Predicting decadal-scale estuarine sedimentation for planning catchment development

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Abstract Deposition of typically fine-grained terrigenous sediment in coastal-plain estuaries can smother habitats, chronically raise turbidity and change substrate texture. To help plan catchment development and choose mitigation measures that will secure environmental goals in the estuary, we have built a model that predicts rates and locations of estuarine sedimentation on the decadal time scale. The USC model combines information from several underlying models, including a catchment model (based on GLEAMS) for predicting daily sediment runoff, and an estuary hydrodynamics/sediment-transport model. The estuary model is used to evaluate event-scale sediment transport and deposition patterns under a range of weather conditions, which are held in a database that the USC model accesses. Multiple grainsizes are treated in the USC model. A bed-sediment weighted mean grainsize controls erosion of the mixed-grain bed, but, once in suspension, the constituent grainsizes disperse according to their respective fall speeds. These features allow for bed armouring, which reduces the resuspension of all grainsizes, and for different constituent grainsizes to "unmix" while in suspension. The USC model is run in a Monte Carlo mode to capture extreme sediment-generation events. The USC model has been implemented for the Central Waitemata Harbour (Auckland, New Zealand) in a study to predict sedimentation and heavy-metal accumulation in the harbour as the Auckland region continues to grow over the next 100 years. The model predictions are being used for, amongst other things, identifying significant sediment and metal sources in the catchment, and testing the efficacy of different types of stormwater treatment and options for controlling heavy-metal generation at source. The model was calibrated against measured (radioisotopic) sedimentation rates over the past 50 years. The calibration primarily consists of relaxing and strengthening sediment-transport pathways in the model until all of the dynamic sinks in the model simultaneously accumulate sediment at realistic rates. The hindcast sedimentation rates are generally smaller than the radioisotopic sedimentation rates; however, the patterns of sedimentation are similar in all important respects. A further reality check on the model performance is provided by examining patterns of sediment dispersal, specifically, the origins of sediments that deposit in the various parts of the harbour. The model predictions for the period 2001–2100 show a complicated response in the harbour to a reduction in catchment sediment runoff expected over the next 15–20 years, which in turn is due to the supply of greenfield development sites becoming exhausted and development as a consequence turning exclusively to infill housing. In some parts of the harbour the sedimentation rate is predicted to be virtually unchanged by this reduction, but in other parts a change in depositional regime is predicted. This has significant implications for the accumulation of heavy metals in the harbour bed sediments.

Key words estuary; sediment transport; sedimentation; model; planning; catchment development; New Zealand

INTRODUCTION

The main pressure on estuarine ecosystems in the North Island of New Zealand is associated with sediments eroded from deforested catchments. Fine-grained sediments, in particular, can smother habitats, raise turbidity and change substrate texture (Ellis *et al.*, 2002; Lohrer *et al.*, 2004). Change from sandy to muddy bed sediments is implicated in the current rapid spread of mangroves in most upper-North Island estuaries (Ellis *et al.*, 2004). Of course, sediment yield is not zero in undisturbed catchments, so estuaries may be thought of as "naturally ageing" as they slowly fill with sediment. The problem is that sediment yield from deforested catchments typically greatly exceeds the yield of the catchment in its native state, and hence estuaries are ageing at an unnatural pace. For instance, sedimentation rates in North Island estuaries are at least a factor of 10 higher now compared to prior to deforestation (Hume & McGlone, 1986; Swales *et al.*, 2002).

To slow estuary ageing, authorities must focus on reducing catchment sediment yields. But, how much is enough, and where in the catchment should effort be focused to most effectively secure environmental goals in estuary receiving waters? To answer these kinds of questions, we have built a model that predicts dispersal of terrigenous sediments and associated rates and locations of estuarine sedimentation.

The USC model makes predictions on the planning time scale (decades and greater), which is much longer than the time scale of typical estuary sediment-transport models. The model predicts sedimentation in different parts of the estuary, which may be compared and used in an assessment of sediment effects, and the change in bed-sediment composition over time, which reflects degradation of habitat. In addition, the model predicts the accumulation of heavy metals in estuary bed sediments, which may be compared to sediment-quality guidelines to infer associated ecological effects. Finally, the model unravels the links between sediment sources in the catchment and sediment sinks in the estuary, showing where mitigation measures on the land can be most effectively focused. The purpose of this paper is to describe how the USC model works and how it is calibrated, and to give an example of its application.

MODELS

The USC model combines information from at least two underlying models: a catchment model for predicting sediment runoff, and an estuary hydrodynamics/sediment-transport model for dispersing and depositing sediments in the estuary receiving waters.

GLEAMS catchment model

The GLEAMS (Groundwater Loading Effects of Agricultural Management Systems; Knisel & Davis, 2000) model is used to predict daily runoff of water and sediment. GLEAMS is a physics-based, field-scale model. Rainfall is apportioned between surface runoff, storage in the soil profile, evapotranspiration and percolation beneath 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; soil loss from mass movement is not. Sediment runoff may be passed through silt control ponds, which attenuate a fraction of the load, depending on pond geometry, runoff and sediment characteristics. GLEAMS-based and similar models (e.g. Watershed Assessment Model, Bottcher *et al*., 1998; Basin New Zealand, Cooper & Bottcher, 1993) have a long history of application in New Zealand, including being used to: predict sediment loss from vegetable growing fields; identify sediment sources in developing catchments; assess impacts of urban and motorway development on estuarine sedimentation; estimate effects of urbanisation on sediment loss; and determine sediment yields associated with rural intensification options.

Estuary model suite

The DHI Water & Environment MIKE3 model suite is used to simulate tidal currents, wind-driven currents, mixing of freshwater runoff with seawater, and sediment transport and deposition. The MIKE3 FM model solves continuity, momentum, temperature, salinity and density equations using a cell-centred finite-volume method. In the horizontal plane, an unstructured grid is used; in the vertical, a structured discretisation is used. The MIKE3 MT model describes erosion, transport and deposition of mud or sand/mud mixtures from a layered bed under the action of currents and waves. In addition to the DHI models, the SWAN spectral wave model (Holthuijsen *et al*., 1993) is used to simulate the surface wave field and associated subsurface water velocities. SWAN uses the water levels and current fields predicted by the MIKE3 FM model in predicting wind-generated waves. The predicted wave heights, periods and directions are in turn used to quantify wave-induced bed shear stress, which then resuspends sediments in the MIKE3 MT model.

The DHI model suite is used to construct a database of sediment dispersal and deposition patterns under a range of tides and weather conditions, and for a range of sediment grainsizes. The basic time scale in the database is an event. For the transfer through tidal creeks and into the main body of the estuary of terrigenous sediments that are eroded from the catchment by rainfall, an event is a rainstorm. For the resuspension and dispersal of estuarine bed sediments by wind waves and tidal currents, an event is a windstorm.

An example of the kind of information held in the database for rainstorm events is given in Fig. 1. This shows the fraction of the terrigenous sediment runoff delivered during a rainstorm to the head of a tidal creek that then passes through the tidal creek and into the main body of the estuary. Simulations are run for a range of sediment constituent grainsizes and rainfalls, which translates into a range of freshwater discharges. For this example, the finer sediments, with correspondingly smaller settling speeds, are more completely flushed from the tidal creek. Regardless of grainsize, more sediment is exported from the tidal creek as rainfall (freshwater discharge) increases; when rainfall reaches 20–30 mm, the tidal creek starts to behave like a river that directly debouches into the main body of the estuary.

Figure 2 provides an example of the kind of information held in the database for windstorm events and shows erosion depth in a subestuary under different winds and for a range of bed-sediment median grainsizes. Subestuaries are km-scale compartments with common depth and exposure. Each DHI simulation to estimate erosion depth starts with sediments in the given subestuary being stationary (on the bed), and is run until the eroded sediment settles somewhere in the model domain, or is lost to external sinks. The erosion depth is evaluated from the mass of sediment removed from the subestuary. Figure 2 shows that sediments are not resuspended when the wind is calm. This is common in the typically small (compared to, say, eastern seaboard of the USA) North Island estuaries, for which sediment resuspension is dominated by wind waves (Green & McDonald, 2001; Green & Coco, 2007).

An example of the way patterns of sediment dispersal are represented in the database is given in Fig. 3, which shows how sediment that is eroded from one "origin" subestuary is deposited in all the other subestuaries (the "destination" subestuaries). In each panel, the vertical axis is the fraction of the eroded material that deposits in each destination subestuary (horizontal axis). Simulations are run for different sediment constituent grainsizes, and for different tide ranges, wind speeds and wind directions.

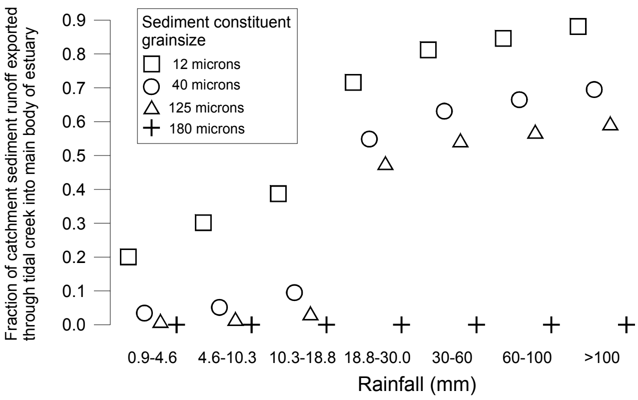

Fig. 1 Fraction of catchment sediment runoff exported from tidal creek as a function of rainfall.

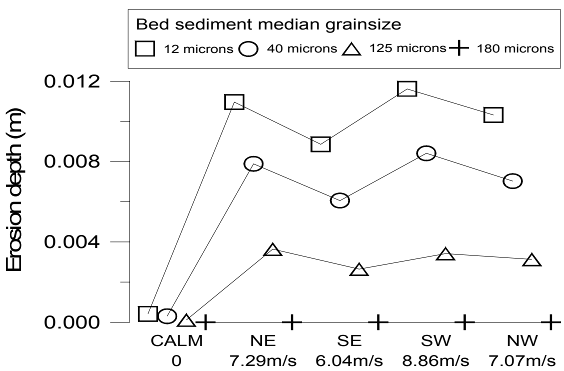

Fig. 2 Subestuary erosion depth under an average tide and a range of winds.

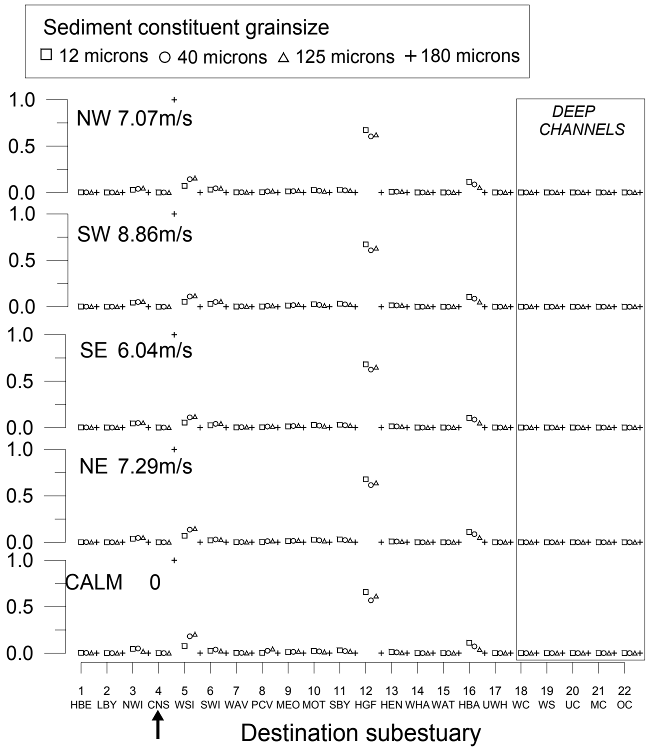

Fig. 3 Dispersal of sediment eroded from origin subestuary #4 (see text for explanation).

USC model

Various daily time series are used to drive the USC model, including sediment runoff, rainfall and wind speed and direction. GLEAMS is used to construct the time series of daily sediment runoff, as follows. The simulation period is divided into a number of sub-periods; for instance, a 50-year simulation period (2001–2050) might be divided into 5 × 10-year sub-periods (2001–2010, 2011–2020, 2021–2030, 2031–2040, 2041–2050). The land use in each sub-period is then specified; in total, these represent the particular future development scenario being investigated. GLEAMS is now run separately for each land use, driven by a historical daily rainfall time series, say 25 years long. Each run of GLEAMS creates a 25-year time series, corresponding to the historical rainfall, of daily sediment runoff from the catchment under the particular land use. The GLEAMS outputs are now subsampled, as follows. To create the daily sediment runoff for the period 2001–2010, 5 × 2-year blocks (say) are randomly selected from the appropriate 25-year GLEAMS series, and these blocks are placed back-to-back. The procedure is repeated until a time series of daily sediment runoff for the entire period 2001–2050 is created. The advantage of this scheme, which is significant, is that the effects of antecedent rainfall on sediment generation, which can create large variability in the response of the catchment to rainfall, can be captured. For example, sediment yield may be higher under intense rainfall after an extended period of dry weather, compared to less intense rainfall when the ground is partly saturated. These effects are captured in GLEAMS, and they get transferred to the time series that will drive the USC model by using *sequences* of GLEAMS output. Note that there is an implicit assumption here, *viz*. that rainfall in the future will be much the same as it was in the past. Of course this may not be warranted. A by-product of this sampling procedure is a daily rainfall time series for the simulation period, which is also required for driving the USC model. A corresponding wind time series can be readily constructed given wind statistics conditional on rainfall. Extreme sediment-generation weather events are captured in the 25-year GLEAMS series, but they are not necessarily captured in the time series constructed for driving the USC model. To rectify this, the USC model is run N times in a Monte Carlo package, with each USC model run in the package driven by a different 50-year (in this example) time series of daily sediment runoff, randomly constructed, as just described. *N* is typically order 10^2, and the results from the package of USC simulations are averaged. Other model parameters and/or inputs may be randomly varied as well; for example, the erosion depths and/or dispersal patterns shown in Figs 1–3.

In essence, the USC model builds up its set of predictions by reading along the various weather and sediment runoff time series, looking up information in the database (e.g. Figs 1–3), and injecting terrigenous sediment into the estuary and shifting estuarine sediment back-and-forth amongst subestuaries accordingly.

A key feature of the model is that the bed sediment in each subestuary is represented as a column comprising a series of layers. Layers are added when sediment is deposited, and removed when sediment is eroded. Layer thicknesses may vary, depending on how they develop during the simulation. Sediments may be composed of multiple constituent grainsizes. The proportions of the constituent grainsizes in each layer of the sediment column may vary, depending on how they develop in the simulation. Under some circumstances, the constituent grainsizes in the model interact with each other, and under other circumstances they act independently of each other. For example, the erosion rate is determined by a weighted-mean grainsize of the bed sediment (determined over the thickness of an active layer) that reflects the combined presence of the constituent grainsizes. Note, in this regard, that Fig. 2 shows erosion depth as a function of bed-sediment median grainsize. This has an important consequence: if the weighted-mean grainsize of the bed sediment increases, it becomes more difficult to erode, and so effectively becomes armoured as a whole. This reduces the erosion of all the constituent grainsizes, including the finer fractions, which otherwise might be very mobile. In contrast, the individual grainsizes, once released from the bed by erosion and placed in suspension in the water column, are dispersed independently of any other grainsize that may also be in suspension (note that Fig. 3 shows dispersal of different sediment constituent grainsizes). Dispersion of suspended sediments is very sensitive to grainsize, which leads to another important consequence: the constituent grainsizes may unmix once they are in suspension and going their separate ways. This can cause some parts of the estuary to, for instance, accumulate finer sediments over time and other parts to accumulate coarser sediments. In some parts of the estuary or under some weather sequences, sediment layers may become permanently sequestered by the addition of subsequent layers of sediment, which raises the level of the bed and results in a positive sedimentation rate. In other parts of the estuary or under other weather sequences, sediment layers may be exhumed, resulting in a net loss of sediment. Other parts of the estuary may be purely transportational. However, even in that case, it is possible, with a fortuitous balance, for there to be a progressive coarsening or fining of the bed sediments.

EXAMPLE IMPLEMENTATION OF THE USC MODEL

The USC model has been implemented in the Central Waitemata Harbour (CWH) in a study conducted for the Auckland Regional Council. The CWH was divided into 17 subestuaries (Fig. 4(a)) and the catchment was divided into 15 subcatchments. The CWH is a drowned-valley estuary that receives drainage from the Upper Waitemata Harbour and opens to the east coast of the upper North Island of New Zealand (Fig. 4(b)). It has a surface area of ~80 km^2, and opens into the Hauraki Gulf, which is sheltered from ocean waves. Two large embayments – Shoal Bay to the north and Hobsons Bay to the south – open out from the throat of the harbour, which is crossed by the Auckland Harbour Bridge. The main body of the harbour, to the west of the throat, comprises tidal flats around the fringes, expanses of subtidal flats (to 5 m deep), deeper channels (10–15 m deep) and tidal creeks (Whau River, Henderson Creek) that discharge along the southwestern shore. The tide is semidiurnal with a range of 1–2 m, and the water column in the main body of the harbour is typically well-mixed. The CWH receives runoff from a 205 km^2 land catchment, about half of which discharges via Henderson Creek. Even in flood, freshwater runoff through Henderson Creek is insufficient to stratify the water column in the main body of the harbour. Bed sediments in the main body typically contain less than 10% mud, and the median grainsize is 130–170 μm. Bed sediments in the tidal creeks are finer.

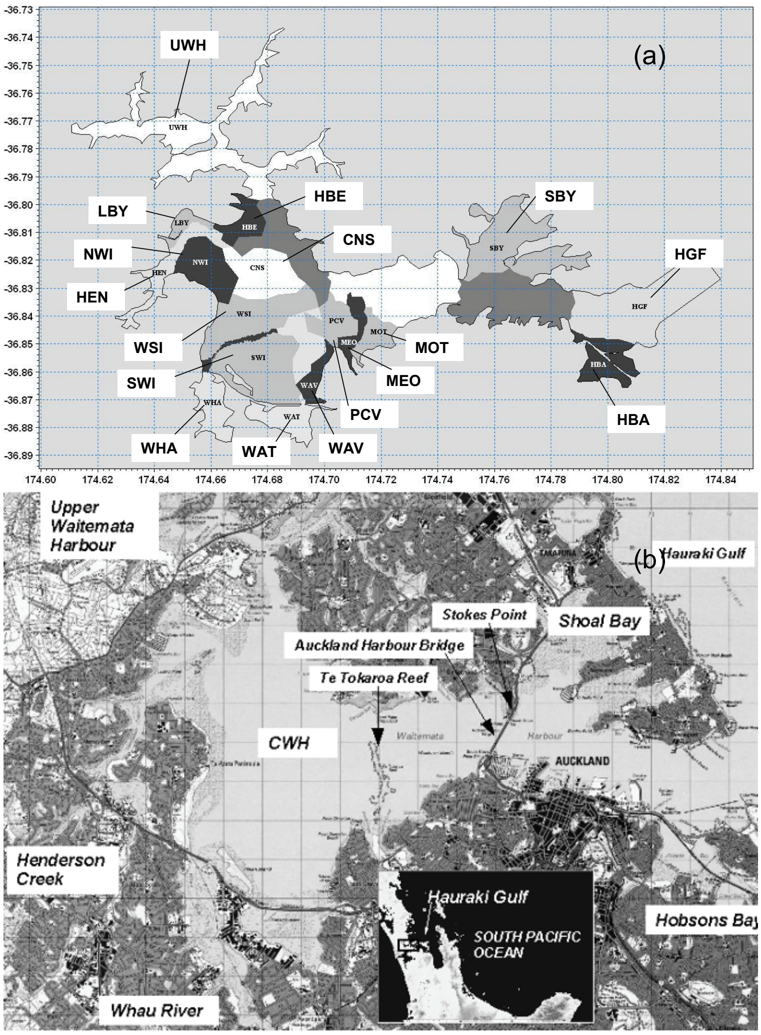

Fig. 4 (a) Subestuaries. (b) Location map.

USC model calibration against sedimentation data

The USC model was run for the historical period 1940–2001, with sediment inputs from the catchment, hindcast by GLEAMS, appropriate to that period. The aim of the calibration process was to adjust various terms in the USC model so that its hindcasts of sedimentation rate during the historical period came to match observations from that same period. The main adjustment related to the behaviour of "dynamic sinks" in the model, as follows.

The database of dispersal and deposition patterns (example patterns are shown in Figs 1–3) describes, in effect, the strength and direction of sediment-transport pathways or "connections" amongst subestuaries. These connections form a complex network, with multiple cross-connections and interactions possible. The network of connections determines which parts of the estuary ultimately accumulate sediments, which are termed here "dynamic sinks", because they arise from the behaviour of the system (cf. a static sink that would be created by, for instance, simply preventing erosion in that part of the estuary). Any small errors associated with the connection strengths and directions – which are determined by the DHI simulations – may interact and grow. This kind of problem is unavoidable in any scheme that seeks to extrapolate error-prone calculations beyond the scale at which the calculations are first performed. In the case of the USC model, we are attempting to scale-up patterns of sediment dispersal that apply at a roughly daily time scale to a final time scale that is order 10^4 times larger than daily. If the Central Waitemata Harbour is primarily dispersive, in the sense that sediments are passed more-or-less randomly in all directions amongst subestuaries, then the growth of errors should be minimised. But, that notion cannot be entirely true, since there obviously will be preferred sediment-transport routes. The goal in the calibration of the USC model, which is obtained by relaxing and strengthening connections appropriately, is to get all of the dynamic sinks in the model domain to simultaneously accumulate sediment at realistic rates.

By radioisotopic dating of sediment cores, Swales *et al*. (2007) determined an average sedimentation rate over the past 50 years or so of 3.2 mm/year for intertidal sites in the Central Waitemata Harbour (range 0.7–6.8 mm/year), and 3.3 mm/year for subtidal sites (range 2.2–5.3 mm/year). Sedimentation rates were more variable at intertidal sites compared to subtidal sites. The USC hindcast sedimentation rates are generally smaller than the radioisotopic sedimentation rates by about 25%; however, the patterns of sedimentation are similar in important respects, as follows (refer to Fig. 5): (a) The hindcast sedimentation rates in Henderson Creek and the Whau River (5.7 and 3.7 mm/year, respectively), which are both tidal creeks, exceeded the hindcast sedimentation rates at all places outside of the tidal creeks. This concurs with previous observations of sedimentation in tidal creeks in the Auckland region (Swales *et al*., 2002). (b) The largest hindcast sedimentation rate outside of the tidal creeks, with one exception, was in Shoal Bay (2.2 mm/year). The largest radioisotopic sedimentation rate outside of the tidal creeks was also in Shoal Bay. This is an interesting result, and is explainable by another observation, to be described below. (c) The exception noted above is Limeburners Bay (3.3 mm/year). Limeburners Bay may be viewed as an extension of Henderson Creek, from which sediments are primarily received. (d) The hindcast sedimentation rates are smaller along the southern shore of the harbour throat to the west of the Auckland Harbour Bridge compared to the intertidal flats in the main body of the harbour further to the west. This is broadly in line with Swales *et al*.'s designation of the southern shore as a "temporary sink". (e) The hindcast sedimentation rates are smaller in the subtidal flats in the main body of the harbour compared to the intertidal flats. The radioisotopic data show the same pattern in at least one part of the main body of the harbour.

Patterns of sediment dispersal

A further reality check on the model performance is provided by examining patterns of sediment dispersal, specifically the origins of sediments that deposit in each subestuary. For instance, although sediments from all sources are generally well mixed together in the main body of the harbour, deposition plumes are still traceable from respective subcatchment outlets. For instance,

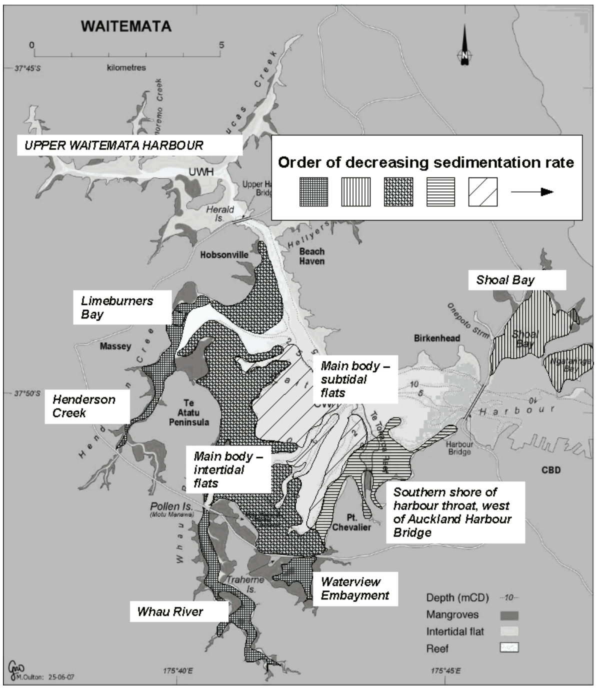

Fig. 5 Hindcast sedimentation rates.

the northwestern intertidal flats are dominated by sediments deriving from the Henderson Creek subcatchment, but the southwestern intertidal flats are dominated by sediments from the Whau River subcatchment. Te Tokaroa Reef acts as a barrier to sediment dispersal, with sediments discharged from subcatchments on either side of the reef prevented from mixing locally. With one exception, sediments and metals that deposit in tidal creeks (Henderson Creek, Whau River) and sheltered embayments (Limeburners Bay, Waterview Embayment, Hobsons Bay) are sourced from the respective immediately adjacent subcatchment. Shoal Bay is the exception, which accumulates sediments from every subcatchment except those that drain into the harbour on the southern shore of the throat to the east of the Auckland Harbour Bridge. Some preliminary exploratory simulations with the DHI model suite suggest that Shoal Bay siphons off suspended sediment carried by ebb-tide flows through the harbour throat. This process is aided by an eddy that is shed downstream on the ebb tide from Stokes Point (see Fig 4(b), this headland forms the western end of the entrance to Shoal Bay). Sediments discharged from subcatchments that empty on the southern shore of the throat to the east of the Bridge are not entrained in this eddy, which explains why they do not accumulate in any significant quantity in Shoal Bay.

MODEL PREDICTIONS

The population in Auckland City is expected to increase significantly over the next 50 years. A substantial part of the increased population will be housed by infill development, although there are still greenfield areas in the region that may be developed. The Auckland Regional Council contracted NIWA in 2005 to conduct the Central Waitemata Harbour Contaminant Study. The main aim of the Study is to predict sedimentation and heavy metal (zinc, copper) accumulation in the bed sediments of the Central Waitemata Harbour under a number of development scenarios over the next 100 years (2001–2100) with a view to, amongst other things, identifying significant sediment and metal sources, and testing the efficacy of different types of stormwater treatment and options for controlling heavy-metal generation at source. The USC model was used to make the predictions, which authorities are presently assessing. An interesting prediction regarding sedimentation is shown here.

Catchment sediment runoff is predicted to decrease by about one-half over the next 100 years, with most of the reduction occurring over the next 15–20 years as greenfield sites are exhausted and development turns more towards infill. As a result of this, the predicted sedimentation rates in the harbour are smaller, by one-third to two-thirds, than historical (past 50 years) sedimentation rates. However, the decrease is not predicted to be uniform; in fact, the model predicts that fundamental changes in depositional regime will result in some parts of the harbour.

The sedimentation rate is predicted to reduce in the main body of the harbour, as catchment sediment runoff reduces (Fig. 6). For the tidal creeks, which are sinks, the sedimentation rate will not be greatly affected. A possible explanation is related to a differential reduction in sediment runoff, as follows. Given that much of the sediment runoff generated during larger rainfall events is exported from the tidal creeks, and virtually all of the sediment runoff generated during smaller rainfall events is deposited inside the tidal creeks (Fig. 1), then if sediment runoff during larger events is reduced more than sediment runoff during smaller events, this would not necessarily translate into a marked change in sedimentation rate.

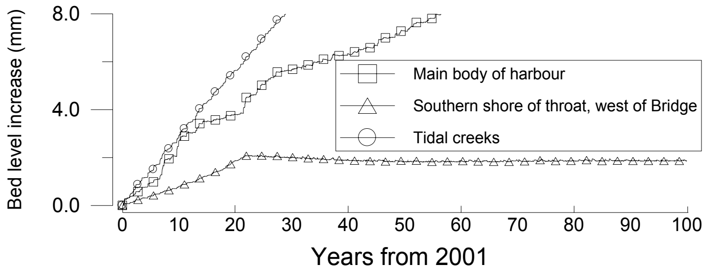

Fig. 6 Predicted change in bed-sediment level, 2001–2100.

In contrast, subestuaries along the southern shore of the harbour throat, to the west of the Auckland Harbour Bridge (see Fig. 5) are predicted to erode, for a time, as the catchment sediment runoff reduces, and then reach a new transportational regime. Here, the reduction in sediment runoff from the catchment effectively reduces sediment inputs to the point where they are matched by erosion and removal of sediments (to other parts of the harbour) by waves and currents.

The predictions have important implications for the future accumulation of heavy metals in the harbour bed sediments. Zinc and copper concentrations are predicted to rise continuously in the tidal creeks, where sedimentation will remain virtually constant. For the main body of the harbour, where the sedimentation rate is predicted to decline, the rise in heavy-metal concentrations will be retarded. This occurs because physical and biological processes will be more effective at mixing high-concentration sediment-metal inputs arriving from the land into the lower-concentration pre-existing bed sediments under the reduced sedimentation rate. When the subestuaries in the harbour throat become transportational, the metal concentrations there will stabilise. The stable concentration will not really be an "equilibrium" concentration. Rather, it is more the case that these subestuaries become "moribund" when deposition switches off.

CONCLUSIONS

The USC model combines information in physically-based ways from underlying models to make predictions of estuarine sedimentation on the planning time scale, which is orders of magnitude greater than typical estuary sediment-transport models. The model is proving to be a useful tool for resource managers, since it makes explicit predictions about the future state of the environment given certain management actions. The model also provides a comprehensive depiction of how different parts of the estuary receiving waters are "connected" to different parts of the catchment, which promotes catchment-scale thinking. Predictions for the Central Waitemata Harbour reveal a complicated response to a reduction in catchment sediment runoff expected over the next 15–20 years, which has implications for the accumulation of heavy metals.

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