_n}$ and $t_2 = t_{\rightarrow E_{m+1}}$.

If n = 1 and m is the last event in the simulation period (54 or 108 years), then t_1 to t_2 encompasses the entire simulation period (54 or 108 years). In that case, $\eta_{jcatch,[t_1-t_2],kest} = \eta_{jcatch,54\,years,kest}$ and $\eta_{jcatch,[t_1-t_2],kest} = \eta_{jcatch,108\,years,kest}$ are the amounts of sediment deposited in subestuary *kest* over 54 years and 108 years, respectively, that originates from subcatchment *jcatch*.

Finally, if n = 1 and m is incremented by 1, then at each increment $\eta_{jcatch,[t_1-t_2],kest} = \eta_{jcatch,CUM,kest}$, which is the cumulative amount of sediment deposited in subestuary *kest* that originates from subcatchment *jcatch*.

> $\eta_{jcatch,54\,years,kest}$ (one value for the 54-year simulation period), $\eta_{jcatch,108\,years,kest}$ (one value for the 108-year simulation period) and $\eta_{jcatch,CUM,kest}$ plotted against time are principal outputs of the study. These terms show which subcatchments the sediments deposited in the subestuaries come from.

The total mass of contaminant that deposits in subestuary *kest* in the period t_1 to t_2 and that originates from subcatchment *jcatch* is given by:

$$\lambda_{jcatch,[t_1-t_2],kest} = CONTFROMCATCHMENT_{jcatch,[t_n-t_m],kest}$$

where $t_1 = t_{\rightarrow E_n}$ and $t_2 = t_{\rightarrow E_{m+1}}$.

Alternatively, the contaminant that deposits in subestuary *kest* in the period t_1 to t_2 and that originates from subcatchment *jcatch*, expressed as a percentage of the total amount of contaminant deposited in the subestuary (i.e., from all subcatchments), is given by:

$$\lambda_{jcatch,[t_1-t_2],kest} =$$

$$(CONTFROMCATCHMENT_{jcatch,[t_n-t_m],kest} / TOTALCONT_{[t_n-t_m],kest})*100$$

where $t_1 = t_{\rightarrow E_n}$ and $t_2 = t_{\rightarrow E_{m+1}}$.

If n = 1 and m is the last event in the simulation period (54 or 108 years), then t_1 to t_2 encompasses the entire simulation period (54 or 108 years). In that case, $\lambda_{jcatch,[t_1-t_2],kest} = \lambda_{jcatch,54\,years,kest}$ and $\lambda_{jcatch,[t_1-t_2],kest} = \lambda_{jcatch,108\,years,kest}$ are the amounts of contaminant deposited in subestuary *kest* over 54 years and 108 years, respectively, that originates from subcatchment *jcatch*.

Finally, if n = 1 and m is incremented by 1, then at each increment $\lambda_{jcatch,[t_1-t_2],kest} = \lambda_{jcatch,CUM,kest}$, which is the cumulative amount of contaminant deposited in subestuary *kest* that originates from subcatchment *jcatch*.

> $\lambda_{jcatch,54\,years,kest}$ (one value for the 54-year simulation period), $\lambda_{jcatch,108\,years,kest}$ (one value for the 108-year simulation period) and $\lambda_{jcatch,CUM,kest}$ plotted against time are principal outputs of the study. These terms show which subcatchments the contaminants deposited in the subestuaries come from.

A.3.4 Fate of sediments and contaminants that originate in each subcatchment

The movements of sediments and contaminants are tracked in the prediction scheme to allow calculation of several terms that describe where sediments that originate in each subcatchment become deposited. These are:

- $\varepsilon_{kest,54\,years,jcatch}$, which is the amount of sediment originating in subcatchment *jcatch* that is deposited in subestuary *kest* over the 54-year simulation period. $\varepsilon_{kest,54\,years,jcatch}$ can be expressed as a mass or as a percentage of the total amount of sediment that originates from subcatchment *jcatch* <u>and that passes through any controls and enters the estuary</u>. Note that if there are no controls and no redispersal of sediments in the estuary between events (i.e., all *R2* = 0) then $\varepsilon_{kest,54\,years,jcatch}$ simply reflects *R*.

- $\varepsilon_{kest,108\,years,jcatch}$ likewise describes the fate of sediments over the 108-year simulation period.

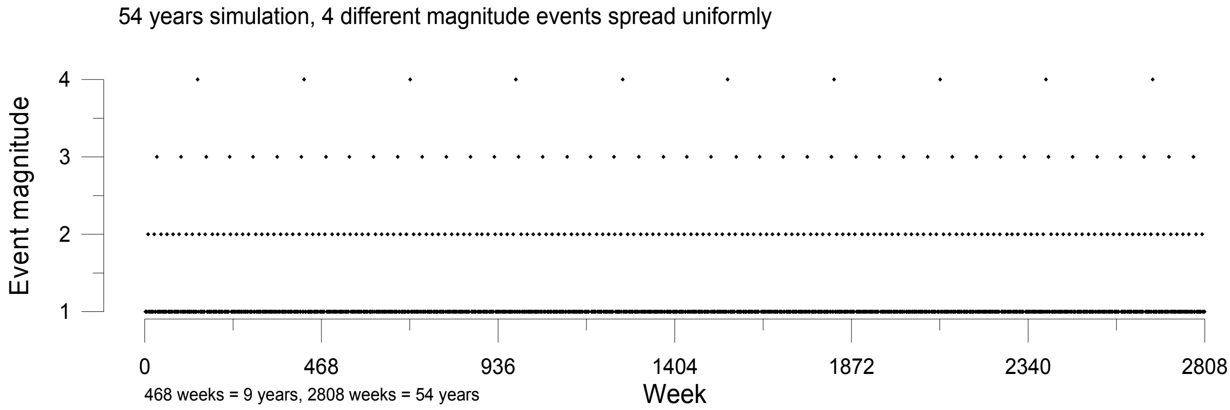
- $\varepsilon_{kest,CUM,jcatch}$, which varies through time, and which is the cumulative amount of sediment that originates in subcatchment *jcatch* and that is deposited in subestuary *kest*. Again, $\varepsilon_{kest,CUM,jcatch}$ can be expressed as a mass or as a percentage of the total, cumulative amount of sediment that originates from subcatchment *jcatch* <u>and that passes through any controls and enters the</u>

estuary. Again, note that that if there are no controls and no redispersal of sediments in the estuary between events (i.e., all *R2* = 0) then $\varepsilon_{kest,CUM,jcatch}$ simply reflects *R*.

$\varepsilon_{kest,54\,years,jcatch}$ (one value for the 54-year simulation period), $\varepsilon_{kest,108\,years,jcatch}$ (one value for the 108-year simulation period) and $\varepsilon_{kest,CUM,jcatch}$ plotted against time are principal outputs of the study. These show where sediments originating from each subcatchment become deposited.

- $\phi_{kest,54\,years,jcatch}$, $\phi_{kest,108\,years,jcatch}$ and $\phi_{kest,CUM,jcatch}$ are the analogous terms describing contaminant fate.

$\lambda_{kest,54\,years,jcatch}$ (one value for the 54-year simulation period), $\lambda_{kest,108\,years,jcatch}$ (one value for the 108-year simulation period) and $\lambda_{kest,CUM,jcatch}$ plotted against time are principal outputs of the study. These show where contaminants originating from each subcatchment become deposited.



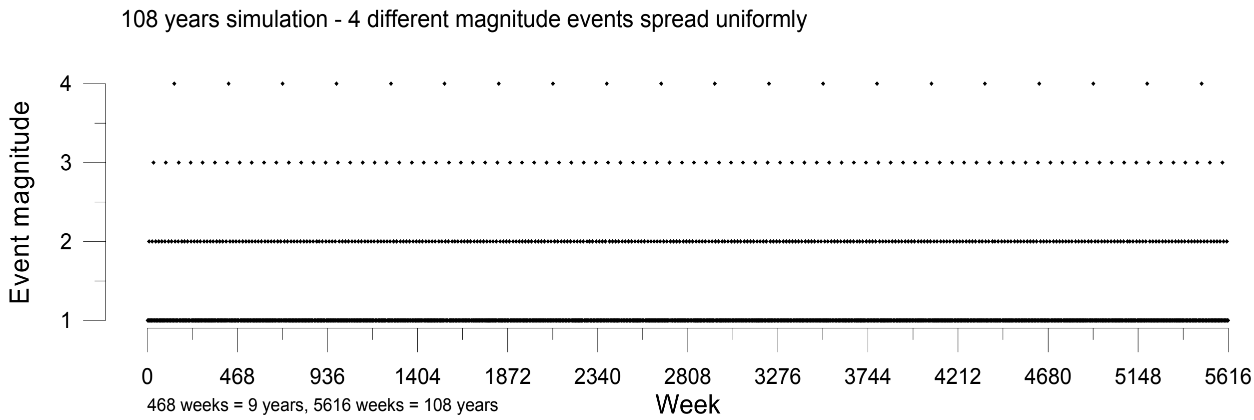


Figure A.3 Four different magnitude events spread uniformly throughout simulation periods of 54 and 108 years. Note, event magnitude *E0* denotes between events.

APPENDIX B. Estuary Hydrodynamics and Particle-Tracking Model

B.1 Introduction

For the purposes of this study, the Upper Waitemata Harbour is defined as the tidal area upstream of the constriction formed by Beach Haven Wharf at the entrance of Hellyers Creek (latitude 36° 47.5'), which covers an area of 9.8×10^6 m^2.

B.1.1 DHI model suite

MIKE 21 is a professional hydraulic engineering software package for two-dimensional free-surface flows that has been developed by DHI Water & Environment (Denmark)[1]. It is applicable to simulations of hydraulics, water quality and sediment transport in rivers, lakes, estuaries, bays, coastal areas, seas and other water bodies. MIKE 21 is the result of more than 10 years of continuous development and is tuned through the experience gained from many applications world-wide. With its exceptional flexibility, speed and user-friendly environment, MIKE 21 provides a complete and effective design environment for engineering, coastal management, water quality and planning applications.

A primary feature of the MIKE 21 modelling system is the integrated modular structure with a variety of add-on modules. The two modules utilized in this study are:

> The hydrodynamic (HD) module of MIKE 21 solves the time-dependent conservation equations of mass and momentum in two dimensions, where the flow is decomposed into mean quantities and turbulent fluctuations. The flow field and water levels are computed over a regular grid of square cells which defines the resolution of the predicted values. The HD module simulates unsteady flow taking into account bathymetry (including intertidal areas) and external forcing such as meteorology, tidal elevations, currents and other hydrographic conditions.
>
> The Particle Analysis (PA) module takes the results of the HD simulations as an input and seeds the domain with thousands of particles at specified point sources. These particles are then tracked as they get advected by the hydrodynamic field. Superimposed on this advection motion is a random-walk diffusion motion and, optionally, a fall velocity to account for vertical movement due to the pull of gravity on the sediment particles.

[1] See http://www.dhisoftware.com/.

B.1.2 Bathymetric grid

Bathymetry data were collected during various boat surveys using a GPS and echo-sounder, hydrological charts and aerial photos. The data were collated in ArcGIS (Eagle Ltd.) to the NZTM (New Zealand Transverse Mercator) coordinate system, using chart datum as the vertical datum. SURFER (Golden Software Ltd) software was then used to interpolate the survey data (using the Kriging technique) to generate a regular grid of 20 m × 20 m. The grid was imported into the DHI system for final manual editing. The entrance to the Upper Harbour provides an ideal open boundary, however, the model is more robust if the intertidal areas near the open boundary are removed and the bathymetry is made smooth in this vicinity. Manual editing of the upper reaches of the subestuaries was also required to ensure the channels were adequately represented, as the width of some of the channels was close to the resolution of the model. The final bathymetric grid is shown in Figure B.1.

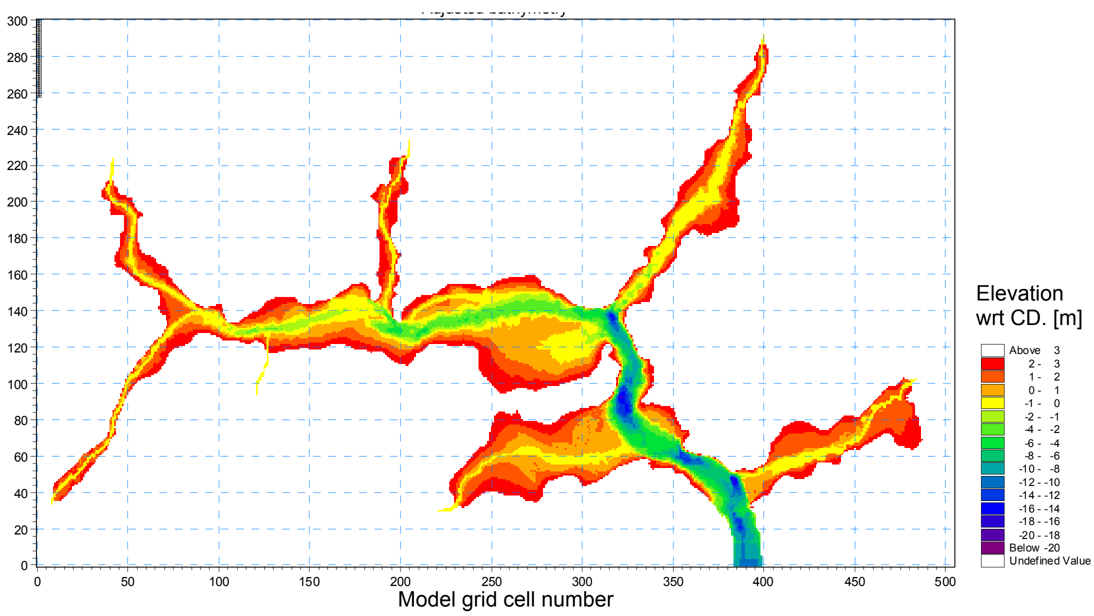


Figure B.1 Final bathymetric grid with cells 20 m × 20 m.

B.2 Calibration

B.2.1 Field study

An initial field study was conducted over the period September 12th to November 15th 2002. The data collected were to be used to a) drive the model by specifying water levels at the open boundary, and b) calibrate both the hydrodynamic model and particle analysis (dispersion) modules. Field data collected included:

1) An S4 current meter and a DOBIE water level recorder with optical backscatter sensor (OBS) for measuring suspended-sediment concentration (SSC) were located mid-channel just south of Catalina Bay (NZMG 2660187, 6488366) in water depth of 9 m Chart Datum (CD).

2) An Acoustic Doppler Current Profiler (ADCP) and DOBIE were located just off the Paremoremo Creek headland. These instruments were placed within the main channel in 5 m of water (CD), but close to the channel edge to avoid being a navigation hazard (NZMG 2656331, 6490807).

3) Four further DOBIEs were placed on or near intertidal flats around the estuary at the following locations (NZMG): 2659253, 6491759; 2657744, 6489197; 2654107, 6490782; 2653233, 6492595

All instrument locations are shown in Figure B.2.

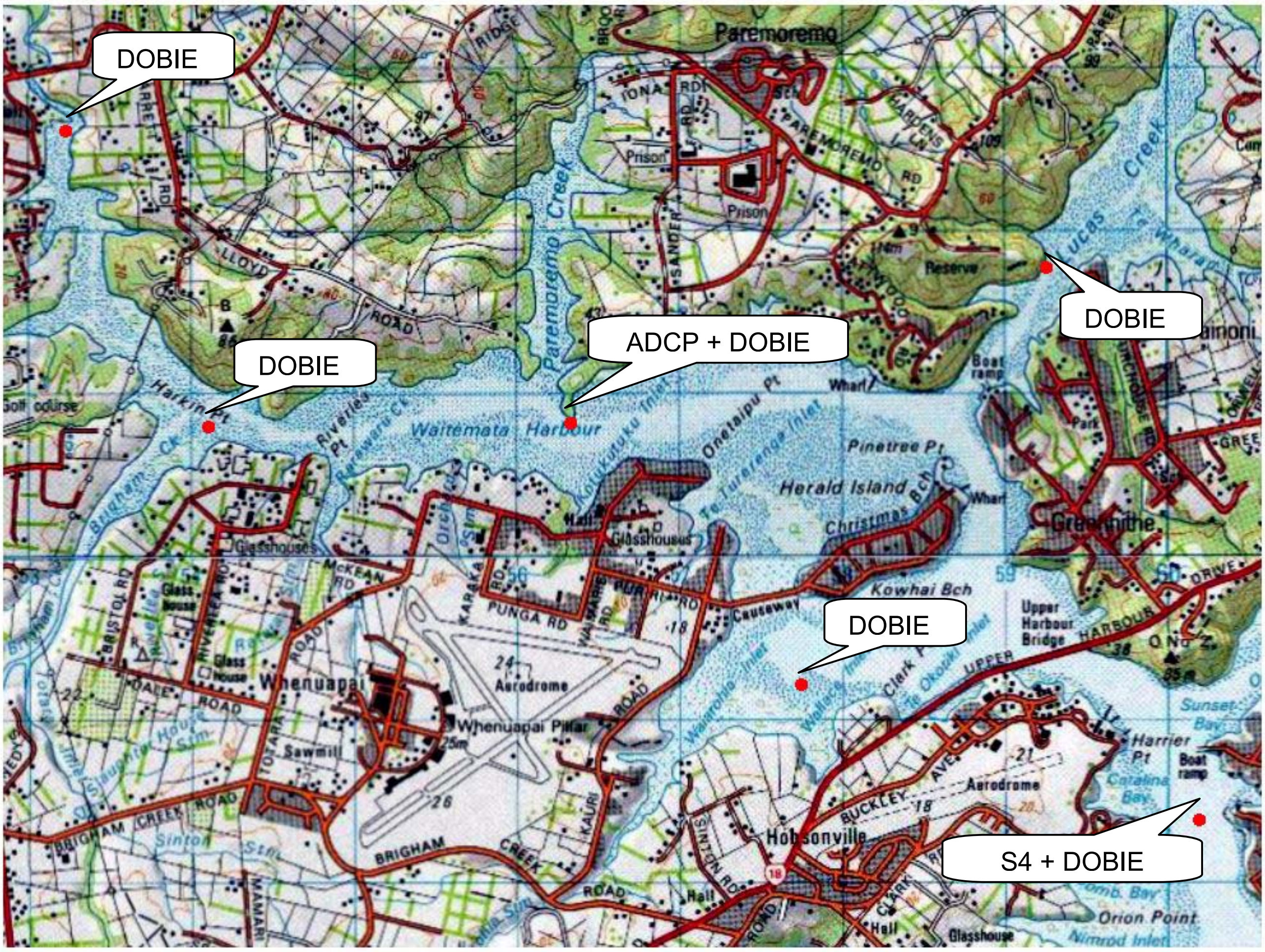


Figure B.2 Location of instruments.

To drive the hydrodynamic model, water levels need to be specified at the open boundary (the entrance to the UWH). To perform basic tidal analyses and to identify the spring/neap tidal cycle, water-level records of over 30 days are required. To achieve this, a two-month deployment was conducted. It was hoped that a significant rainfall event would be captured at the same time, which would provide calibration data for currents and suspended-sediment concentration (SSC).

Unfortunately, a significant rainfall event did not occur during this deployment period, necessitating redeployment of DOBIEs (in Paremoremo, Rangitopuni and Lucas Creeks, and at the UWH entrance) from 6 December 2002 to 15 January 2003. A small rainfall event did occur during this period, however, biofouling of the instruments made the data unusable.

The field study was therefore successful in obtaining hydrodynamic data needed for driving and calibrating the hydrodynamic model (see 'Hydrodynamic Calibration' section). The field study was, however, unsuccessful in obtaining adequate data to calibrate the dispersion module (see 'Particle Analysis Calibration' section).

B.2.2 Hydrodynamic calibration

A hydrodynamic simulation was run for the period 12/9/2002 18:00 to 17/10/2002 23:30 for the purposes of calibrating and verifying the hydrodynamic model. This 35-day period started and finished at low tide. The first 12 hours of the simulation was used as a warm-up and was not included in the analysis. A model time step of 10 s was used, giving a maximum Courant number[4] of 6.4. The calibration simulation was driven by a time series of water levels obtained from the DOBIE instrument located mid-channel on the model open boundary. The freshwater input was 5 m^3/s (1 m/s) for Rangitopuni and 1 m^3/s (1 m/s) for all the other streams.

Calibration parameters included the gridded bathymetry and bottom roughness coefficient (Mannings n = 32 was found to be suitable). Simulated water levels were compared to measured (DOBIE) data from Lucas, Paremoremo, Rangitopuni and Brighams Creeks and Waiarohia inlet. Velocity predictions were compared to measured currents (ADCP and S4) off the Paremoremo headland.

The predicted water levels compare very well with the measured data (Figures B.3 to B.7 compare predicted and measured water levels for an example period 1/10/2002 to 6/10/2002). Analysis of a single mean tidal cycle (4/10/2002) (Figure B.8) shows that the mean tidal signal can be accurately represented by a sinusoidal curve with amplitude 1.37 m (range 2.74 m) and period 12.4 hrs.

[4] The Courant number is the ratio of the model timestep to a cell residence time. For numerical stability, the timestep cannot be so large that the water could move more than a cell length for a given flow velocity.

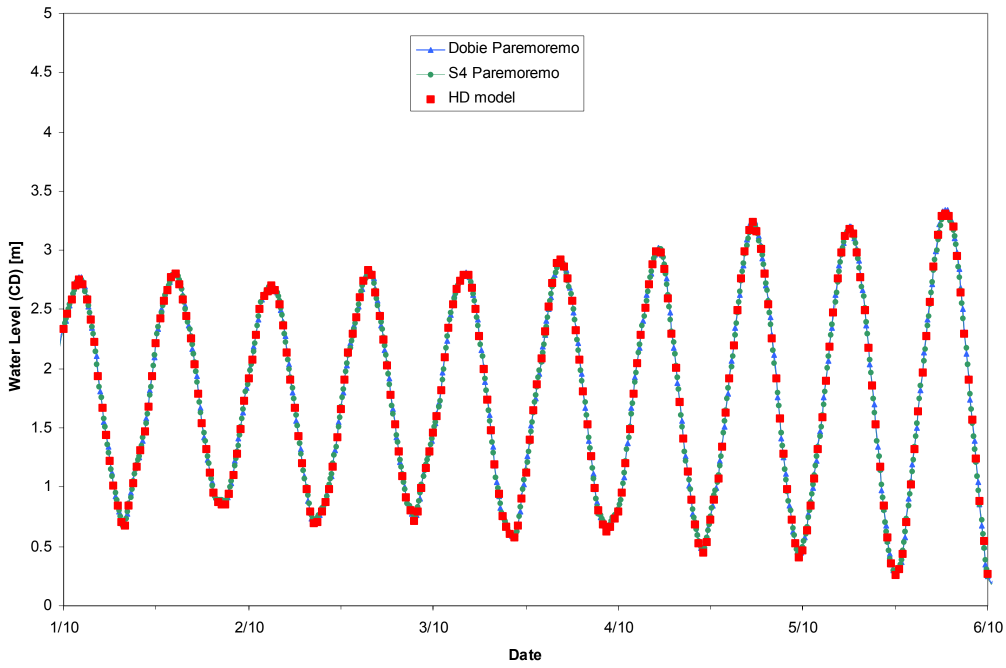


Figure B.3 Verification of water levels: comparison of predicted ('HD Model') and measured (S4 and DOBIE) at Paremoremo.

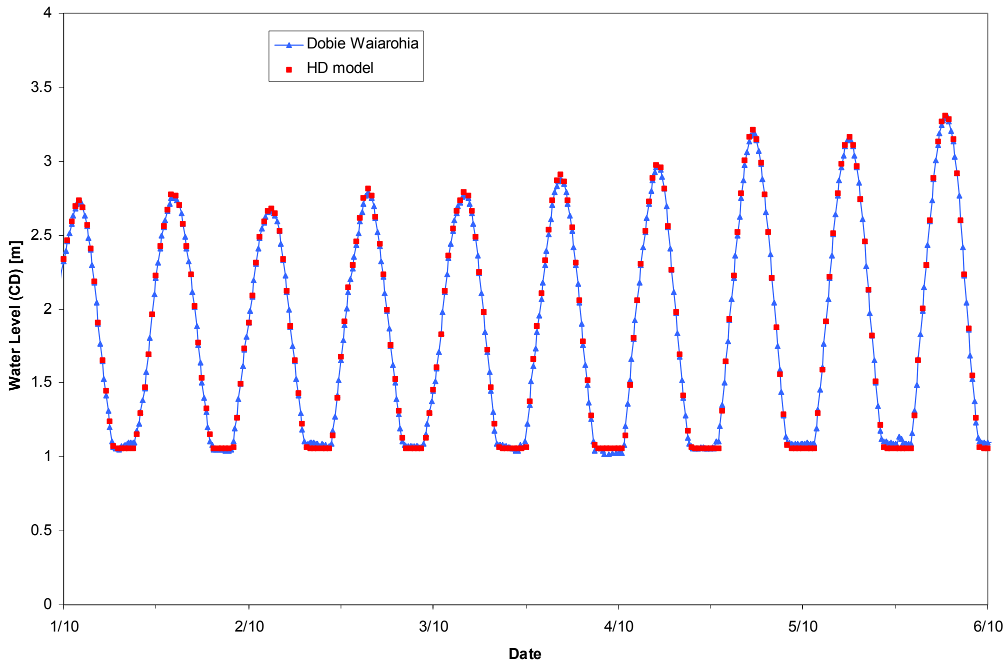


Figure B.4 Verification of water levels: comparison of predicted ('HD Model') and measured (DOBIE) at Waiarohia.

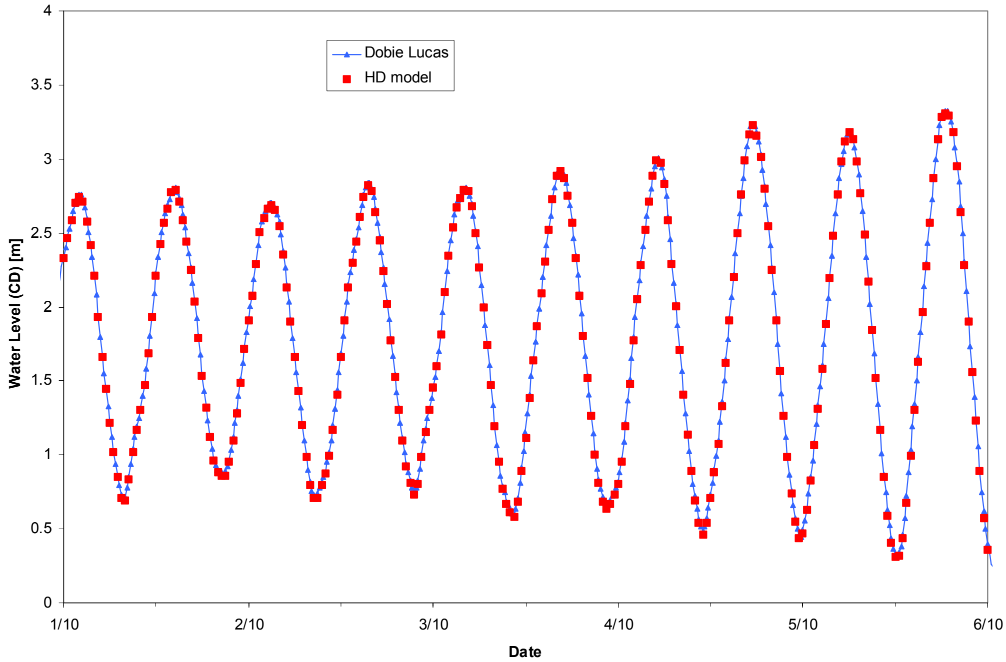


Figure B.5 Verification of water levels: comparison of predicted ('HD Model') and measured (DOBIE) at Lucas Creek.

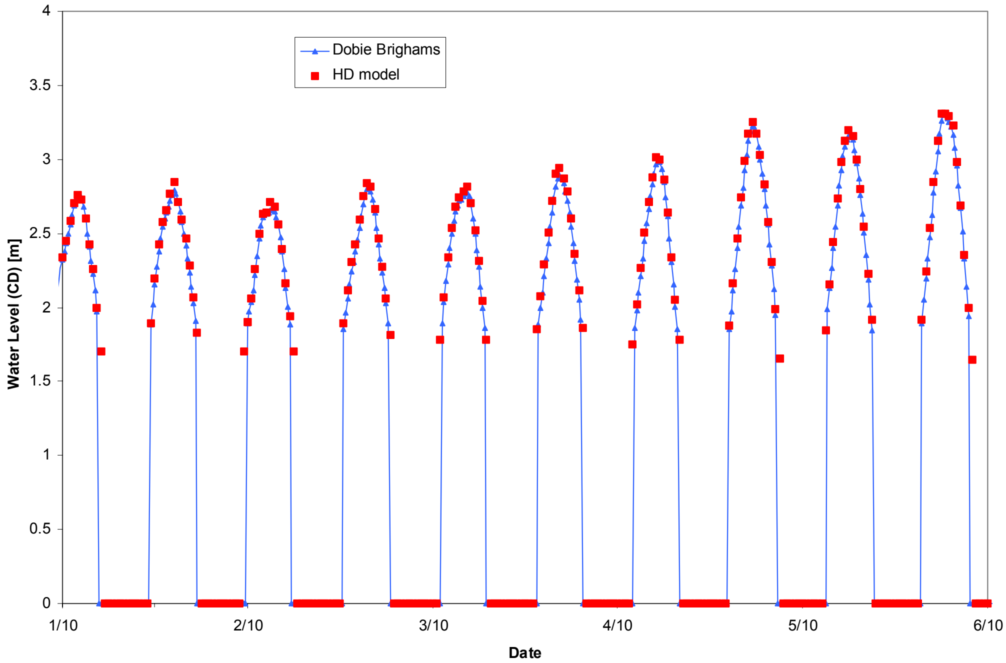


Figure B.6 Verification of water levels; comparison of predicted ('HD Model') and measured (DOBIE) at Brighams Creek. A water level of zero is shown when the instrument is exposed during low tide.

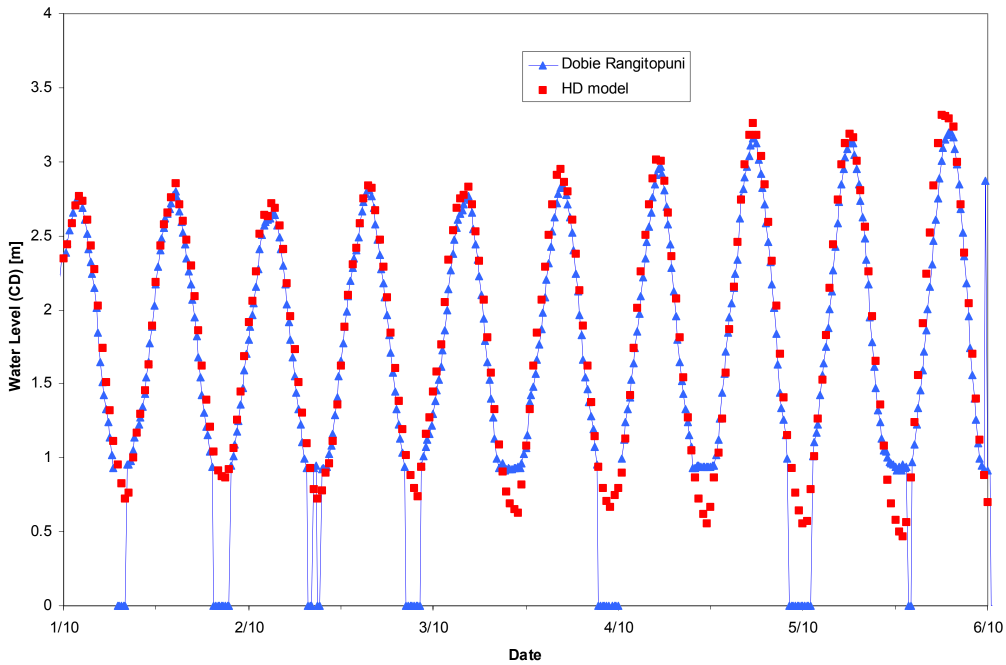


Figure B.7 Verification of water levels: comparison of predicted ('HD Model') and measured (DOBIE) at Rangitopuni. A water level of zero is shown when the instrument is exposed during low tide.

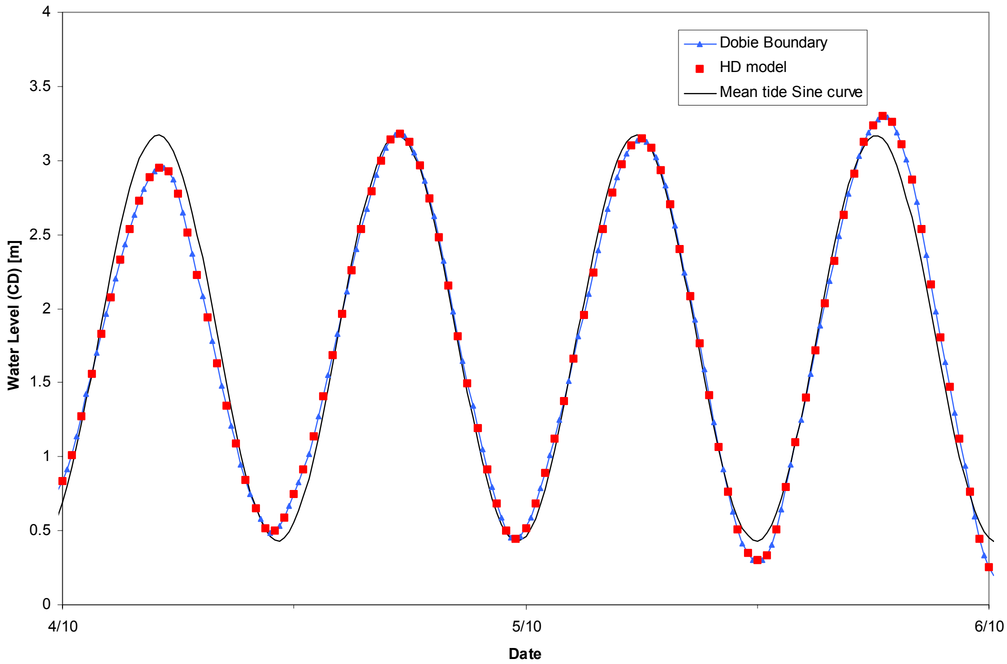


Figure B.8 Measured (DOBIE) and predicted ('HD model') water levels during a mean tide can be described by a sine curve representing the M2 tide.

Predicted velocities were compared with measured currents off the Paremoremo headland, and were found to compare well with both the S4 current meter (single point measurement) and the ADCP (current velocities at various depths throughout the water column). Figure B.9 compares the results for an example period 4/10/2002 to 6/10/2002. During the ebb tide, the comparison is very good, with the slightly higher measured values being due to the fact that the model gives depth-averaged speed. The lack of vertical variation in the currents measured by the ADCP indicates that there is either little freshwater stratification, or that there is no slip between freshwater and salt water layers. The measured velocities during the flood tide are significantly lower than during the ebb tide. This is attributed to local bathymetry effects (a channel splitting a sandbank on the seaward side of the headland). The model reproduces this effect, though to a lesser extent. For the model to completely reproduce this very localised effect, the model grid resolution would need to be significantly increased.

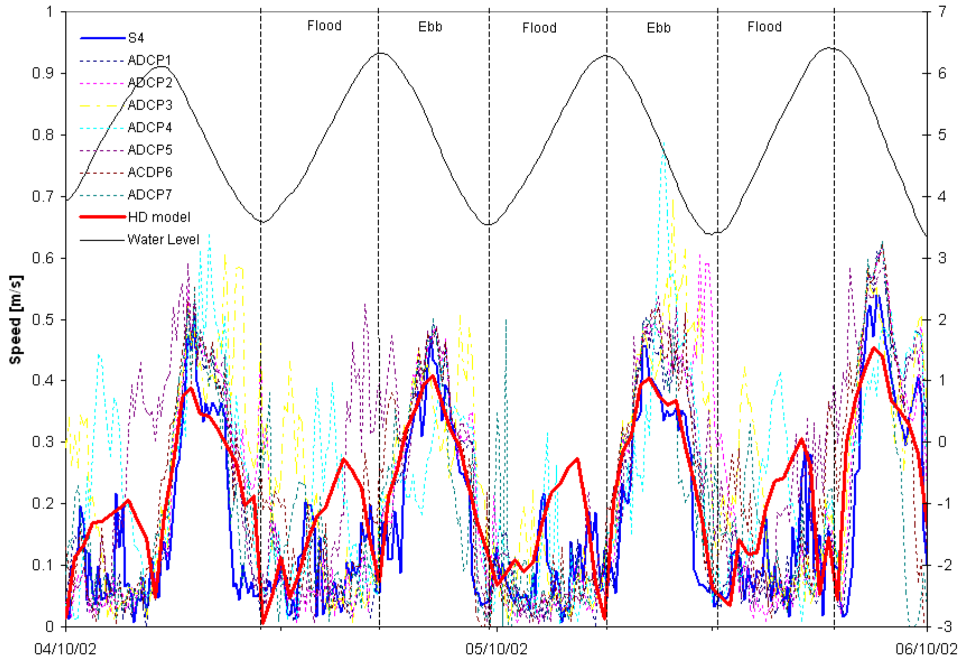


Figure B.9 Verification of velocities: comparison of predicted ('HD Model') and measured (S4 and ADCP) off Paremoremo headland. Near-bed ADCP records are denoted by 'ADCP1', with the index increasing with height above the bed.

B.2.3 Particle transport calibration

Three methods of calibrating the Particle Analysis (PA) module for sediment transport were attempted, but with little success.

> Method 1: using SSC data from DOBIE field deployments. Due to a lack of significant rainfall events and instrument failure, the field data were unsuitable for quantitative calibration analysis.
>
> Method 2: using dye tests performed by Parnell (1981) within Lucas Creek. Dye was released in the upper reaches of Lucas Creek and comprehensive concentration measurements recorded. However, the majority of this experiment took place in the narrow upper reaches of Lucas Creek, either upstream of the model domain or in channels not adequately represented by the 20-m grid. The difficulties associated with simulating a tracer without having the source point within the model domain, and the very few measurements taken in adequately represented regions of the model, made this calibration attempt impractical.
>
> Method 3: using salinity gradient data reported by Williams and Rutherford (1983). The salinity gradient down Rangitopuni Creek and throughout the main body of the UWH was measured after several flood events. Technical difficulties associated with injecting particles from a single source and using the Particle Analysis module to simulate freshwater mixing with ambient salinity resulted in an unsatisfactory calibration. Limited estimates of the dispersion coefficient could, however, be made using this method.

As a valid alternative to direct calibration, sensitivity tests were performed on the diffusion parameters in the PA module. In this study, the PA module is used to predict the proportion of sediment particles which settle in defined regions of the UWH, which is represented by the parameter *R*. Since the exact location of deposition within each region is not required, an approximate value of the dispersion coefficient is likely to suffice for estimating *R*.

Three sets of sensitivity tests were performed, relating to the longitudinal (streamwise), transverse and vertical dispersal coefficients. Each of these dispersal coefficients was defined as being proportional to the local velocity, i.e., dispersal coefficient [m^2/s] = local velocity [m/s] × factor [m]. The input parameters required to define the diffusion coefficients are therefore the proportionality factor and the minimum and maximum values which the dispersal coefficient can take.

The streamwise dispersal coefficient can be initially estimated as follows. The maximum streamwise distance (S_{max}) that a particle can jump by turbulent diffusion during a time step (Δt) is given by:

$$S_{\max} = \sqrt{6 \times D_l \times \Delta t}$$

A random number governs the actual distance moved, but on average a particle will move a distance S_{ave}, given by:

$$S_{ave} = \sqrt{2 \times D_l \times \Delta t}$$

The diffusion coefficient (D_l) [m^2/s] can be estimated from:

$$D_l = k \times \Delta x^2 / \Delta t$$

where Δx is the cell dimension (20 m), Δt is the model time step (e.g., 5 or 10 seconds) and k is a coefficient in the range of 0.003 to 0.075. Therefore, D_l can be in the range 0.24 to 6 m^2/s, and the average distance that a particle can move in one time step is in the range 1.5 to 7.7 m.

A particle moves by advection and dispersion, although in tidal estuaries, advection accounts for the majority of the tidal movement. Therefore, we can assume that the distance moved by diffusion must be less than that due to advection. Tidal currents range between 0 and 0.7 m/s, which means that a particle can move a maximum of approximately 3.5 m by advection in a single 5 second time step. Using this limit, the distance moved on average (S_{ave} above) by turbulent diffusion (for a 5 second time step) is:

$$3.5 = \sqrt{2 \times D_l \times 5}$$

which results in a maximum diffusion coefficient D_l of 1.225 m^2/s.

The longitudinal diffusion was varied between a minimum of 0.1 and a maximum of 1.2, with results for R varying by less than 5%. The values of longitudinal diffusion coefficient selected for use in the sediment transport simulations were: minimum = 0.1 m^2/s; maximum = 1.0 m^2/s; factor = 2 m.

The transverse diffusion was varied between a minimum of 0 and a maximum of 0.1, with results for R showing very little consequent variation (less than 1%). The values of transverse diffusion coefficient selected for use in the sediment transport simulations were: minimum = 0 m^2/s; maximum = 0.01 m^2/s; factor = 0.01 m.

The vertical diffusion is the most difficult to determine experimentally because any freshwater stratification within the water column is likely to reduce diffusion transport. In these sensitivity tests the vertical diffusion coefficient was varied between a minimum of 0 and a maximum of 0.01. R was found to be more sensitive at high values of vertical diffusion coefficient, with deposition occurring more rapidly. There was less than 3%

variation in *R* with maximum vertical diffusion in the range 0.0001 – 0.00001 m^2/s. The values of vertical diffusion coefficient selected for use in the sediment transport simulations were: minimum = 0 m^2/s; maximum = 0.0001 m^2/s; factor = 0.0001 m.

B.3 Analysis of Catchment Model Results

The 27-year daily time series of flow down Rangitopuni Creek from the catchment model (Section 4.3.1.1) was analysed to extract all flood events for which the flow exceeded 1 m^3/s. This resulted in 611 flood events over the 9862-day period. These events were ranked in descending order of magnitude and the event discharge (m^3) was plotted against each flood event rank (Figure B.10). Four "event groups" were then selected, with a representative event being identified for each group. The total volume of freshwater discharged by each representative event multiplied by the number of events in each group was approximately the same as the actual events summed over the 27-year period. The representative event for the largest group was chosen to be the largest event. Hence, this is more of an "extreme event", rather than a "representative event". The analysis resulted in the event groups shown in Table B.1.

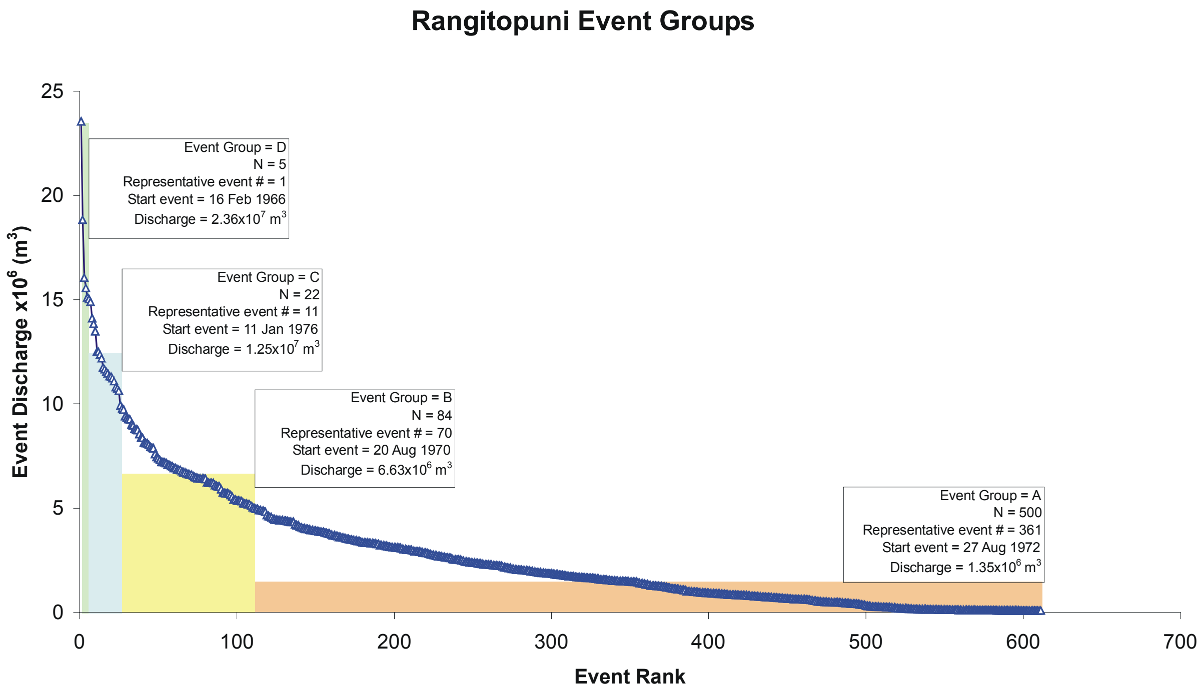


Figure B.10 Plot of flood event discharge (m^3) against event rank (blue line) and the division into event groups, each with a representative event.

Table B.1 Event groups and representative events obtained from analysis of catchment model results.

Event Group	Number of events in group	Representative event discharge [m^3/s]	Event group total discharge [m^3/s]	Representative event start date
A	500	1.35E+06	6.75E+08	27-Aug-72
B	84	6.63E+06	5.57E+08	20-Aug-70
C	22	1.25E+07	2.75E+08	11-Jan-76
D	5	2.36E+07	1.18E+08	16-Feb-66
			1.62E+09	Total volume discharged over 27 years by event groups
			1.81E+09	Total volume discharged by catchment model time series in 27 years
			1.74E+09	Total volume discharged by catchment model events > 1 m^3/s in 27 years

Each representative event is a flood event predicted by the Rangitopuni catchment model. The same flood dates are used to provide freshwater discharge and sediment loads[5] for flood events in each of the catchment areas, predicted by the catchment model. These are shown in Table B.2. To input the representative events into the estuary hydrodynamic model one of two methods can be used: 1) the daily time series for the event could be taken from the catchment model, or 2) the event could be described by a standard triangular artificial hydrograph, with maximum flow at 1/3 duration, based on the event discharge. Because the correct shape of the hydrograph will probably not be captured by a daily time series (which is what is used by the catchment model) and an "event group average" is being modelled, the latter method was selected. A time series with a 30-min interval was constructed to describe the hydrograph. The duration of each flood was set as 5 days, followed by 5 days of base flow. The simulated flood event period was therefore 20 tidal cycles, starting and finishing at high tide.

[5] Not used within the hydrodynamic model, but required for the sediment transport model.

Table B.2 Freshwater discharge and sediment loads of each representative flood event used to construct the flood hydrograph and sediment load time series.

	Group	freshwater	sediment
Rangitopuni		[m^3]	[kg]
27/08/1972	A	1.35E+06	1.16E+03
20/08/1970	B	6.63E+06	1.96E+06
11/01/1976	C	1.25E+07	8.72E+06
16/02/1966	D	2.36E+07	3.12E+07
Paremoremo			
27/08/1972	A	1.66E+05	1.26E+01
20/08/1970	B	8.38E+05	2.80E+05
11/01/1976	C	1.55E+06	1.35E+06
16/02/1966	D	2.92E+06	5.02E+06
Lucas			
27/08/1972	A	5.21E+05	9.74E+03
20/08/1970	B	2.50E+06	1.05E+06
11/01/1976	C	4.58E+06	4.52E+06
16/02/1966	D	8.76E+06	1.60E+07
Hellyers			
27/08/1972	A	2.28E+05	6.00E+03
20/08/1970	B	9.89E+05	7.00E+04
11/01/1976	C	1.96E+06	1.80E+05
16/02/1966	D	3.56E+06	1.80E+06
Waiarohia			
27/08/1972	A	1.33E+05	4.37E+02
20/08/1970	B	6.39E+05	3.90E+04
11/01/1976	C	1.33E+06	2.11E+05
16/02/1966	D	2.43E+06	9.95E+05
Rarawaru			
27/08/1972	A	5.29E+04	1.95E+02
20/08/1970	B	2.55E+05	1.00E+04
11/01/1976	C	5.32E+05	5.24E+04
16/02/1966	D	9.72E+05	2.71E+05
Brighams			
27/08/1972	A	3.52E+05	4.50E+01
20/08/1970	B	1.50E+06	1.32E+05
11/01/1976	C	2.73E+06	4.88E+05
16/02/1966	D	5.33E+06	3.52E+06

B.4 Hydrodynamic Simulations

All of the hydrodynamic simulations were driven by specifying an M2 (mean) tide water level at the boundary to the UWH, which was represented by a sine curve with period 12.4 hrs (44640 sec), amplitude 1.37 m (tidal range of 2.74 m), and reference level 1.8 m above Chart Datum.

B.4.1 Warm-up simulation

A warm-up simulation was used prior to each flood simulation to ensure the correct initial momentum over the entire estuary. Freshwater input consisted of baseflow only. An arbitrary start date (15/11/2004 07:12 am) was used, which has no physical relevance. The warm-up simulation had a duration of 2 tidal cycles, starting and finishing at high tide.

B.4.2 Flood event simulations

Four flood simulations were performed, one for each of the representative flood events. The freshwater input for each of the streams was input as an artificial triangular hydrograph, with peak flow occurring at 1/3 of the flood duration. Each simulation used the results of the warm-up simulation as an initial condition, and then continued the prediction for a further 10 days, starting and ending at high tide. An arbitrary start date of 16/11/2004 08:00 was used, giving a finish date of 26/11/2004 16:00. The first 5 days of each simulation consisted of the rising and falling hydrograph, representing the flood event. A 5-day period of baseflow was then used to let the remaining suspended sediment fall out of the water column and deposit on the estuary bed. Initial tests showed that after 5 days of baseflow, the majority of the sediment would deposit, with only a small fraction being transported out of the UWH and into the middle harbour.

B.5 Particle Analysis Simulations

Two particle fall velocities were used in the sediment-transport simulations: 0.01 cm/s (silt) and 0.1 cm/s (sand). In order to positively identify the origin of particles that deposit in the various subestuaries, discharges from each of the seven subcatchments were modelled separately. Fifty-six sediment-transport simulations were therefore performed: 4 flood events for each of the 2 sediment sizes from each of the 7 catchments.

Each sediment-transport simulation covered the same time period as the hydrodynamic simulations (16/11/2004 08:00 to 26/11/2004 16:00), which was used to provide the flow field for transporting particles. Events 1 and 2 used a 10-s time step, whereas a 5-s time step was required for events 3 and 4 due to the higher floodwater velocities. Resuspension of deposited material was taken into account in the model (over the 5-day flood event and during the subsequent 5-day baseflow period) using a critical Shields parameter for initiation of sediment motion of 0.2. Output from the simulation was the accumulated net sedimentation [kg/m^2] at the end of the 10-day simulation

For each of the 56 sediment-transport simulations, the total mass deposited within each subestuary was summed and expressed as a fraction of the total sediment mass released during the flood event, thus giving estimates of *R*. The results for *R* are shown in the main body of this Report.

The same set of 56 scenarios was used to find *R3*. However, for this purpose the flow field for the smallest flood event was used, with the aim of approximating baseflow. Also, no sediment was released from the subcatchments. Instead, sediment was released from the most significant mudbank within each subestuary, during the first tidal cycle only and only when the tide level ensured that the release site was covered by water. All release sites were at approximately the same elevation of 0.9 m above Chart Datum. At the end of each 10-day simulation, the pattern of redistributed sediment was output from the model from which *R3* was calculated. The results for *R3* are shown in the main body of this Report.

B.6 References

Parnell, K. E. (1981). Estuarine Water Dispersion and Exchange in Lucas Creek, Upper Waitemata Harbour. M.A. Thesis, University of Auckland

Williams, B. L.; Rutherford, J. C. (1983) The Flushing of Pollutants and Nutrients from the Upper Waitemata Harbour. Water Quality Centre Report No. 1.

APPENDIX C. Contaminant Concentration Profiles in Lucas Creek

One of the problems with the existing local data is that it is highly site-specific. Measurements were from single cores and samples that were collected down the core were from quite small volumes (typically 1 – 2 cm^3, which is smaller than, or of comparable size to, the main bioturbation features, these being crab burrows). They were also much smaller compared to other bioturbation features such as disturbance by larger animals or disturbance by human activities (e.g., propeller scouring, urban litter).

Stratigraphic records of contaminant concentrations in 2 sets of sediment cores were measured in Lucas Creek. The two sampling sites were: (1) in the main body of the estuary near the ARC long-term baseline marine sediment monitoring site, which represents average conditions in the estuary; and (2) further upstream, where contamination and settling rates would be higher. The important difference between this and earlier studies is that attempts were made to get good "average" data. The depth profiles were the average of 9 cores collected over an area of 25 m by 5 m on a homogeneous mud bank. Sampling over this area would overcome the small-scale differences observed on intertidal mudbanks (Morrisey et al., 1999; Auckland Regional Council, 1998).

The first set of 9 cores is shown in Figure C1. There was a steady build-up in Zn and Cu over time from what appears to be background levels below 30 cm.

The second set of 9 cores is shown in Figure C2. The deepest samples at 45 cm did not reach background (pre-urban) concentrations, showing a much higher deposition rate at this upper site. Figure C2 shows a steady build-up in Zn and Cu over time, with a recent decline in the uppermost layers. The reason for the decline in concentration at the surface is likely to be due to dilution by subsoils that are low in Zn and Cu. At the time of sampling, there was a large earthworking operation nearby which drained directly to the estuary near the sample site, and fine, light, clay-like sediments were observed on the opposite bank.

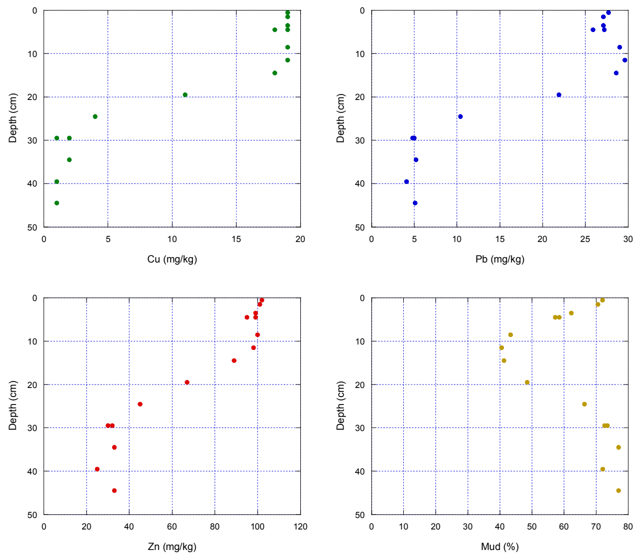


Figure C1. Concentration profiles of Zn, Cu and Pb in the mud fraction of the top 45 cm of sediment from the lower mudflat in Lucas Creek, Auckland. Metals were extracted with 2 M HCl from the mud fraction.

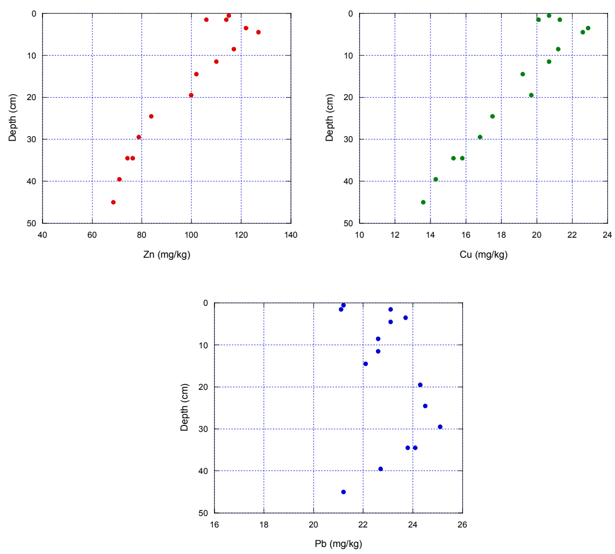


Figure C2. Concentration profiles of Zn, Cu and Pb in the top 45 cm of sediment from the upper mudflat in Lucas Creek, Auckland. Metals were extracted from the whole sediment with hot concentrated acid.

Figure C1 also shows a steady build-up in Pb from 45 to 30 cm depth, followed by a decline to present-day levels. This is consistent with reduced Pb loads following its removal from petrol.

There is good agreement in the profiles amongst the 3 metals, taking into account the difference in inputs (Cu and Zn inputs increasing, and concentrations being diluted by subsoils; Pb inputs increasing, then decreasing, as well as its concentration being decreased by dilution by subsoils).

The two cores indicate two different sediment mixing behaviours. The upper core composite was taken in a narrower part of the estuary, and while well downstream from the head of the estuary, might be expected to exhibit greater sedimentation rates. This was borne out by the failure to reach background concentrations at the lowest section (45 cm depth) of the core.

The lower core composite was taken in a much wider part of the estuary, where sedimentation rates should be lower. This seems to be the case, with the background concentrations being reached by 30 cm.

A likely reason for the differences between the two profiles are due to the differences in sedimentation rates. In the lower core, bioturbation is relatively rapid and so the profile closely approximates that predicted by a single well-mixed surface layer. Therefore the concentration is constant in the upper completely mixed layer (the upper 13 cm of the profile). In the upper core, complete mixing by bioturbation cannot keep pace with the sedimentation rate, so there are gradients in the concentrations throughout the core – for Zn and Cu there is a gradual increase, followed by a decreasing gradient near the surface.

This explanation is borne out especially by the differences in behaviour in Pb concentrations. In the upper core, relatively large changes in Pb concentrations occur (note the large drop in Pb at 24.5 cm, accompanying a small drop in Cu or Zn). In contrast, there is only a small decrease in the Pb concentrations in the lower core. This is consistent with strong bioturbation/lower sedimentation rates, so that as Pb inputs decrease; there will be a gradual decrease in the average concentrations in the upper 13 cm bioturbated layer, rather than a decreasing Pb concentration gradient.

The profile of Zn, Cu and Pb concentrations in the lower core thus indicate homogeneous mixing, with a mixing depth of 13 cm (rather than the value of 15 cm used previously in the USC model).

Such a mixing depth is not appropriate to the upper core, and possibly another mixing model is appropriate as well. This illustrates the difficulty in choosing a universal model for the whole upper harbour. Because the lower core represents a wider area of the harbour, and because we are predicting estuary-average concentrations, we chose to retain the homogeneous mixing model for the Upper Waitemata Harbour.

C.1 References

Auckland Regional Council (1998). Distributions of contaminants in urbanised estuaries: predictions and observations. Auckland Regional Council Technical Report.

Morrisey, D.J.; DeWitt, T.H.; Roper, D.S.; Williamson, R.B. (1999). Variation in the depth and morphology of burrows of the mud crab, Helice crassa, among different types of intertidal sediment in New Zealand. Marine Ecology Progress Series 182, 231-242.

APPENDIX D. Calibration and Verification of GLEAMS

Daily rainfall data were obtained from NIWA's climate database for the Whenuapai airbase site from 1966 to 1992 (27 years). Mean monthly meteorological data required by the model were obtained from numerous sites in the Auckland region because no single site held a complete unbroken record.

Soils information for the study region was obtained from a database held by Landcare Research. This describes the key soil properties required by the model such as drainage rates, texture and organic content. Where required, Malcolm McLeod (Soil Scientist, Landcare Research) interpreted information from the database.

Topography across the study region was derived from the 30-m resolution digital elevation model held by NIWA, from which slope angles were calculated. Existing landuse was derived primarily from aerial photographs supplemented by information provided by ARC and the TA's.

Minimal calibration of GLEAMS was necessary (a strength of the model), although some modification and assessment of SCS curve numbers, which determine the volume of surface runoff, was conducted.

Validation of model predictions was made through comparison with observed loads calculated from a series of suspended-sediment measurements made by the Auckland Regional Authority in the late 1970s and early 1980s (van Roon, 1983). The results (Figure D1) show modelled and observed loads in each subcatchment for 1980, the year when the most intensive sampling was conducted. In addition, predicted long-term averages are presented. The Y-axis scale is logarithmic because sediment loads vary considerably due to the differences in subcatchment size. The results indicate that the model has predicted the correct order of magnitude of sediment loss.

The specific yields of sediment (per unit of catchment area) are lowest from the three Waitakere subcatchments (Rarawaru, Waiarohia and Brighams), primarily due to the flat terrain. Lucas Creek (ongoing earthworks), Paremoremo (steep slopes) and the Rangitopuni provide the greatest yields.

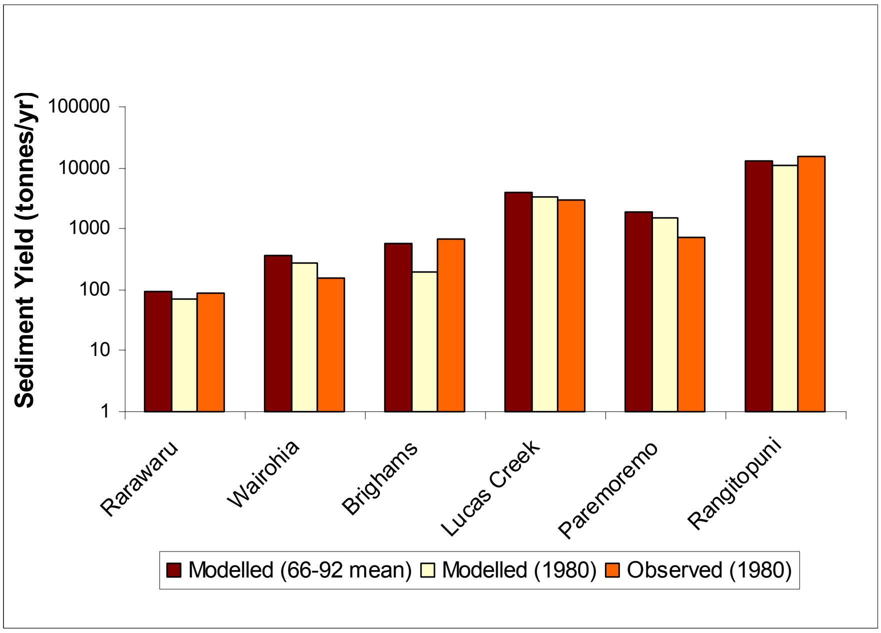


Figure D1. Modelled and observed annual sediment yields for the UWH subcatchments. Note the logarithmic scale.

D.1 References

van Roon, M.R. (1983). *Water Quality in the Upper Waitemata Harbour and Catchment*. Auckland Regional Council.

APPENDIX E. Verification of Model Predictions: Annual Average Sedimentation Rates

E.1 Introduction

Annual average sediment accumulation rates (SAR) in surface sediments are predicted as a part of the larger contaminant-accumulation prediction. Predicted SAR for each arm of the UWH the 54-year simulation under the "existing" scenario, denoted by $\delta_{ANNUALAVG,\ 54years,\ kest}$ is shown in table E.1. For details of the simulation, the reader is referred to NIWA Client Report HAM2003-087/2 – Results: Zinc, Existing Scenario.

Table E.1 **Predicted SAR, existing scenario.**

Subestuary	$\delta_{ANNUALAVG,54\,years,kest}$ (mm/year)
1=Hel	0.53
2=Luc	7.89
3=Par	4.86
4=Ran	21.71
5=Bri	10.73
6=Rar	0.70
7=Wai	0.13
8 = MWH	–
9 = Upp	12.55
10 = Mid	4.11
11 = Low	3.07

Annual sedimentation rates in each subestuary predicted by the model and averaged over the simulation period can now be compared to measured SAR, averaged over the past 30–50 years or so, which have been established by coring. A favourable comparison between predicted and observed indicates that sediment loads from the catchment, sediment dispersal/deposition patterns, and sediment redispersal/redeposition patterns are being treated correctly in the model. The comparison will not be strictly valid, since the predictions are forward-looking and the observations are backward-looking, however this problem is minimised by applying the comparison only to predictions under the existing landuse scenario. The most comprehensive information on SAR in Auckland estuaries over the last 50 years is provided by Swales et al. (2002b), who dated sediment cores from 30 intertidal and subtidal sites. Although SAR for earlier historical periods are also available they are not relevant to the validation of predicted SAR for the existing landuse.

Heavy-metal profiles can be used in a qualitative way to calculate SAR by identifying a systematic increase in heavy-metal concentrations with the onset of urbanisation (~1960). The SAR provided by heavy metal or pollen profiles are qualitative in the sense that they do not provide absolute dating. Radioisotopes (e.g., 210Pb, 137Cs, 14C) in theory can provide absolute dates in that the age of a sediment layer is primarily determined by the decay constant of a particular radioisotope. Biological and physical mixing of sediments complicates this picture.

It should also be noted that time-averaged SAR mask the fact that sedimentation has accelerated in Auckland estuaries during the last 50 years. For example, 210Pb profiles in sediment cores taken from Te Matuku Bay (Waiheke Island) indicate that SAR has doubled from ~3 to ~6 mm per year and from 2.5 to 3.5 mm per year in Okura estuary since ~1950 (Swales et al., 2002b).

E.2 Hellyers Creek

Measurements are from Williamson and Morrisey (2000) and unpublished data held by A. Swales (cores collected in 1995). SAR are based on dating of sediment cores using heavy-metal profiles, catchment history and unpublished data held by Swales. Urbanisation of Kaipatiki catchment began in the mid-1950's and ~80% of the catchment had been urbanised by the mid-1970's.

Sediment cores collected at 4 intertidal sites in 1995 in the Kaipatiki creek arm of Hellyers Creek were used to calculate SAR based on heavy-metal profiles. Core K1 was collected at the head of Kaipatiki arm whereas core K4 was collected in the main body of Hellyers Creek. Post-1960 SAR based on heavy-metal profiles are summarised in Table E.2.

Table E.2 SAR measured in Hellyers Creek.

Core	SAR (mm/year)
K1	11.4
K2	8.6
K3	8.6
K4	5.7
Average	**8.6**

The predicted value of 0.5 mm/year is an order of magnitude lower than the measured average SAR of 8.6 mm/year. The discrepancy may be explained by the fact that the measured rate reflects the rapid urbanisation that occurred over the past 50 years in the catchment, which would have been accompanied by high sediment yields, but the prediction is based on the 2001 landuse, which is mature urban, and therefore accompanied by a much lower sediment yield.

E.3 Lucas Creek

Hume and McGlone (1986) derived SAR for an intertidal site near the mouth of Lucas Creek (L12) based on pollen and 14C dating. They assigned the primary rise in pine pollen to 1840 AD (European settlement), coinciding with 0.4 m depth, from which they derived a SAR of 3 mm/year. However, Swales et al. (2002b) found that pine pollen became abundant in Auckland estuary sediments from the early 1950's, so that it is possible that 0.4 m depth is much younger than Hume and McGlone (1986) determined, in which case SAR for the topmost 0.4 m of the sediment column is ~13 mm/year. The predicted SAR in Lucas Creek of 7.9 mm/year is similar to the measured value.

E.4 Paremoremo and Rangitopuni Creeks

No SAR measurements are available for either of these creeks. The predicted SAR of 4.9 mm/year for Paremoremo is within the range of SAR for the last 50 years (2–7 mm/yr) measured on intertidal flats in several drowned-valley estuaries (Swales et al., 2002b). However, SAR derived from dated cores collected from intertidal flats in tidal creeks are between 5–15 mm/year (Vant et al. 1993; Oldman and Swales, 1999; Swales et al., 2002a; 2002b) and typically reduce away from the catchment outlet. The predicted SAR for Rangitopuni of 21 mm/year is a little higher than typical data from the upper reaches of tidal creeks.

E.5 Brighams Creek

Vant et al. (1993) derived SAR for two intertidal cores and one subtidal core site based on pollen and 14C dating. They assigned a date of 1950 AD for the first appearance of pine pollen in sediments. Table E.3 lists the calculated SAR

Table E.3 SAR measured in Brighams Creek.

Core	SAR (mm/year)
B1 (intertidal)	5.7
B2 (intertidal)	9.0
B3 (channel)	2.6

The predicted SAR of 10.7 mm/year is similar to the 5.7–9.0 mm/year measured by Vant et al. (1993) at two intertidal core sites.

E.6 Rarawaru and Waiarohia Creeks

No SAR measurements are available for either of these creeks. The predicted SAR of 0.7 and 0.1 mm yr-1 for the existing landuse scenario are an order of magnitude lower than values measured in similar estuarine environments over the last 50 years or so. As at Lucas Creek, this might reflect the difference between landuse over the past 50 years and current (2001) landuse, which the existing-scenario simulation is based on.

E.7 Main Body

Predicted SAR for tidal flats in the main body of the UWH flanking the main tidal channel show a seaward decline from 12.6 to 3.1 mm/year. These values are consistent with measured SAR over the last 50 years (2–7 mm/year on intertidal flats in several drowned-valley estuaries (Swales et al., 2002b).

E.8 Comment on Bioturbation Depth

The bioturbation depth of 0.11 m selected for modelling contaminant profiles is supported by actual depths of surface mixing derived from Pb210 profiles in sediment cores (Swales et al., 2002b). A surface mixed layer of ≤ 0.05 m is typical of sediments in the main body of estuaries. In tidal creeks, the mud crab (*Helice crassa*) burrows to ≤ 0.10 m (Morrisey et al. 1999). The maximum depth of the surface-mixed layer observed by Swales et al. (2002b) was 0.13 m at a subtidal core site in Whitford embayment.

E.9 Comment on Bathymetry

Sedimentation over decadal timescales may result in substantial changes in subestuary bathymetry. For example, the average increase in bed elevation in Brighams Creek over 54 years is predicted to be 0.46 m. This may alter current patterns and associated dispersal of contaminants and sediments, which has not been accounted for here (although, in principle it can be, by recomputing new values of R as the estuary bathymetry evolves).

E.10 References

Hume, T.M.; McGlone, M.S. (1986). Sedimentation patterns and catchment use changes recorded in the sediments of a shallow tidal creek, Lucas Creek, Upper Waitemata Harbour, New Zealand. *New Zealand Journal of Marine and Freshwater Research 20*: 677–687.

Morrisey, D.J.; DeWitt, T.H.; Roper, D.S.; Williamson, R.B. (1999). Variation in the depth and morphology of burrows of the mud crab *Helice crassa* among different types of intertidal sediment in New Zealand. *Marine Ecology Progress Series 182*: 231–242.

Oldman, J.O.; Swales, A. (1999). *Maungamaungaroa Estuary numerical modelling and sedimentation*. NIWA Client Report ARC70224.

Swales, A.; Williamson, R.B.; Van Dam, L.; Stroud, M.J.; McGlone, M.S. (2002a). Reconstruction of urban stormwater contamination of an estuary using catchment history and sediment profile dating. *Estuaries 25(1)*: 43–56.

Swales, A.; Hume, T.M.; McGlone, M.S.; Pilvio, R.; Ovenden, R.; Zviguina, N.; Hatton, S.; Nicholls, P.; Budd, R.; Hewitt, J.; Pickmere, S.; Costley, K. (2002b). *Evidence for the physical effects of catchment sediment runoff preserved in estuarine sediments: Phase II (field study)*. NIWA Client Report HAM2002-067.

Vant, W.N.; Williamson, R.B.; Hume, T.M.; Dolphin, T.J. (1993). *Effects of future urbanisation in the catchment of Upper Waitemata Harbour*. NIWA Consultancy Report No. ARC220.

Williamson, R.B.; Morrisey, D.J. (2000). Stormwater contamination of urban estuaries. 1. Predicting the build-up of heavy metals in sediments. *Estuaries 23(1)*: 56–66.

APPENDIX F. Verification of Model Predictions: Contaminant Concentration Profiles in Lucas Creek

F.1 Introduction

Validation of subcatchment sediment loads is achieved by comparing predicted with measured sediment deposition rates in the subestuaries as explained in Appendix E. A similar, although somewhat more complicated approach, is taken here to validate the contaminant loads.

This validation involves comparing the measured and predicted depth profile through the sediment of zinc concentrations in the Lucas Creek subestuary. As noted previously, this is quite a severe test of the model, because the estuarine sediment zinc concentration depth profile that exists today has developed over a long period of time from a large suite of interacting processes, with the influence of these processes changing by the year. The model must simulate these processes and their changes over time. The validation of the contaminant model involved testing its ability to predict the observed zinc concentration profile in the sediment core from the lower of the two sites in the Lucas Creek subestuary described in Appendix C.

F.2 Development History of the Lucas Catchment

The zinc concentration profile used for the validation extended to sediments derived from the catchment in pre-urban times. It was possible, therefore, to run the validation from the year when urbanisation commenced, assumed to be 1950, through to the year when the core was collected, 2002. The primary model inputs required were the sediment and zinc loads for each year between 1950 and 2002. These loads are related to the amounts of residential, commercial and industrial development, so the first step to estimating the loads was to determine how much of each type of development had occurred each year. The development history of the Lucas subcatchment was derived from landuse data for 2003 contained in the NSCC database and the numbers of dwellings in the catchment determined by the NZ census in 1971, 1976, 1981, 1991, 1996 and 2001. The numbers of dwellings in each year were interpolated and extrapolated in a sensible manner to produce a development trend that fitted the census and database records.

There are no data for the historical development of either commercial or industrial activities in the Lucas catchment. The area identified as "commercial" in 2003 was small relative to the "industrial" area so we combined both as "industrial". We constructed an historical trend for industrial landuse by assuming that, prior to 1970, industrial activity was equivalent to 10% of the dwellings and that from 1970 to 2002, the area of industrial landuse increased in a linear rate to reach the level recorded in 2003. The annual sediment and zinc loads were then estimated from the amount of development; the sediment loads were as described previously (Section 4.3.1.1); and the zinc loads from the different urban landuses were as described below.

The primary unit of proposed future development for the Upper Waitemata Harbour subcatchments is an urban or rural dwelling. The relevant input parameter for the model is, therefore, the load of contaminant generated by one of these dwellings (i.e., g dwelling^{-1} year^{-1}). This load includes the load emitted by vehicles and commercial activities associated with the dwelling, such as the local shops or supermarket, but does not include other more intensive commercial or industrial activities. Emissions from major through-traffic, i.e., not associated with the dwellings, for example, traffic on motorways, are also not included in the dwelling load. These are modelled as separate inputs as appropriate, e.g., the emissions from vehicles on the future SH18 motorway link through the Waiarohia and Lucas catchments.

The best critically-evaluated estimates of the loads of contaminants draining from urban catchments are still those derived by Williamson (1991). The Williamson median values for zinc and copper are 750 and 90 g ha^{-1} year^{-1}, respectively (Williamson did not derive loads for PAH; the derivation of the loads used here is described in NIWA Client Report HAM2003-087/8 – Results: PAHs, Existing Scenario). These "urban" loads combine residential, commercial and industrial contributions, so for the purposes of the upper Waitemata Harbour study, where loads for each of these three urban landuses are required, it was necessary to separate these contributions. The way in which this was achieved is described below for zinc. The same procedure with minor variations was used for the other metals and PAHs as described in the relevant reports.

The primary information source used to derive landuse loads for the various contaminants was the work NIWA has been undertaking for Metrowater/Auckland City Council to measure urban landuse loads for Auckland City. These loads were compared with those from Williamson (1991) and with data from the international literature. This process lead us to conclude that a reasonable zinc load for a completely residential catchment is about 600 g ha^{-1} year^{-1} or about 80% of the Williamson "urban" load (The derivation of the commercial and industrial loads is described below).

There are, on average, about 12 dwellings per hectare in urban residential catchments of Auckland City. This is also the number used by NSCC in their estimates of future urban development in North Shore catchments (future development projections provided by Kath Coombes). Dividing the zinc load by 12 gives 50 g dwelling^{-1} year^{-1}.

This 50 g includes the zinc naturally present in the sediment generated from a residential catchment. Williamson estimated the median sediment load from urban catchments to be 375 kg ha^{-1} $year^{-1}$ and this is reasonably consistent with the Metrowater/Auckland City Council urban landuse loads which ranged between about 400 and 1000 kg ha^{-1} $year^{-1}$. Sediment loads from commercial and industrial areas, with their high proportions of impervious surfaces, would be expected to be a bit less than the loads from residential areas, but these differences are probably small enough to be ignored for this study. For the purposes of determining the "natural" load of zinc attached to sediment, a sediment load of 500 kg ha^{-1} $year^{-1}$ was assumed (the load assumed is not critical because the natural zinc load is only about 2% of the dwelling load as explained below). Dividing by 12 dwellings ha^{-1} gives a sediment load of 42 kg $dwelling^{-1}$ $year^{-1}$. The concentration of zinc in this sediment is about 50 mg kg^{-1} giving a dwelling sediment natural zinc load of about 2 g $dwelling^{-1}$ $year^{-1}$. Thus, the zinc load originating from sources other than sediment is about 48 g $dwelling^{-1}$ $year^{-1}$.

The contaminant loads for commercial and industrial landuse were estimated from the same sources of information. The zinc loads for commercial and industrial landuses were estimated to be 2.4 and 7 times greater than the residential landuse load, i.e., 1400 g ha^{-1} a^{-1} and 4200 g ha^{-1} a^{-1}, respectively. Table 4-4 in ARC TP10 gives a range of 1700 to 4900 g ha^{-1} a^{-1} for "commercial" landuse (by implication this includes our "industrial" landuse). Our commercial load is a little less than this range but our industrial load is consistent with the TP10 range. We believe that these estimates of the loads are the best that can be made from the information available at this time.

The final step in deriving the annual zinc loads for the Lucas catchment between 1950 and 2002 was to multiply the dwelling load by the number of residential dwellings and the areas of commercial and industrialactivities that existed in the catchment each year.

The natural contaminant load, i.e., the load associated with sediment because of its geochemical nature (this natural load exists only for zinc, copper and lead; OCs are not natural and natural PAH concentrations are very low), was modelled as a component of the modelled sediment load. This natural load was used as the main calibration parameter for sediment metal concentrations, i.e., the natural load was adjusted to minimise differences between model predicted and measured sediment metal concentrations. If the natural load has to be increased substantially to obtain good agreement between modelled and measured sediment metal concentrations, then this implies that there are other sources of the metal that have not been correctly accounted for in the model. This situation was encountered, as explained for the existing scenario.

One objective of the validation exercise described below was to confirm the accuracy of the dwelling load for zinc. In this case, therefore, the natural zinc load required to produce good agreement between the modelled and measured sediment zinc concentration profile had to be realistic, i.e., consistent with the natural zinc concentrations in the sediment.

F.3 Validation Results

The primary model output is the contaminant concentration in the surface layer of the estuary sediment at the end of each year in the simulation period. To compare these annual surface-layer concentrations (moving forward in time) with the present-day concentration profile (looking back in time), requires an understanding of how the profile is generated over time so that a predicted profile can be generated from the model results. The following sequence of steps is a simplified but adequate description of the profile generation process.

1. Throughout a year the annual load of sediment with its attached contaminant deposits to form a layer, say 3 to 10 mm, by year-end, i.e., the annual sediment deposition rate.

2. During the year this layer is bioturbated into the underlying 100 to 150 mm of sediment, diluting the contaminant concentration in the annual layer to a value close to the concentration in the underlying sediment. Our model assumes that by the end of the year the top 110 mm of the sediment has a uniform contaminant concentration.

3. By the end of the subsequent year, another annual increment has deposited but because this increment raises the sediment surface by 3 to 10 mm (or an amount equal to the SDR), the bioturbated layer does not extend to the same depth as it did the previous year. This leaves a thin layer of sediment at the previous year's concentration immediately beneath the new bioturbated layer.

4. This process continues to eventually produce the sediment depth profile of contaminant concentrations that is observed today.

The above sequence of steps was applied to the model predictions of progressive (i.e., from 1950 through to 2002) annual surface sediment zinc concentrations to produce the zinc concentration depth profile that the model predicted we should find in the sediment in 2002. This predicted profile is compared to the measured profile from the core Figure F1.

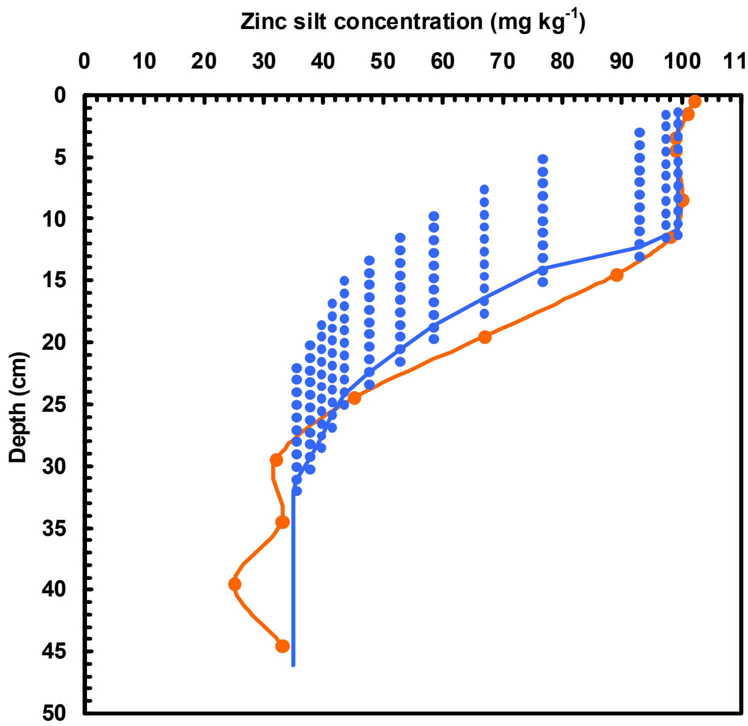


Figure F1 Sediment zinc concentration depth profile in lower Lucas Creek estuary. Red points and line are measured concentrations and profile. The blue points are the predicted zinc concentrations within the bioturbation depth. From left to right the vertical set of blue points show the concentrations in the bioturbated layer for each fifth year between 1950 and 2000 and then for 2001 and 2002. The blue line is the zinc concentration profile that would develop from the surface sediment zinc concentrations predicted for each year.

The derivation of the predicted profile can be best understood by starting at the left-hand set of vertical blue points. These points represent the predicted concentration profile in the bioturbated layer in 1950. Note that the solid blue line beneath these points is at the same concentration because prior to urban development it is reasonable to assume that the zinc concentration was the same at all depths. The next set of blue points to the right (higher zinc concentration) is the predicted concentration in the bioturbated layer in 1955. During this five year period about 20 mm of sediment was deposited. Assuming that the thickness of the bioturbated layer remained the same i.e., about 110 mm, then a 20 mm layer at the bottom of the 1950 bioturbated layer would have remained unaltered right through to the present-day. The rest of the 1950 bioturbated layer was mixed with the 20 mm of new sediment deposited between 1950 and 1955. Continuing this process to 2002 gives the pattern shown in the figure.

The blue line traces the concentrations in the remaining unaltered layers at the base of each annual profile of bioturbated sediment. This predicted line agrees quite well with the red line plotted through the measured zinc concentrations. The pre-urban concentration in the silt fraction was assumed to be about 35 mg $kg^{-1.}$ During the middle part of the development period the predicted concentrations were lower than the measured concentrations. This could be because our predicted sediment loads for this period are too high, bioturbation was deeper during that period, or our zinc loads are too low. Considering the large number of parameters used in the model for which there are little supporting data, the overall agreement is encouraging. For this catchment, the predicted sediment and zinc loads, as well as the many other input parameters for the model, are certainly in the right ballpark.

F.4. References

Williamson, R.B. (1991) *Urban Runoff Data Book.* Water Quality Centre Publication No. 20.

APPENDIX G. Summary of Principal Outputs of the Prediction Scheme

Contaminant concentration in estuarine sediments	
$\beta_{surface,kest}$	
Sediment-deposition rate	
$\delta_{ANNUALAVG,54years,kest}$, $\delta_{ANNUALAVG,108years,kest}$	
Origin of sediments/contaminants that deposit in each subestuary	
$\eta_{jcatch,54years,kest}$, $\eta_{jcatch,108years,kest}$, $\eta_{jcatch,CUM,kest}$	sediments
$\lambda_{jcatch,54years,kest}$, $\lambda_{jcatch,108years,kest}$, $\lambda_{jcatch,CUM,kest}$	contaminants
Fate of sediments/contaminants that originate in each subcatchment	
$\varepsilon_{kest,54years,jcatch}$, $\varepsilon_{kest,108years,jcatch}$, $\varepsilon_{kest,CUM,jcatch}$	sediments
$\phi_{kest,54years,jcatch}$, $\phi_{kest,108years,jcatch}$, $\phi_{kest,CUM,jcatch}$	contaminants