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Northland Sediment Study

Whangarei Harbour Sediment Budget

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Executive summary

The aim of the Northland Sediment Study (NSS) is to develop a model that will integrate science and economics to assess the potential economic costs of meeting a range of attribute states for sediment and *E. coli* in Whangarei Harbour and freshwater environments that drain into Whangarei Harbour.

The NSS comprises two objectives:

1. To develop model frameworks and outputs that will enable the assessment of catchment sediment and *E. coli* loads and the expression of the environmental outcomes of these loads as attributes.
2. To incorporate the model frameworks and outputs developed in Objective 1 into a catchment economic model that will be used to identify cost-effective ways to manage sediment and *E. coli* loads in the Whangarei Harbour catchment.

Green et al. (2015) argued the case for using the annual-average sedimentation rate (AASR) as the single estuary attribute in the Northland Sediment Study on the basis that it is reasonable to assume that AASR is indicative of a wide range of sediment-related effects in Whangarei Harbour.

This report develops a sediment budget for Whangarei Harbour from which AASR in a number of individual depositional basins may be evaluated. The precise method for evaluating AASR from the sediment budget is given.

Equations are developed that relate catchment sediment runoff and mass of marine sediments transported by waves and currents to sedimentation rate in an estuary depositional basin.

Four depositional basins in Whangarei Harbour are identified which are presently depositing sediment of catchment origin. These are the unvegetated intertidal flats in the upper harbour, Parua Bay and Munro Bay, both in the lower harbour, and along the northern shore from Onerahi Peninsula east to Jacksons Bay, in the middle harbour.

Results from sediment coring reported by Swales et al. (2013) are used to estimate present-day sedimentation rate and density of deposited sediment in each of the four depositional basins. By combining sedimentation rate and deposited-sediment density with the area of the depositional basin, the mass of sediment depositing each year in each of the basins is estimated.

Results from Compound-Specific Stable Isotope source tracking reported by Swales et al. (2013) are used to estimate the percentage of the sediment depositing in each basin that is attributable to a catchment source. The remainder is assumed to be sediment of marine origin.

Using results from numerical model simulations of harbour sediment transport, terms in the “sediment fate matrix” are estimated. The sediment fate matrix gives the fraction of sediment derived from each of 11 subcatchments of Whangarei Harbour that deposits in each of the four harbour depositional basins on an annual-average basis.

Combining the sediment fate matrix with present-day catchment sediment runoff predicted by the SedNetNZ catchment sediment model yields the measured present-day sedimentation rate in each depositional basin.

Equations are given for predicting the change in sedimentation rate in a depositional basin resulting from either a decrease (for example, because of mitigation) or an increase in subcatchment sediment loads.

1 Introduction

1.1 The Northland Sediment Study

Northland Regional Council (NRC) has identified that sediment and *E. coli* are key water quality challenges in the Northland region (e.g., Ballinger et al., 2014).

As a result, the Ministry for Primary Industries (MPI) commissioned the Northland Sediment Study (NSS).

The aim of the NSS is to develop a model that will integrate science and economics to assess the potential economic costs of meeting a range of attribute states[1] for sediment and *E. coli* in Whangarei Harbour and freshwater environments that drain into Whangarei Harbour.

The Northland Sediment Study comprises two objectives:

1. Develop model frameworks and outputs that will enable the assessment of catchment sediment and *E. coli* loads and the expression of the environmental outcomes of these loads as attributes. MPI has contracted NIWA to deliver this objective.
2. Incorporate the model frameworks and outputs developed in Objective 1 into a catchment economic model that will be used to identify cost-effective ways to manage sediment and *E. coli* loads in the Whangarei Harbour catchment. MPI is contracting another provider to deliver this objective.

Objective 1 of the NSS comprises 6 workstreams.

- **Workstream A** – Preparation. The tasks in Workstream A are: identify catchment locations for attribute evaluation; identify harbour habitats for attribute evaluation; digest feedback from November 19 (2014) workshop convened by the Ministry for the Environment on possible sediment attributes; develop thinking on possible *E. coli* attributes for freshwater and the estuary receiving waters, including a methodology for evaluating possible *E. coli* attributes from the products of the catchment and estuary modelling.
- **Workstream B** – Attributes. The tasks in Workstream B are: make final choice of estuary sediment attributes; make final choice of freshwater sediment attributes; make final choice of freshwater and estuary *E. coli* attributes.
- **Workstream C** – Whangarei catchment modelling. The tasks in Workstream C are: SedNetNZ sediment modelling; CLUES *E. coli* modelling.
- **Workstream D** – Mitigation costs and efficiencies. The task in Workstream D is to agree on and specify mitigation (sediment and *E. coli*) costs and efficiencies to be included in the economic model.
- **Workstream E** – Whangarei Harbour sediment budget. The task in Workstream E is to establish an annual-average sediment budget for Whangarei Harbour.
- **Workstream F** – external review.

[1] The words "attribute" and "state" herein have the meanings ascribed by the National Policy Statement for Freshwater Management (NPSFM) (2014). An "attribute" is a measurable characteristic of freshwater, including physical, chemical and biological properties that support particular values. An "attribute state" is the level to which an attribute is to be managed to provide for a particular value.

The products from each workstream are to be provided to Objective 2 for incorporation in the catchment economic model.

1.2 The National Policy Statement for Freshwater Management

The National Policy Statement for Freshwater Management (NPSFM) (amended in 2014) establishes a legal and policy framework for building a national limits-based scheme for freshwater management. The Policy requires maintaining or improving overall water quality in a region and safeguarding of the life-supporting capacity, ecosystem processes and indigenous species (including their associated ecosystems) of freshwater. It also requires protection of (secondary) contact recreation.

Regional councils are required to have set freshwater objectives by 2030 that reflect national and local values; set flow, allocation and water quality limits to ensure freshwater objectives are achieved; address over-allocation; manage landuse and water in an integrated way; and involve iwi and hapū in freshwater decision-making. Councils and communities can choose the timeframes to meet freshwater objectives and limits.

The management process prescribed by the NPSFM centres on limiting resource use in “freshwater management units” in order to achieve specific, agreed values. The steps involved are:

- Agree on desired values, which are the intrinsic qualities that people appreciate or benefit from, or the uses to which people put freshwater. Examples are mahinga kai (Maori traditional food and other natural resources, including the places they are obtained and the practices around their acquisition) and swimming.
- For each value, identify the aspects to be managed. For example, for the value of ecosystem health, the aspects to be managed might include trophic state, toxicants and light.
- For each aspect to be managed, identify attributes. Attributes are the characteristics or properties of freshwater associated with each aspect to be managed. Examples are *E. coli* contamination, which is reflective of a health risk, or the DIN burden, which has a bearing on aesthetics (e.g., by stimulating periphyton blooms).
- Decide on the state of each attribute that is necessary to provide for the value at the desired level. This might be a particular DIN concentration during low flow.
- Convert attribute states into “SMART” (specific, measurable, achievable, realistic and time-bound) management objectives.
- Formulate limits to resource use that will result in the achievement of the objectives. There are two types of limit: limits to extraction (e.g., the amount of water taken for irrigation) and limits to disposal of contaminants (e.g., dairy-shed effluent).
- Develop a suite of management actions that, when implemented, will limit resource use accordingly.

The relationships between values, attributes and states in a range of freshwater environments are codified in the National Objectives Framework (NOF).

Estuaries and coastal systems are specifically excluded from consideration in the NPSFM, but they must be “given regard to” when setting limits for freshwater.

The Northland Sediment Study is designed to answer the question: what might it cost to manage, under the NPSFM, sediment and *E. coli* across a whole catchment that includes an estuary at the base of the freshwater drainage network?

The question is to be answered by developing a catchment economic model that links together sources and sinks of sediment and *E. coli* and overlays mitigation costs and efficiencies. Put simply, the model will allow different types and levels of mitigation to be applied to the catchment and will show, firstly, how sediment and *E. coli* in the waterways and in the estuary change as a result and, secondly, the costs incurred in applying the mitigation.

1.3 Estuary sediment attribute decided for the Northland Sediment Study

Green et al. (2015) argued the case for using the annual-average sedimentation rate (AASR) as the single estuary attribute in the Northland Sediment Study on the basis that it is reasonable to assume that AASR is indicative of a wide range of sediment-related effects in Whangarei Harbour. They defined AASR as the mass of sediment deposited per year divided by the product of the settled-sediment density and the area over which sediment deposits.

1.4 This report

This report, which arises from Workstream E – Whangarei Harbour sediment budget, develops a sediment budget for Whangarei Harbour from which AASR in a number of individual depositional basins may be evaluated.

The precise method for evaluating AASR from the sediment budget is given.

2 Theory

D_e, the mass of catchment-derived sediment deposited in **depositional basin** *e* during the time period Γ, is given by:

$$D_e = \sum_{c=1}^{C} L_c F_{c,e} \quad (1)$$

where:

- L_c is the total (i.e., sum of all sediment grainsizes) mass of sediment that is discharged into the harbour from **subcatchment** *c* during the time period Γ, and there are *C* subcatchments;
- $F_{c,e}$ is the total-sediment fate matrix, which is the fraction of the total sediment mass that is discharged from subcatchment *c* and that deposits in depositional basin *e* during the time period Γ.

Note that $0 < F_{c,e} < 1$ for all (c, e). If all of the depositional basins are accounted for (this might include the water column, if sediment does not settle on the bed, and the coastal ocean, if sediment escapes from the estuary) then the sum of $F_{c,e}$ over all values of c and e must be identically 1, otherwise, that sum must be less than 1. In the former case all of the catchment sediment is accounted for in the budget; in the latter case it is not.

Assuming that sediment of both catchment and marine origin can deposit in each depositional basin, then the sedimentation rate S_e in depositional basin e is related to the deposited subcatchment sediment D_e by:

$$S_e = \frac{D_e + M_e}{\rho_e A_e \Gamma} \quad (2)$$

where S_e is a vertical rate of accretion with units length per time, M_e is the mass of marine sediment deposited in depositional basin e during the time period Γ, ρ_e is the density of the deposited sediment in depositional basin e, and A_e is the area over which deposition occurs in depositional basin e.

Substituting (1) into (2), S_e is seen to be related to the sediment discharged from each subcatchment L_c by:

$$S_e = \frac{\left(\sum_{c=1}^{C} L_c F_{c,e}\right) + M_e}{\rho_e A_e \Gamma} \quad (3)$$

The time period Γ for this application will be one year; hence, S_e is the annual sedimentation rate.

3 Construction of the sediment budget for Whangarei Harbour

Figure 3-1 provides a handy summary of the nomenclature used in the following development.

Hatea River	Name of freshwater/catchment sediment source used in harbour modelling
●	Location of freshwater/catchment sediment source used in harbour modelling
Hatea River	Name of reporting zone used in SedNetNZ
HR (1)	Name (number, *c*) of **subcatchment** used in harbour sediment budget
UI (1)	Name (number, *e*) of **depositional basin** used in harbour sediment budget
Upper harbour	Informal division of the harbour

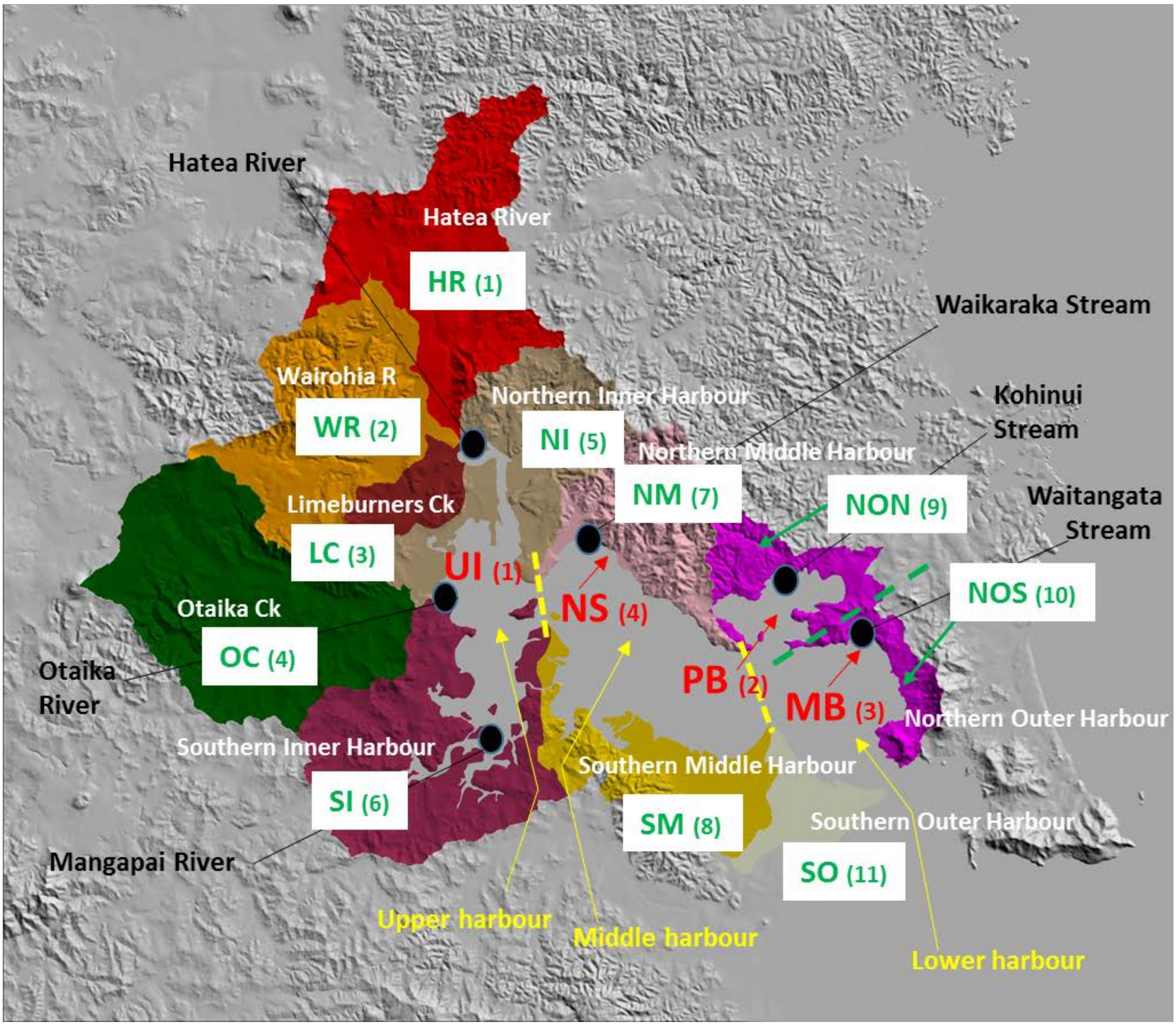

Figure 3-1: Summary of the nomenclature used in the Whangarei Harbour sediment budget.

3.1 Depositional basins

Using information from sediment-transport modelling, geochemical and radioisotopic dating of sediment cores and application of the Compound-Specific Stable Isotope (CSSI) source-tracking method, Swales et al. (2013) (hereinafter "S2013") identified three areas in the upper Whangarei Harbour (i.e., west of Limestone Island, see Figure 3-2) that deposit catchment sediments and three long-term "mud sinks" east of Onerahi Peninsula (Figure 3-2). These are:

- Upper harbour mangrove habitats, which are assumed to be accreting at a rate that is equal to the long-term rate of relative sea-level rise (1.5 mm/y at the Ports of Auckland).
- Upper harbour saltmarsh habitats, also assumed to be accreting at a rate that is equal to the long-term rate of relative sea-level rise (1.5 mm/y at the Ports of Auckland).
- Upper harbour unvegetated intertidal flats, accreting at a spatially-averaged rate of 4 mm/y.
- Parua Bay, in the lower harbour (Figure 3-2), where the intertidal flat is accumulating sediment (2.9 mm/y) at a similar rate to the central subtidal basin (2.2 mm/y).
- Munro Bay, in the lower harbour (Figure 3-2), where mud has been depositing from the mid-1950s, burying the previous shell-rich sands.
- Along the northern shore from Onerahi Peninsula east to Jacksons Bay, in the middle harbour (Figure 3-2).

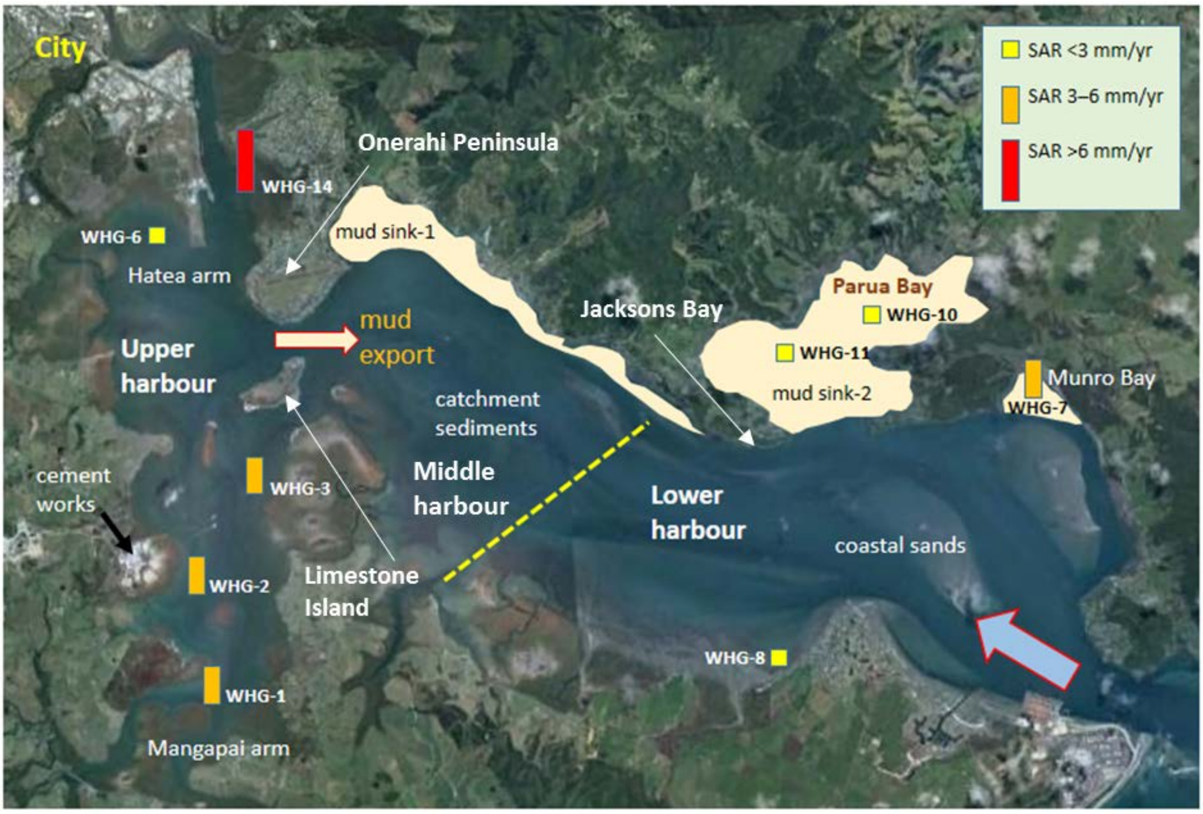

Figure 3-2: Location map, including the locations of the three long-term mud sinks east of Onerahi Peninsula identified by Swales et al. (2013). Reproduced from Swales et al. (2013). The light yellow areas showing the mud sinks correspond to (from west to east) the **NS**, **PB** and **MB** depositional basins in the harbour sediment budget.

For application in the Northland Sediment Study, we follow S2013 and choose the upper harbour unvegetated intertidal flats, Parua Bay, Munro Bay and the northern shore from Onerahi Peninsula east to Jacksons Bay as depositional basins. These depositional basins are given the codes, respectively, **UI**, **PB**, **MB** and **NS**. Depositional basin **UI** is shown in Figure 3-3, and the others are shown in Figure 3-2.

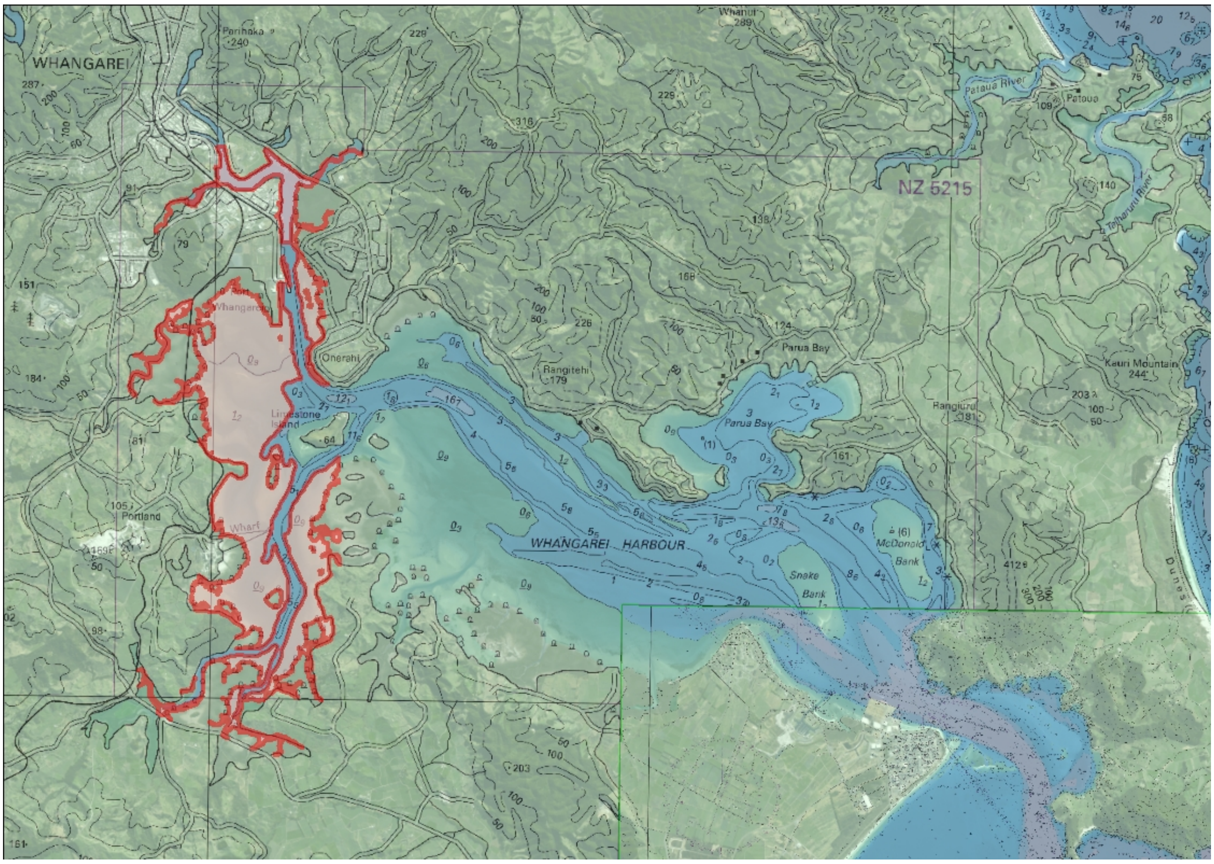

Figure 3-3: The upper harbour unvegetated intertidal flats defined by Swales et al. (2013). This is the **UI** depositional basin.

Hence, E, the total number of depositional basins, is 4.

- We disregard the upper harbour mangrove and upper harbour saltmarsh habitats as the sediment accumulation rate is thought to be controlled by the rate of sea level rise in these basins, as described by S2013.

These are not necessarily all of the depositional basins in Whangarei Harbour. Insufficient information precluded other possible basins from being included in the analysis.

Table 3-1 lists the depositional basins and provides some basic data for each basin. Notes follow the table.

Table 3-1: Whangarei Harbour depositional basins to be considered in the Northland Sediment Study. Refer to notes following the table for explanations.

Location	Depositional basin	e	A (m^2)	S (mm/y)	ρ (t/m^3)
Upper harbour unvegetated intertidal flats	**UI**	1	2,660,000	4.0	1.18
Parua Bay	**PB**	2	3,500,000	2.5	1.25
Munro Bay	**MB**	3	518,900	3.1	1.00
Northern shore from Onerahi Peninsula east to Jacksons Bay	**NS**	4	1,459,000	1.0	1.25

A (area of depositional basin)

- S2013 reported the area of the upper harbour unvegetated intertidal flats, which corresponds to the **UI** depositional basin, as 2,660,000 m^2. This excluded 2.3 km^2 of intertidal flat west of and between Knight Point (south of Limestone Island) and Onerahi Peninsula where cores showed that sediment is not accumulating. Shown in Figure 3-3

- The respective areas of the **PB**, **MB** and **NS** basins were calculated using the ACME planimeter tool, which measures area from Google Map images (http://acme.com/planimeter/). The areas measured are those denoted by S2013 as the "mud sinks" in Figure 3-2 (the light yellow areas).

S (sedimentation rate)

- S2013 estimated the sediment accumulation rate averaged over **UI** as 4 mm/y from radioisotopic (lead-210) dating of three cores in the Mangapai Arm (WHG-1, WHG-2, WHG-3; sediment accumulation rates of 4.9 [applicable to the period 1949–2012], 3.0 [1909–2012] and 3.0 [1969–2012] mm/y, respectively) and two cores in the Hatea Arm (WHG-6 and WHG-14; sediment accumulation rates of 2.8 [1830–2012] and 6.5 [1974–2012] mm/y, respectively).

- For **PB**, S = 2.5 mm/y is an intermediate value between the two lead-210 sediment accumulation rates reported by S2013 (2.2 mm/y [1935–2012] and 2.9 mm/y [1953–2012] for cores WHG-10 and WHG-11, respectively).

- For **MB**, lead-210 dating of core WHG-7 yielded a sediment accumulation rate of 3.1 mm/y [1957–2012].

- S = 1.0 mm/y for **NS** is an estimate only. No cores were collected in this area. Compared to **PB** in particular, S for **NS** has been estimated as quite low. The reason is that **NS** is very elongated in shape and exposed to winds from the south, which will generate waves that will tend to scour the area of fine sediment. Compared to **NS**, **PB** is embayed, which will afford protection to winds and waves.

ρ (deposited-sediment density)

- S2013 reported the deposited-sediment (dry-bulk) density averaged over **UI** as 1.18 t/m^3.

- ρ = 1.25 t/m^3 for **PB** is based on measurements reported by S2013 for the dry-bulk density of upper layers in cores WHG-10 and WHG-11.

- ρ = 1.00 t/m^3 for **MB** is based on the dry-bulk density of the surface layer of core WHG-7 reported by S2013.

- ρ = 1.25 t/m^3 for **NS** is an estimate only.

3.2 Catchment sediment runoff

The SedNetNZ catchment sediment model has been used to predict the total mass of sediment runoff per year from each of ten "catchment reporting zones" under the present-day catchment landuse (John Dymond, Landcare Research, personal communication). The reporting zones are shown in Figure 3-4.

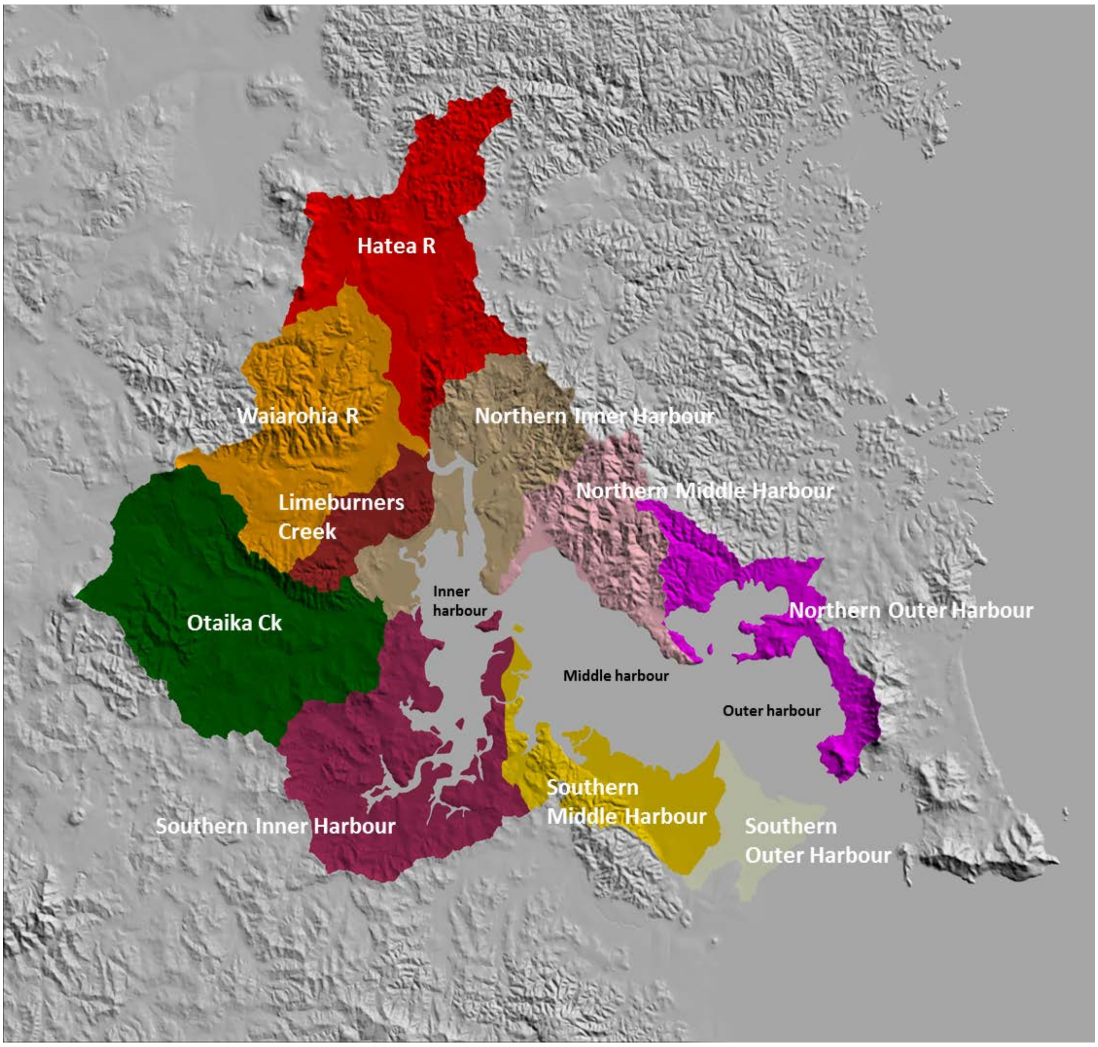

Figure 3-4: Catchment reporting zones used in the SedNetNZ model.

Eleven subcatchments have been defined for the purposes of developing the harbour sediment budget (C = 11). The correspondence between the SedNetNZ reporting zones and the subcatchments is given in Table 3-2 (see also Figure 3-1).

Table 3-2: Correspondence between SedNetNZ catchment reporting zones and subcatchments, with mass of sediment discharged per year (L_c) into the harbour from each subcatchment. Sediment runoff is predicted by SedNetNZ for the present-day catchment landuse.

SedNetNZ catchment reporting zone	Subcatchment	c	Subcatchment sediment load, L_c (t/y)
Hatea River	HR	1	4,482
Waiarohia River	WR	2	4,932
Limeburners Creek	LC	3	1,038
Otaika Creek	OC	4	11,204
Northern Inner Harbour	NI	5	2,143
Southern Inner Harbour	SI	6	2,424
Northern Middle Harbour	NM	7	2,944
Southern Middle Harbour	SM	8	555
Northern 2/3 of Northern Outer Harbour	NON	9	1,238
Southern 1/3 of Northern Outer Harbour	NOS	10	781
Southern Outer Harbour	SO	11	0

Note:

- The Northern Outer Harbour reporting zone is divided into two subcatchments: the **NON** subcatchment and the **NOS** subcatchment. **NON** occupies the northern part of the Northern Outer Harbour reporting zone, and **NOS** occupies the southern part of the Northern Outer Harbour reporting zone.

Table 3-2 also shows the annual sediment runoff predicted by SedNetNZ for the present-day landuse distributed by subcatchment. Note:

- The **NON** subcatchment carries 61% of the sediment runoff from the Northern Outer Harbour reporting zone (John Dymond, Landcare Research, personal communication).

- The **NOS** subcatchment carries 39% of the sediment runoff from the Northern Outer Harbour reporting zone (John Dymond, Landcare Research, personal communication).

The sediment discharged to the harbour from each reporting zone is composed entirely of fine silt (John Dymond, Landcare Research, personal communication).

3.3 Information available on harbour sediment-transport patterns

We have several types of quantitative information on harbour sediment-transport patterns that can be used in estimating the sediment fate matrix.

The first type of information is maps presented by S2013 that show the percentage of each of four “end members”, or sources, of sediment in the surface layer (top 2 cm) of harbour sediments. The maps have been produced from CSSI (compound-specific stable isotope) analyses of sediment samples. The method is fully described in S2013. Some of the maps are reproduced in Figure 3-5 to Figure 3-8. The locations of the end member, or source, samples used in the CSSI analysis are shown as blue filled circles in the figures. Three of the end members represent sediments from catchments (the Hatea River catchment, the Otaika River catchment and the Mangapai River catchment) and the fourth is from Calliope Bay, which represents “coastal sediment”.

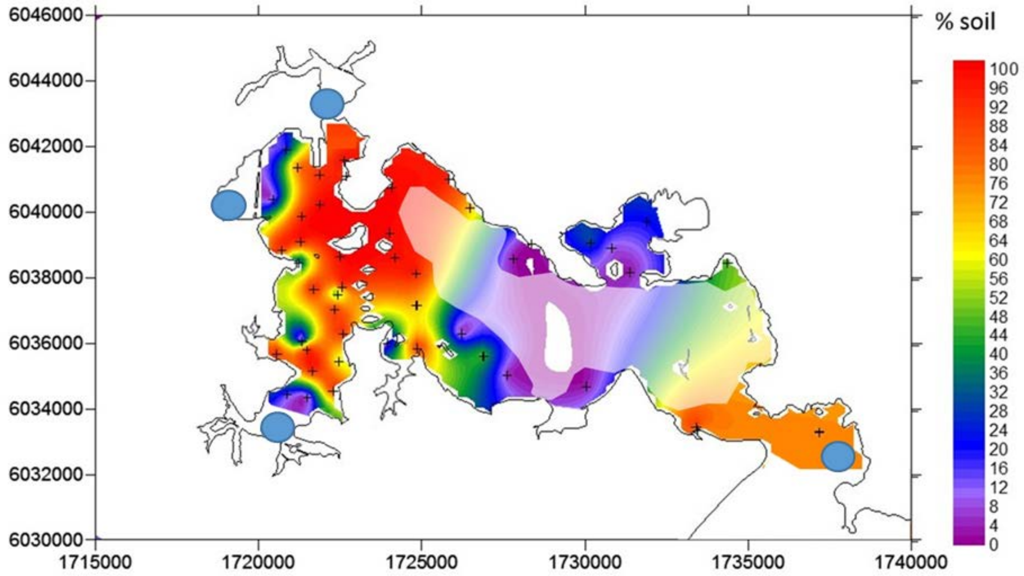

Figure 3-5: Percentage of Hātea River catchment sediments in surface layer (top 2 cm) of harbour sediments. The fogged area covers indicative extrapolated areas with no data support. Map co-ordinate system: NZTM2000. Reproduced from Swales et al. (2013). The blue filled circles represent the locations of end member, or source, sediments. From north to south on the left side of the figure the source represents sediment from the Hatea River catchment, the Otaika River catchment and the Mangapai River catchment. The source on the right side of the figure is from Calliope Bay, which represents "coastal sediment".

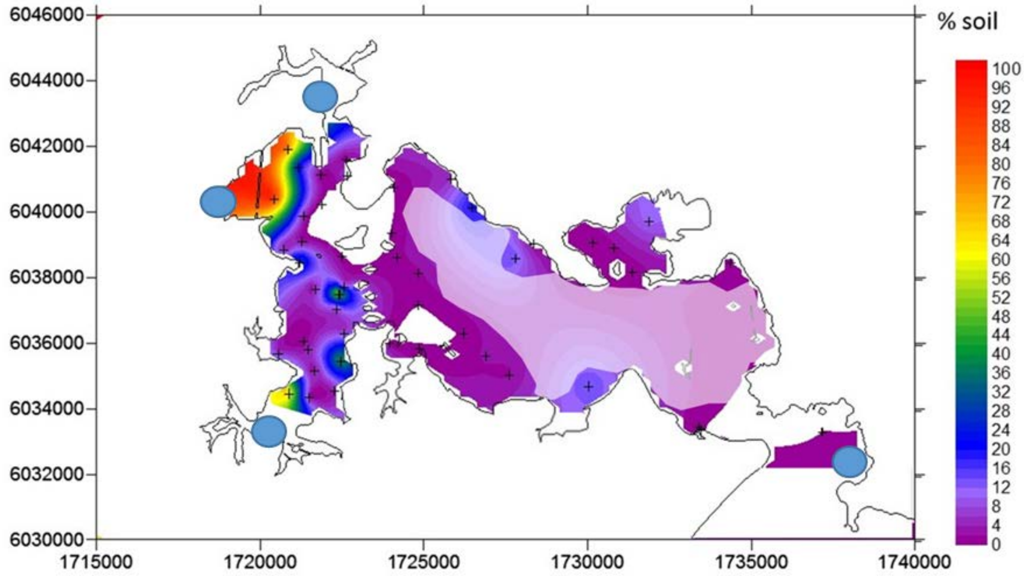

Figure 3-6: Percentage of Otaika River catchment sediments in surface layer (top 2 cm) of harbour sediments. The fogged area covers indicative extrapolated areas with no data support. Map co-ordinate system: NZTM2000. Reproduced from Swales et al. (2013). The blue filled circles represent the locations of end member, or source, sediments. From north to south on the left side of the figure the source represents sediment from the Hatea River catchment, the Otaika River catchment and the Mangapai River catchment. The source on the right side of the figure is from Calliope Bay, which represents "coastal sediment".

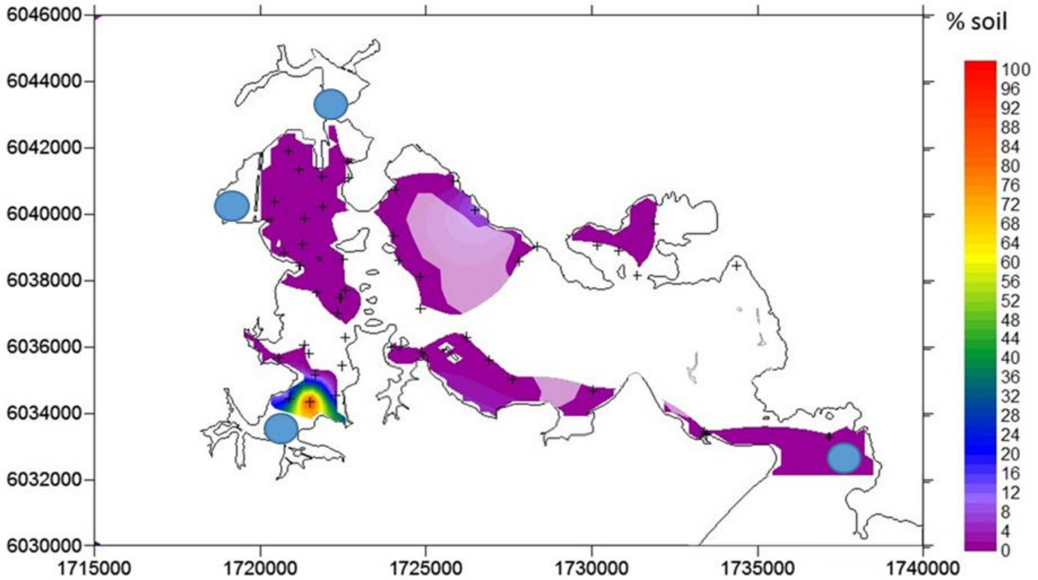

Figure 3-7: Percentage of Mangapai River catchment sediments in surface layer (top 2 cm) of harbour sediments. The fogged area covers indicative extrapolated areas with no data support. Map co-ordinate system: NZTM2000. Reproduced from Swales et al. (2013). The blue filled circles represent the locations of end member, or source, sediments. From north to south on the left side of the figure the source represents sediment from the Hatea River catchment, the Otaika River catchment and the Mangapai River catchment. The source on the right side of the figure is from Calliope Bay, which represents "coastal sediment".

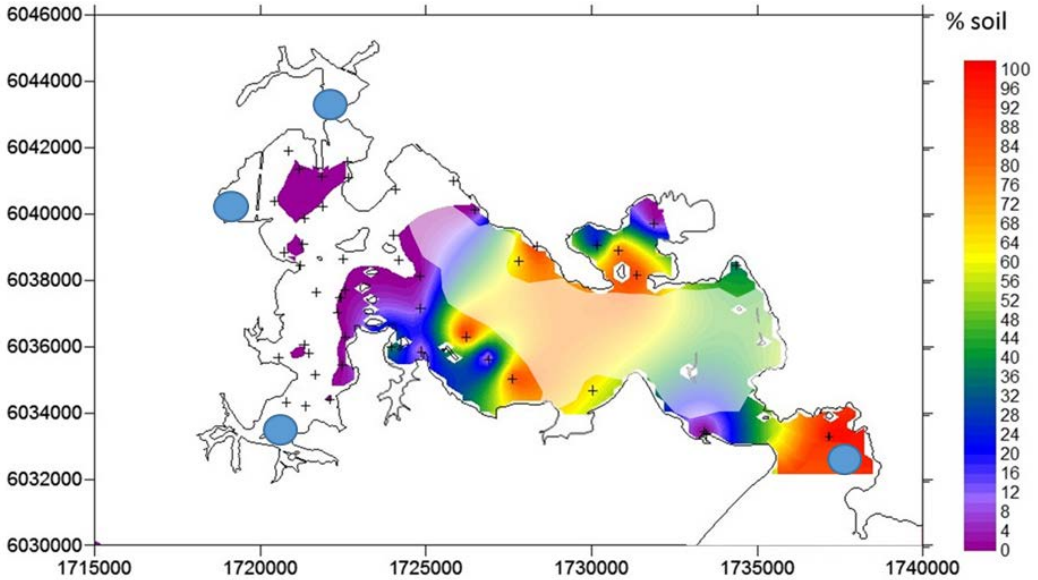

Figure 3-8: Percentage of Calliope Bay sediments in surface layer (top 2 cm) of harbour sediments. The fogged area covers indicative extrapolated areas with no data support. Map co-ordinate system: NZTM2000. Reproduced from Swales et al. (2013). The blue filled circles represent the locations of end member, or source, sediments. From north to south on the left side of the figure the source represents sediment from the Hatea River catchment, the Otaika River catchment and the Mangapai River catchment. The source on the right side of the figure is from Calliope Bay, which represents "coastal sediment".

The second type of information is simulations by a numerical model of the fate in the harbour of fine silt (20 micron particle size) discharged from the Hatea, Otaika and Mangapai Rivers under yearly-average freshwater runoff, freshwater runoff associated with a 1-year ARI storm and freshwater runoff associated with a 10-year ARI storm. These simulations were reported by S2013.

For these simulations, a five-layer three-dimensional hydrodynamic model was implemented and forced at the outer boundaries using the mean tidal range. No wind or wave effects were included.

Each river source was initially run at average flow and suspended-sediment concentration for 7.5 days then increased to the peak flood discharge and suspended-sediment concentration over 0.75 days, at which point the inputs were relaxed back to average conditions. The model was then run for a further 11 days to simulate post-event transport, Stokes settling and deposition of sediment. Erosion of the pre-existing bed sediments was excluded so that only the fate of the sediment discharged from the three rivers was determined.

The key outputs from the modelling were maps of net sediment accumulation by the end of the simulation. An example of the model predictions is shown in Figure 3-9.

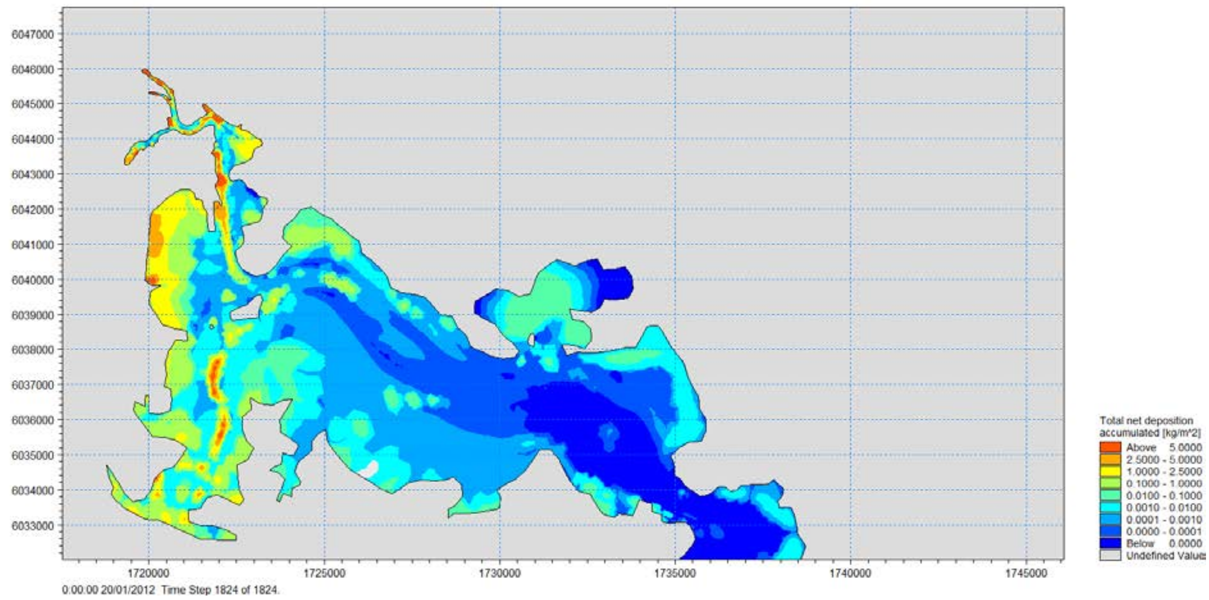

Figure 3-9: Deposition of fine silt discharged from the Hatea, Otaika and Mangapai Rivers (combined) under freshwater runoff associated with a 1-year ARI storm. The units are kg of fine silt deposited per m^2 of seabed. Reproduced from Swales et al. (2013).

For the Northland Sediment Study, we reanalysed S2013's model outputs to calculate the fraction of fine silt from each of the three model river sources that deposits in each of the **UI**, **PB**, **MB** and **NS** depositional basins during each of the events simulated (i.e., the yearly-average freshwater and sediment runoff, freshwater and sediment runoff associated with a 1-year ARI storm, and freshwater and sediment runoff associated with a 10-year ARI storm). This was done by dividing the model domain into areas corresponding to each of the **UI**, **PB**, **MB** and **NS** depositional basins and then summing the sediment deposited (as shown in, for example, Figure 3-9) in each basin. The results are given in Table 3-3 as the average over the three events.

Table 3-3: The fraction of fine silt discharged from Hatea River, Otaika River, Mangapai River, Waikaraka Stream, Kohinui Stream and Waitangata Stream (sources of freshwater and sediment used in harbour model simulations) that deposits in each of the UI, PB, MB and NS depositional basins averaged over the yearly-average runoff, runoff associated with a 1-year ARI storm and runoff associated with a 10-year ARI storm.

	Source in harbour model simulations					
Depositional basin	Hatea River	Otaika River	Mangapai River	Waikaraka Stream	Kohinui Stream	Waitangata Stream
UI	0.011	0.118	0.272	0.202	0.000	0.010
PB	0.071	0.037	0.027	0.150	1.000	0.100
MB	0.009	0.001	0.001	0.002	0.050	0.419
NS	0.003	0.037	0.028	0.000	0.000	0.000

We also ran a set of new model simulations with the harbour numerical model which were specifically designed for the Northland Sediment Study. These discharged fine silt at:

- the head of the **NS** depositional basin approximately where the Waikaraka Stream discharges, representing sediment discharged from the **NM** subcatchment;
- the head of the **PB** depositional basin approximately where the Kohinui Stream discharges, representing sediment discharged from the **NON** subcatchment; and
- the head of the **MB** depositional basin approximately where the Waitangata Stream discharges, representing sediment discharged from the **NOS** reporting zone.

We call these sources “Waikaraka Stream”, “Kohinui Stream” and “Waitangata Stream”, respectively. See Figure 3-1 for where these sources are located relative to the 11 subcatchments.

As in S2013, the simulations covered the yearly-average freshwater and sediment runoff, freshwater and sediment runoff associated with a 1-year ARI storm, and freshwater and sediment runoff associated with a 10-year ARI storm. As above, we calculated the fraction of fine silt from each of the stream sources that deposits in each of the **UI**, **PB**, **MB** and **NS** depositional basins in each simulation.

The results are given in Table 3-3 as the average over the three events.

3.4 Estimation of the sediment fate matrix

3.4.1 Depositional Basin **UI** (e = 1)

Rearranging equation (2) and inserting the data in Table 3-1 (A_1 = 2,660,000 m^2, ρ_1 = 1.18 t/m^3, S_1 = 4 mm/y) yields $D_1 + M_1$ = 12,555 t of sediment of catchment and marine origin depositing per year in the **UI** basin.

Figure 3-8 shows that less than about 5% of the sediment depositing in the upper harbour is attributable to the Calliope Bay source, which is representative of “coastal sediment”. We equate the Calliope Bay “coastal sediment” with sediment of marine origin in our model and, accordingly, we assume that 5% of the 12,555 t of sediment depositing in **UI** is of marine origin. Therefore M_1 = 628 t and D_1 = 11,927 t.

We now assume that:

- the Hatea River source used in the harbour sediment-transport modelling discharges fine silt from the **HR** (c = 1), **WR** (c = 2), **LC** (c = 3) and **NI** (c = 5) subcatchments
- the Otaika River source used in the harbour sediment-transport modelling discharges fine silt from the **OC** (c = 4) subcatchment

- the Mangapai River source used in the harbour sediment-transport modelling discharges fine silt from the **SI** (c = 6) subcatchment
- the Waikaraka Stream source used in the harbour sediment-transport modelling discharges fine silt from the **NM** (c = 7) subcatchment
- the Kohinui Stream source used in the harbour sediment-transport modelling discharges fine silt from the **NON** (c = 9) subcatchment, and
- the Waitangata Stream source used in the harbour sediment-transport modelling discharges fine silt from the **NOS** (c = 10) subcatchment.

Since the sediment discharged from the catchment is fine silt (section 3.2) and the model simulations are of fine silt, we simply pick values for the sediment fate matrix out of Table 3-3, which gives:

- $F_{1,1}$ = 0.011, which is the fraction of the sediment (fine silt) discharged from the **HR** subcatchment (c = 1) that is deposited in **UI** (e = 1)
- $F_{2,1}$ = 0.011, which is the fraction of the sediment (fine silt) discharged from the **WR** subcatchment (c = 2) that is deposited in **UI** (e = 1)
- $F_{3,1}$ = 0.011, which is the fraction of the sediment (fine silt) discharged from the **LC** subcatchment (c = 3) that is deposited in **UI** (e = 1)
- $F_{4,1}$ = 0.118, which is the fraction of the sediment (fine silt) discharged from the **OC** subcatchment (c = 4) that is deposited in **UI** (e = 1)
- $F_{5,1}$ = 0.011, which is the fraction of the sediment (fine silt) discharged from the **NI** subcatchment (c = 5) that is deposited in **UI** (e = 1)
- $F_{6,1}$ = 0.272, which is the fraction of the sediment (fine silt) discharged from the **SI** subcatchment (c = 6) that is deposited in **UI** (e = 1)
- $F_{7,1}$ = 0.202, which is the fraction of the sediment (fine silt) discharged from the **NM** subcatchment (c = 7) that is deposited in **UI** (e = 1)
- $F_{9,1}$ = 0.000, which is the fraction of the sediment (fine silt) discharged from the **NON** subcatchment (c = 9) that is deposited in **UI** (e = 1)
- $F_{10,1}$ = 0.010, which is the fraction of the sediment (fine silt) discharged from the **NOS** subcatchment (c = 10) that is deposited in **UI** (e = 1)

Furthermore, we assume that no sediment from either the **SM** or **SO** subcatchments is deposited in **UI** (i.e., $F_{8,1} = F_{11,1}$ = 0). This makes little difference to the results since, in the case of the former, the sediment load is very small compared to the rest of the reporting zones, and in the case of the latter, the sediment load is in fact zero (Table 3-2).

Applying these values for the sediment fate matrix to the catchment sediment runoffs given in Table 3-2 accounts for about one quarter (23%) of the catchment sediment that we estimate deposits in **UI** each year. That is, D_1 = $\sum_{c=1}^{11} L_c F_{c,1}$ = 2,724 t of catchment sediment, which is about 23% of the required 11,927 t.

This is an encouraging result given that the model simulations on which our choices for $F_{c,1}$ are based are quite limited.

To deliver the required amount of fine silt to **UI** we increase $F_{c,1}$, c = 1, 2, 3 and 5 (sediment from the **HR**, **WR**, **LC** and **NI** subcatchments, delivered by the Hatea River in the harbour model simulations). We do this because the modelled values $F_{c,1}$, c = 1, 2, 3 and 5 are rather small relative to $F_{4,1}$ (sediment from the **OC** subcatchment, delivered by the Otaika River in the harbour model simulations) and $F_{6,1}$ (sediment from the **SI** subcatchment, delivered by the Mangapai River in the harbour model simulations), even though all of these rivers drain into the upper harbour. Also, the CSSI data indicate that sediment from the Hatea River is a dominant source of sediment deposited in

UI (see Figure 3-5). We also adjust $F_{4,1}$ and $F_{6,1}$ upwards slightly to come more in line with the adjusted values $F_{c,1}$, c = 1, 2, 3 and 5.

The final values for $F_{c,1}$ are given in Table 3-4. A greater fraction of the sediment from the **SI** subcatchment is retained in **UI**, which seems reasonable since the Hatea River (which drains the **HR**, **WR**, **LC** and **NI** subcatchments) and the Otaika River (which drains the **OC** subcatchment) discharge closest to the outlet from the upper harbour to middle harbour. Note, also, that a considerable fraction of the sediment from subcatchment **NM**, which discharges through the Waikaraka Stream into the middle harbour in the harbour model simulations, gets transported into and deposited in the upper harbour.

Table 3-4: Values for the sediment fate matrix, depositional basin UI (e = 1).

	Subcatchment										
	HR	WR	LC	OC	NI	SI	NM	SM	NON	NOS	SO
c	1	2	3	4	5	6	7	8	9	10	11
$F_{c,1}$	0.426	0.426	0.426	0.414	0.426	0.545	0.202	0.000	0.000	0.010	0.000

3.4.2 Depositional Basin PB (e = 2)

Rearranging equation (2) and inserting the data in Table 3-1 (A_2 = 3,500,000 m^2, ρ_2 = 1.25 t/m^3, S_2 = 2.5 mm/y) yields $D_2 + M_2$ = 10,938 t of sediment of catchment and marine origin depositing per year in the **PB** basin.

Figure 3-8 suggests that about 50% of the sediment depositing in Parua Bay is attributable to the Calliope Bay source, which is representative of "coastal sediment". Accordingly, we assume that 50% of the 10,938 t of sediment depositing in **PB** is of marine origin. Therefore M_2 = 5,469 t and D_2 = 5,469 t.

Again, since the sediment discharged from the catchment is fine silt (section 3.2) and the model simulations are of fine silt, we simply pick values for the sediment fate matrix out of Table 3-3, and we again assume that no sediment from either the **SM** or **SO** subcatchments is deposited in **PB** (i.e., $F_{8,2} = F_{11,2}$ = 0). As noted previously, this makes little difference to the results since, in the case of the former, the sediment load is very small compared to the rest of the reporting zones, and in the case of the latter, the sediment load is in fact zero (Table 3-2).

Applying these values for the sediment fate matrix to the catchment sediment runoffs given in Table 3-2 accounts for about 57% (3,137 t) of the catchment sediment that we estimate deposits in **PB** each year. Again, this is an encouraging result given that the model simulations on which our choices for $F_{c,2}$ are based are quite limited.

We now make the following adjustments to deliver the required amount of fine silt to **PB**.

- We consider a value of 1 for $F_{9,2}$ (the fraction of sediment from **NON** subcatchment that discharges into **PB** depositional basin) calculated from the harbour modelling to be extremely unlikely, even though Kohinui Stream (drains **NON**) discharges at the head of Parua Bay (depositional basin **PB**) in the model. Accordingly, we arbitrarily reduce $F_{9,2}$ to 0.6 to allow some sediment from **NON** to escape from **PB** into the wider harbour.
- With that reduction in $F_{9,2}$ we are now simply adjust every other value of $F_{c,2}$ upwards by a factor of about 2 to achieve the necessary fine silt deposition in **PB**.

The final values for $F_{c,2}$ are given in Table 3-5.

Table 3-5: Values for the sediment fate matrix, depositional basin PB (e = 2).

	Subcatchment										
	HR	WR	LC	OC	NI	SI	NM	SM	NON	NOS	SO
c	1	2	3	4	5	6	7	8	9	10	11
$F_{c,2}$	0.150	0.150	0.150	0.131	0.150	0.137	0.300	0.000	0.600	0.200	0.000

We note that subcatchment **NON**, which drains directly into the **PB** depositional basin, deposits the largest fraction of its sediment load.

3.4.3 Depositional Basin **MB** (e = 3)

Rearranging equation (2) and inserting the data in Table 3-1 (A_3 = 518,900 m^2, ρ_3 = 1.00 t/m^3, S_3 = 3.1 mm/y) yields $D_3 + M_3$ = 1609 t of sediment of catchment and marine origin depositing per year in the **MB** basin.

Figure 3-8 suggests that about 40% of the sediment depositing in Munro Bay is attributable to the Calliope Bay source, which is representative of “coastal sediment”. Accordingly, we assume that 40% of the 1609 t of sediment depositing in **MB** is of marine origin. Therefore M_3 = 644 t and D_3 = 965 t.

As before, since the sediment discharged from the catchment is fine silt (section 3.2) and the model simulations are of fine silt, we simply pick values for the sediment fate matrix out of Table 3-3, and we again assume that no sediment from either the **SM** or **SO** subcatchments is deposited in **MB** (i.e., $F_{8,3} = F_{11,3}$ = 0).

Applying these values for the sediment fate matrix to the catchment sediment runoffs given in Table 3-2 accounts for about 54% of the catchment sediment that we estimate deposits in **MB** each year (522 t, compared to 965 t required).

To deliver the required amount of fine silt to **MB** we simply increase all values of $F_{c,3}$ by about a factor of two. The final values for $F_{c,3}$ are given in Table 3-6.

We note that subcatchment **NOS**, which drains directly into the **MB** depositional basin, deposits the largest fraction of its sediment load.

Table 3-6: Values for the sediment fate matrix, depositional basin MB (e = 3).

	Subcatchment										
	HR	WR	LC	OC	NI	SI	NM	SM	NON	NOS	SO
c	1	2	3	4	5	6	7	8	9	10	11
$F_{c,3}$	0.013	0.013	0.013	0.008	0.013	0.006	0.004	0.000	0.080	0.754	0.000

3.4.4 Depositional Basin **NS** (e = 4)

Rearranging equation (2) and inserting the data in Table 3-1 (A_4 = 1,459,000 m^2, ρ_4 = 1.25 t/m^3, S_4 = 1 mm/y) yields $D_4 + M_4$ = 1,824 t of sediment of catchment and marine origin depositing per year in the **NS** basin.

Figure 3-8 suggests that about 10% of the sediment depositing in the **NS** basin is attributable to the Calliope Bay source, which is representative of “coastal sediment”. Accordingly, we assume that 10% of the 1,824 t of sediment depositing in **NS** is of marine origin. Therefore M_4 = 183 t and D_4 = 1,641 t.

As before, since the sediment discharged from the catchment is fine silt (section 3.2) and the model simulations are of fine silt, we simply pick values for the sediment fate matrix out of Table 3-3, and we again assume that no sediment from either the **SM** or **SO** subcatchments is deposited in **NS** (i.e., $F_{8,4} = F_{11,4} = 0$).

Applying these values for the sediment fate matrix to the catchment sediment runoffs given in Table 3-2 accounts for about 32% of the catchment sediment that we estimate deposits in **NS** each year.

To deliver the required amount of fine silt to **NS** we increase $F_{7,4}$ from the very small value calculated from the harbour modelling (< 0.000, to 3 decimal places) to a value of 0.2, where $F_{7,4}$ is the fraction of sediment from the subcatchment (**NM**) that discharges into the head of depositional basin **NS**. (**NM** discharges into the head of **NS** through Waikaraka Stream in the harbour modelling.) We take this action because it seems very unlikely that virtually no sediment from **NM** would deposit in **NS**, given their physical arrangement. The final values for $F_{c,4}$ are given in Table 3-7. We note that subcatchment **NM**, which drains directly into the **NS** depositional basin, deposits the largest fraction of its sediment load.

Table 3-7: Values for the sediment fate matrix, depositional basin NS (e = 4).

	Subcatchment										
	HR	WR	LC	OC	NI	SI	NM	SM	NON	NOS	SO
c	1	2	3	4	5	6	7	8	9	10	11
$F_{c,4}$	0.040	0.040	0.040	0.037	0.040	0.056	0.200	0.000	0.000	0.000	0.000

4 Summary

The annual deposition rate in depositional basin **UI** (e = 1) is given by

$$S_1 = \frac{(\sum_{c=1}^{11} L_c F_{c,1}) + M_1}{\rho_1 A_1 \Gamma} \quad (4)$$

where $F_{c,1}$ is given in Table 3-4, L_c is given in Table 3-2, ρ_1 and A_1 are given in Table 3-1 and M_1 = 628 t.

- We commented in section 3.4.1 on the relative amounts of sediment from the **HR**, **WR**, **LC**, **OC**, **NI** and **SI** subcatchments, all of which drain into the upper harbour, and the **NM** subcatchment, which drains into the middle harbour.

The annual deposition rate in depositional basin **PB** (e = 2) is given by

$$S_2 = \frac{(\sum_{c=1}^{11} L_c F_{c,2}) + M_2}{\rho_2 A_2 \Gamma} \quad (5)$$

where $F_{c,2}$ is given in Table 3-5, L_c is given in Table 3-2, ρ_2 and A_2 are given in Table 3-1 and M_2 = 5,469 t.

- We noted in section 3.4.2 that, for depositional basin **PB**, which is in the lower harbour, subcatchment **NON**, which drains directly into the **PB** depositional basin, deposits the largest fraction of its sediment load.

The annual deposition rate in depositional basin **MB** (e = 3) is given by

$$S_3 = \frac{(\sum_{c=1}^{11} L_c F_{c,3}) + M_3}{\rho_3 A_3 \Gamma} \quad (6)$$

where $F_{c,3}$ is given in Table 3-6, L_c is given in Table 3-2, ρ_3 and A_3 are given in Table 3-1 and M_3 = 644 t.

- We noted in section 3.4.3 that, for depositional basin **MB**, which is in the lower harbour, subcatchment **NOS**, which drains directly into the **MB** depositional basin, deposits the largest fraction of its sediment load.

The annual deposition rate in depositional basin **NS** (e = 4) is given by

$$S_4 = \frac{(\sum_{c=1}^{11} L_c F_{c,4}) + M_4}{\rho_4 A_4 \Gamma} \qquad (7)$$

where $F_{c,4}$ is given in Table 3-7, L_c is given in Table 3-2, ρ_4 and A_4 are given in Table 3-1 and M_4 = 183 t.

- We noted in section 3.4.4 that, for depositional basin **NS**, which is in the middle harbour, subcatchment **NM**, which drains directly into the **NM** depositional basin, deposits the largest fraction of its sediment load.

5 Discussion

Inserting the subcatchment sediment loads L_c given in Table 3-2 into equations (4) – (7) will yield the sedimentation rates given in Table 3-1. Equations (4) – (7) may be used to predict the change in sedimentation rate resulting from either a decrease (for example, because of mitigation) or an increase in subcatchment sediment loads. Table 3-2 shows how SedNetNZ sediment loads distributed by reporting zone equate to subcatchment loads.

Table 5-1 shows the origin by subcatchment of the mass of sediment deposited in each depositional basin.

Table 5-1: Mass (t) of sediment deposited per year in each depositional basin originating from each subcatchment source.

Depositional basin	Subcatchment										
	HR	WR	LC	OC	NI	SI	NM	SM	NON	NOS	SO
UI	1,910	2,102	442	4,664	913	1,320	595	0	0	8	0
PB	672	739	156	1,469	321	331	883	0	742	156	0
MB	57	62	13	92	27	14	13	0	99	589	0
NS	177	195	41	419	85	135	589	0	0	0	0

- Sedimentation in depositional basin **UI** in the upper harbour is dominated by sediment from catchments that drain into the upper harbour. The subcatchments drained by the Hatea River (**HR**, **WR**, **LC** and **NI**) together deposit the largest mass of sediment. The **OC** (drained by Otaika River) and **SI** (drained by Mangapai River) subcatchments deposit the next largest masses of sediment. This is consistent with the CSSI results of S2013 that show sedimentation in the upper harbour to be dominated by sediments from the Hatea River catchment.

- For depositional basin **PB**, which is in the lower harbour, subcatchments that drain to the upper harbour deposit the largest mass of sediment. This shows the widespread influence of the rivers that drain to the upper harbour. S2013 noted that export of sediments from the upper harbour has increased as the upper harbour has infilled. Depositional basin **PB** also deposits sediments from the adjacent subcatchment **NON** and from **NM**, immediately to the north, and **NOS**, immediately to the south.

- For depositional basin **MB**, which is in the lower harbour, the adjacent subcatchment (**NOS**) deposits the largest mass of sediment.
- For depositional basin **NS**, which is in the middle harbour, subcatchments that drain to the upper harbour deposit the largest mass of sediment. This shows the widespread influence of the rivers that drain to the upper harbour. S2013 noted that export of sediments from the upper harbour has increased as the upper harbour has infilled. Depositional basin **NS** also deposits sediments from the adjacent subcatchment **NM**.

The initial values for the sediment fate matrix were drawn from the results of the harbour sediment-transport modelling. The initial values were tested by looking at how much they delivered of the sediment required to reproduce the present-day measured sedimentation rates (in one case the present-day sedimentation rate was estimated, not measured). Over all four depositional basins, one quarter to one half of the necessary sediment was delivered. We see these results as encouraging, since a factor-of-10 variation between predictions and measurements of marine sediment transport is more the norm. The model simulations on which the initial estimates of the sediment fate matrix were based are quite limited. Most notably, the model does not simulate the transport of sediment between rainstorm events, when waves and currents can redistribute sediments that are deposited in the aftermath of rainstorms. The initial values of the sediment fate matrix were subsequently altered to deliver just the right amount of sediment to each depositional basin; that is, the catchment sediment runoff has been matched to the known (in one case, estimated) sedimentation rates. After the adjustments, 56% of the total catchment sediment runoff is deposited in the four depositional basins. The remainder is not accounted for in the model: it may be lost to the coastal ocean or it may be deposited elsewhere in the harbour. The final adjustments to the sediment fate matrix have been kept as simple as possible (mainly, multiply all the values uniformly by the same factor) unless it was felt there was a good physical reason to do differently (e.g., arbitrarily force more sediment from the adjacent subcatchment out of Parua Bay), or data indicated a change was justified (e.g., retain more sediment from the Hatea River in the upper harbour based on CSSI source-tracking data). Hence, the budget has ultimately been fitted to data, but it still rests on a “process” foundation.

Finally, referring to Figure 5-1, which is the isopleth map of percentage mud (by weight) in the surficial sediments of Whangarei Harbour produced by Millar (1980), we note that the upper harbour bed sediments contain a considerable proportion of “mud”. Seabed texture results from *in situ* vertical mixing as well as deposition of sediments from sources external to the location in question. Although catchment sediments may be deposited on the surface of the seabed during events, they subsequently are mixed down into the “pre-existing” sediments after the original deposition event by physical forces (waves and currents) and the actions of bioturbating organisms. In this way, the pre-existing bed sediment can also be thought of as a source of sediment, in that it is brought up, post-deposition, into the new surface layer. Consider, for instance, the deposition of a layer of silt from the catchment on a bed of marine sand. Ultimately, after some period of vertical mixing, the surface layer will be slightly muddier than the pre-existing marine sand, and slightly sandier than the deposited silt from the catchment. In this way the texture of the seabed evolves. The sediment budget that we have developed herein does not account for these kinds of processes, and therefore cannot explain the seabed texture. Conversely, observations of seabed texture cannot necessarily be used to identify flaws in the harbour sediment budget. The harbour sediment budget could be expanded to address the seabed texture by including information on vertical mixing processes and pre-existing seabed sediments; however, this is beyond the scope of this project.

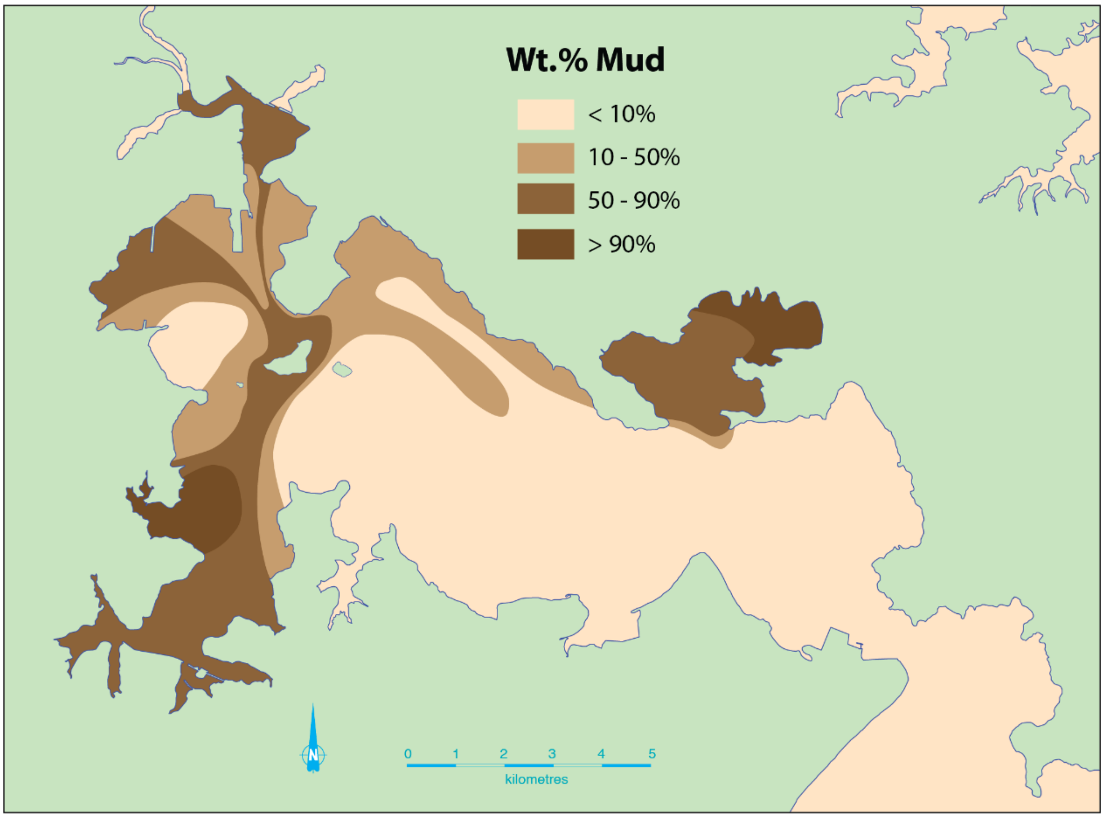

Figure 5-1: Isopleth map of the percentage mud (by weight) in the surficial sediments of Whangarei Harbour (1978). Reproduced from Swales et al. (2013), who in turn reproduced it from Millar (1980) with permission from the Earth and Ocean Sciences Department, University of Waikato.

6 References

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