Managing Sediment and *E. coli* in the Whangarei Harbour Catchment

MPI Technical Paper No: 2016/67

Prepared for the Ministry for Primary Industries by:
Jane White (Ministry for Primary Industries)
Adam Daigneault and John Dymond (Landcare Research New Zealand)
Malcolm Green, Chris Palliser, Sandy Elliot and Chris Tanner (National Institute of Water and Atmospheric Research)

ISBN No: 978-1-77665-389-8 (online)
ISSN No: 2253-3923 (online)

March 2016

New Zealand Government

Growing and Protecting New Zealand

Disclaimer

Requests for further copies should be directed to:

Publications Logistics Officer
Ministry for Primary Industries
PO Box 2526
WELLINGTON 6140

Email: brand@mpi.govt.nz
Telephone: 0800 00 83 33
Facsimile: 04-894 0300

This publication is also available on the Ministry for Primary Industries website at http://www.mpi.govt.nz/news-and-resources/publications/

Acknowledgements

The Ministry for Primary Industries would like to acknowledge the contributions of the following people:

- Darryl Jones, Ben Tait, Duncan Kervell, Dale Hensen, Jean-Charles Perquin and Richard Griffiths (Northland Regional Council)
- Professor Graeme Doole (Economist, University of Waikato)
- Darran Austin (Ministry for Primary Industries Technical Advisor)
- Angela Bell (Ministry for Primary Industries)
- Mike Hayward (MPI Manager, Environmental Economics Unit).

We would also like to thank Vera Power and her team at the Ministry for the Environment for their technical advice and feedback.

Contents

Page

Acknowledgements **i**

Foreword **1**

Executive summary **2**
1.1 The Whangarei harbour Catchment 2
1.2 Managing sediment and *E. coli* 2
1.3 Whangarei harbour catchment modelling 4
1.4 Policy scenarios 5
1.5 Baseline data 5
1.6 Results of the analysis 6
1.7 Limitations of the study 7

2 Introduction **9**
2.1 Whangarei Harbour catchment 9
2.2 Overview of the study 11

3 Determining sediment and *E. coli* attributes **14**
3.1 National Policy Statement for Freshwater Management 14
3.2 Attributes for the Whangarei Harbour study 14

4 Whangarei Harbour catchment sediment modelling **21**
4.1 Sediment loads in the Whangarei Harbour catchment 21
4.2 Data 26
4.3 Changes in attributes from a change in river sediment load 33

5 Whangarei Harbour catchment *E. coli* modelling **37**
5.1 Methodology 38
5.2 Results 44

6 Whangarei Harbour sediment budget **51**
6.1 Theory 51
6.2 Construction of the sediment budget for the Whangarei Harbour 52
6.3 Estimation of the sediment fate matrix 61
6.4 Summary of the harbour sediment budget 65
6.5 Discussion of the harbour sediment budget 66

7 Whangarei Harbour catchment economic modelling **69**
7.1 Methodology 69
7.2 Policy scenarios modelled 78
7.3 Results of the scenario analysis 80
7.4 Scenario-specific findings 86
7.5 Attribute estimates 93

8 Limitations **100**

9 Summary and conclusions **102**

10 Glossary **104**

11 References **107**

Appendix 1: Derivation of turbidity percentiles from flow percentiles **110**

Appendix 2: April 2015 workshop notes: mitigations from sediment and *E. coli* in the Whangarei Harbour catchment **111**

Appendix 3: Wetland mitigation assumptions **115**

Appendix 4: Key baseline estimates by sub-catchment **117**

Appendix 5: Key scenario estimates by sub-catchment **120**

Appendix 6: Sensitivity analysis for lower effectiveness rates **138**

List of Figures

Page

Figure 1: Northland and the Whangarei Harbour catchment 9
Figure 2: Land use in the Whangarei Harbour catchment 10
Figure 3: Proportion of land use area in the Whangarei Harbour catchment 11
Figure 4: Catchment net farm revenue 11
Figure 5: Components of the Whangarei Harbour study 13
Figure 6: Suspended sediment concentration and visual clarity and euphotic depth in the Hātea River (50 percentile) 18
Figure 7: Example of relationship between suspended-sediment concentration and river flow and clarity 19
Figure 8: Embeddedness and the sediment concentration rating curve 20
Figure 9: Land cover in the Whangarei Harbour catchment 22
Figure 10: Highly erodible land in the Whangarei Harbour catchment 22
Figure 11: REC2 sub-catchments for which sediment budgets are constructed 23
Figure 12: Mean total erosion of all processes (landsliding, earthflow, gully, surficial, net bank erosion and floodplain deposition) as modelled by SedNetNZ for each REC2 sub-catchment in the Whangarei Harbour catchment 23
Figure 13: Reporting zones in the Whangarei Harbour catchment and current sediment loads 24
Figure 14: Total sediment load by stream reach in the Whangarei Harbour catchment (tonnes per hectare per year) 25
Figure 15: Total landmass sediment load by stream reach in the Whangarei Harbour catchment (tonnes per hectare per year) 25
Figure 16: Total streambank sediment by stream reach in the Whangarei Harbour catchment (tonnes per hectare per year) 26
Figure 17: Time distribution of water discharge in the Hātea River at Whareora Road (1986–2014) 27
Figure 18: Time distribution of water discharge in the Waiarohia River at Lovers Lane 28
Figure 19: Time distribution of water discharge in the Otaika River at Kay (2011—2015) 28
Figure 20: Log-log plot of turbidity versus flow for the Hātea River at Whareora Road 29
Figure 21: Log-log plot of turbidity versus flow for the Waiarohia Stream at Lovers Lane 29
Figure 22: Log-log plot of turbidity versus flow for the Otaika River at Kay 29

Figure 23: Log-log plot of water clarity versus turbidity for the Hātea River at Whareora Road 30
Figure 24: Log-log plot of water clarity versus turbidity for the Waiarohia Stream at Lovers Lane 30
Figure 25: Log-log plot of water clarity versus turbidity for the Otaika River at Kay 31
Figure 26: Log-log plot of suspended sediment concentration versus turbidity for the Hātea River at Whareora Road 32
Figure 27: Log-log plot of suspended sediment concentration versus turbidity for the Waiarohia Stream at Lovers Lane 32
Figure 28: Log-log plot of suspended sediment concentration versus turbidity for the Otaika River at Kay 32
Figure 29: Whangarei Harbour catchment showing streams of order ≥ 3, lakes, land use, point sources and nodes of importance 37
Figure 30: Measured versus predicted *E. coli* loads for the five calibration sites in the Whangarei Harbour catchment 44
Figure 31: Measured versus predicted *E. coli* yields for the five calibration sites in the Whangarei Harbour catchment 45
Figure 32: *E. coli* load into the Whangarei Harbour by reach (peta *E. coli*) 47
Figure 33: Source of *E. coli* into the Whangarei Harbour 47
Figure 34: Total *E. coli* loads by reach at the freshwater nodes of importance (peta *E. coli*) 48
Figure 35: Source of *E. coli* loads in freshwater environments at the nodes of importance 49
Figure 36: Annual median *E. coli* concentrations (colony forming units per 100 millilitres) 49
Figure 37: 95th percentile of *E. coli* concentrations (colony forming units per 100 millilitres) 50
Figure 38: Summary of the nomenclature used in the Whangarei Harbour sediment budget 52
Figure 39: Location map, including the locations of the three long-term mud sinks east of Onerahi Peninsula (identified by Swales et al, 2013) 53
Figure 40: Upper harbour unvegetated intertidal flats defined by Swales et al (2013) (this is the UI depositional basin) 54
Figure 41: Catchment reporting zones used in the SedNetNZ model 56
Figure 42: Percentage of Hātea River catchment sediments in surface layer (top 2 centimetres) of harbour sediments 58
Figure 43: Percentage of Otaika River catchment sediments in surface layer (top 2 centimetres) of harbour sediments 58
Figure 44: Percentage of Mangapai River catchment sediments in surface layer (top 2 centimetres) of harbour sediments 59
Figure 45: Percentage of Calliope Bay sediments in surface layer (top 2 centimetres) of harbour sediments 59
Figure 46: Deposition of fine silt discharged from the Hātea, Otaika and Mangapai rivers (combined) under freshwater runoff associated with a one-year ARI storm 60
Figure 47: Isopleth map of the percentage of mud (by weight) in the surficial sediments of Whangarei Harbour (1978) 68
Figure 48: Baseline net revenue ($ per hectare per year) 73
Figure 49: Baseline annual-average sedimentation rate for the four Whangarei Harbour depositional basins 75
Figure 50: Annual mitigation costs ($ per hectare) for Whangarei Harbour catchment landowners, by area (hectares) 78
Figure 51: Area (hectares) of implemented mitigation options by scenario 83

Figure 52: Total annual cost ($ per year) by land use 84
Figure 53: Catchment sources of total sediment (tonnes per year) for each policy scenario 85
Figure 54: Spatial impacts of the current fencing scenario (percentage change from baseline) 86
Figure 55: Spatial impacts of the current farm plan scenario (percentage change from baseline) 87
Figure 56: Spatial impacts of fencing all pastoral streams (percentage change from baseline) 88
Figure 57: Spatial impacts of farm plans on all pasture land (percentage change from baseline) 88
Figure 58: Spatial impacts of wetlands on all land (percentage change from baseline) 89
Figure 59: Spatial impacts of the maximum mitigation on all land scenario (percentage change from baseline) 90
Figure 60: Spatial impacts of the harbour sediment reduction scenarios (percentage change from baseline) 91
Figure 61: Spatial impacts of the *E. coli* load reduction scenarios (percentage change from baseline) 92
Figure 62: Spatial impacts of the secondary contact recreation attribute state scenarios (percentage change from baseline) 93
Figure 63: Annual average sedimentation rate (millimetres per year) for four Whangarei Harbour depositional basins 97
Figure 64: Total net farm revenue ($ per year) 117
Figure 65: Total sediment (tonnes per year) 117
Figure 66: Hill/landmass sediment (tonnes per year) 118
Figure 67: Streambank sediment (tonnes per year) 118
Figure 68: Stream *E. coli* loads (peta *E. coli* per year) 118
Figure 69: Harbour *E. coli* loads (peta *E. coli* per year) 119
Figure 70: Spatial impacts for afforestation – all 121
Figure 71: Spatial impacts for afforestation – pasture 122
Figure 72: Spatial impacts for current fencing 123
Figure 73: Spatial impacts for current farm plans 124
Figure 74: Spatial impacts for wetlands - all 125
Figure 75: Spatial impacts for farm plan - all 126
Figure 76: Spatial impacts for fencing – all 127
Figure 77: Spatial impacts for maximum mitigation 128
Figure 78: Spatial impacts for harbour sediment – 20 percent 129
Figure 79: Spatial impacts for harbour sediment – 40 percent 130
Figure 80: Spatial impacts for harbour sediment – 60 percent 131
Figure 81: Spatial impacts for *E. coli* load – 20 percent 132
Figure 82: Spatial impacts for *E. coli* load – 40 percent 133
Figure 83: Spatial impacts for *E. coli* load – 60 percent 134
Figure 84: Spatial impacts for secondary contact “B” 135
Figure 85: Spatial impacts for secondary contact “A” 136

List of Tables

Page

Table 1: Attribute state for various *E. coli* concentrations (colony forming units per 100 millilitres) 15
Table 2: Relationship between suspended sediment concentration, turbidity, water clarity and euphotic depth in the Hātea River 18
Table 3: Comparison of measured sediment loads with those predicted by SedNetNZ 26
Table 4: Number of turbidity, water clarity and sediment concentration samples collected from the Hātea River, Waiarohia Stream and Otaika River near water-level recorders 27
Table 5: Flow percentiles in cubic metres per second of the Hātea, Waiarohia, and Otaika rivers. 28
Table 6: Turbidity percentiles (Nephelometric Turbidity Units) of the Hātea River, Waiarohia Stream and Otaika River 30
Table 7: Water clarity percentiles (metres) of the Hātea River, Waiarohia Stream and Otaika River 31
Table 8: Euphotic depth percentiles (metres) of the Hātea River, Waiarohia Stream and Otaika River 31
Table 9: Suspended sediment concentration percentiles (grams per cubic metre) of Hātea River, Waiarohia Stream and Otaika River 33
Table 10: Suspended sediment concentration percentiles (grams per cubic metres) of the Hātea River, Waiarohia Stream, and Otaika River after a reduction of sediment loads of 50 percent 34
Table 11: Estimation of the decrease in turbidity percentiles from reduced sediment loads 35
Table 12: Estimation of increased water clarity percentiles from reduced sediment loads 35
Table 13: Estimation of increased water clarity percentiles from a 50 percent reduction in sediment loads 36
Table 14: Estimation of increased euphotic depth percentiles from reduced sediment loads 36
Table 15: Estimation of increased euphotic depth percentiles from a 50 percent reduction in sediment loads 36
Table 16: Landuse (hectares) of Whangarei Harbour catchment sites classified as nodes of importance 38
Table 17: The mean annual load ratio of the upper 90 percent confidence interval to the lower 90 percent confidence interval for the River Water Quality Monitoring Network sites 40
Table 18: Calibration site data in Whangarei 41
Table 19: Re-optimisation of the yield coefficients and their standard errors 42
Table 20: Measured and predicted (or modelled) *E. coli* loads at the calibration sites in the Whangarei Harbour catchment 44
Table 21: Concentrations, yields and land uses for the 25 calibration sites 45
Table 22: Total predicted *E. coli* loads to the Whangarei Harbour 46
Table 23: *E. coli* concentrations at the freshwater nodes of importance 48
Table 24: Whangarei Harbour depositional basins included in the study 54
Table 25: Correspondence between SedNetNZ catchment reporting zones and sub-catchments, with mass of sediment discharged per year (L_c) into the harbour from each sub-catchment (sediment runoff is predicted by SedNetNZ for the present-day catchment land use) 57

Table 26: Fraction of fine silt discharged from Hātea River, Otaika River, Mangapai River, Waikaraka Stream, Kohinui Stream and Waitangata Stream 61
Table 27: Values for the sediment fate matrix, depositional basin UI ($\boldsymbol{e}$ = 1) 63
Table 28: Values for the sediment fate matrix, depositional basin PB ($\boldsymbol{e}$ = 2) 64
Table 29: Values for the sediment fate matrix, depositional basin MB ($\boldsymbol{e}$ = 3) 64
Table 30: Values for the sediment fate matrix, depositional basin NS ($\boldsymbol{e}$ = 4) 65
Table 31: Mass (tonnes) of sediment deposited per year in each depositional basin originating from each sub-catchment source 66
Table 32: Data sources for NZ-FARM's modelling of Whangarei Harbour catchment 71
Table 33: List of the main components of NZ-FARM Whangarei Harbour catchment 72
Table 34: Baseline freshwater sediment attribute estimates for three sites in the Whangarei Harbour catchment 74
Table 35: Environmental outputs at Whangarei Harbour catchment sites classified as nodes of importance 76
Table 36: Mitigation cost and effectiveness assumptions 77
Table 37: Whangarei Harbour catchment economic model scenarios 79
Table 38: Baseline area, farm earnings and environmental outputs by land use 80
Table 39: Key model scenario estimates for the entire Whangarei Harbour catchment 82
Table 40: Mean annual mitigation cost ($ per hectare per year)* 85
Table 41: Water clarity and euphotic depth at three Whangarei Harbour catchment sites 95
Table 42: Suspended sediment concentration and embeddedness at three Whangarei Harbour catchment sites 96
Table 43: Estimated *E. coli* concentrations (colony forming units per 100 millilitres) for the Whangarei Harbour catchment's nodes of importance 99
Table 44: Assumptions about wetland applicability and effectiveness 115
Table 45: Cost of wetland construction (all costs assume activities are permitted and do not incur resource consent charges) 116
Table 46: Mitigation effectiveness assumptions (as a percentage change in load relative to no mitigation) 138
Table 47: Scenario model sensitivity estimates 138

Foreword

Since 2009, the Government has been undertaking a comprehensive set of reforms to improve the way we manage fresh water in New Zealand. The reforms emphasise that local communities, through councils, are in the best position to make decisions about managing the fresh water in their region, taking local conditions, needs and aspirations into account.

In 2011, the Government implemented the National Policy Statement for Freshwater Management (NPS-FM). The NPS-FM provides national direction under the Resource Management Act 1991. It requires councils to set objectives and limits for fresh water quality and quantity in a way that is consistent around the country. The NPS-FM also requires councils to ensure land use and water are managed in an integrated way, and that iwi/hapū are involved in freshwater management and their values are reflected in decisions about the management of fresh water.

Policy development is now focusing on the implementation of the NPS-FM. This includes providing better information, tools and processes to support communities to make decisions with their councils about their local rivers and waterways. The aim to increase the value from more efficient use of freshwater, improve freshwater quality and ecosystem health, and ensure economic growth is based on good environmental practice.

To assist with this, the Ministry for Primary Industries and Ministry for the Environment have undertaken several environmental economic studies to build a strong evidence base to support decisions by central government, local government and community stakeholders. These studies demonstrate the link between environmental investment decisions and impacts, help to identify the most appropriate solutions for catchments to achieve particular objectives, challenge assumptions about the likely benefits of different approaches, and help to better target policies.

The economic studies focus on efficient allocation of water and nitrogen discharges, the benefits of transfer and trade, and cost-effective options for maintaining or improving water quality. This paper provides an analysis of mitigations to manage sediment and *E. coli* loads in the Whangarei Harbour catchment.

Executive summary

Sediment and *Escherichia coli* (*E. coli)* have been highlighted as important water quality challenges for the Northland region of New Zealand. The Ministry for Primary Industries (MPI) and the Ministry for the Environment (MfE) worked with the Northland Regional Council (NRC) to conduct a sediment and *E. coli* study in the Whangarei Harbour catchment as part of a joint venture between MPI, MfE and the council.

The study develops a model that integrates science and economics to assess the potential economic costs and environmental outcomes of meeting sediment and *E. coli* objectives and limits in freshwater and estuarine environments in the Whangarei Harbour catchment. Because some management practices, such as riparian planting and stock exclusion, are effective for managing both sediment and *E. coli*, economic modelling can help identify cost-efficient mitigation options and target locations to reduce the loads of both contaminants.

The study is also intended to be a useful case study to inform further work on sediment attributes for the National Objectives Framework (NOF), which sits within the National Policy Statement for Freshwater Management (NPS-FM). In addition, the study has a broader goal of helping further develop a national understanding of cost-effective management of sediment and *E. coli*, especially since both contaminants have typically received less analysis at the catchment scale, relative to nitrogen, and to a lesser extent, phosphorus.

The study has two main objectives:

1. Develop models to assess catchment sediment and *E. coli* loads and determine how to express these loads as freshwater attributes.
2. Incorporate the sediment and *E. coli* models developed in Objective 1 into a catchment economic model to identify cost-effective ways of managing sediment and *E. coli* loads in freshwater rivers and streams and in the Whangarei Harbour itself.

The National Institute of Water and Atmospheric Research (NIWA) was contracted to deliver the first objective and Landcare Research was contracted to deliver the second.

1.1 THE WHANGAREI HARBOUR CATCHMENT

The Whangarei Harbour is located on the south-east coast of Northland. The catchment covers approximately 300 square kilometres and drains through a number of rivers and streams to a large estuarine harbour of nearly 100 square kilometres. Population growth and associated changes in land use will place pressure on the harbour, particularly in the upper areas where water quality if often degraded.

Over a third of the land area comprises sheep and beef farms. A quarter of the catchment is native forest and 9 percent is urban.

1.2 MANAGING SEDIMENT AND *E. COLI*

The National Policy Statement for Freshwater Management (NPS-FM) 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 the life-supporting capacity, ecosystem processes and indigenous species (including their associated ecosystems) of freshwater. It also requires protection of (secondary) contact recreation.

The NPS-FM requires councils to establish freshwater objectives, limits and methods for different attributes that communities deem to be important for a particular catchment or region. The relationship between values, attributes and states in a range of freshwater environments are set out in the National Objectives Framework (NOF) within the NPS-FM. The NPS-FM does not set specific requirements for coastal zones but requires councils to consider the impact on coastal zones when setting freshwater objectives.

E. coli is used as an indicator of risk to human health from contact with fresh water in New Zealand. *E. coli* is a type of bacteria that normally lives in the intestines of people and animals. Most *E. coli* are harmless and are actually an important part of a healthy human intestinal tract. However, some *E. coli* are pathogenic, meaning they can cause illness such as diarrhoea or illness outside of the intestinal tract. The types of *E. coli* that can cause diarrhoea can be transmitted through contaminated water or food or through contact with animals or people.

E. coli is used as an indicator of freshwater faecal contamination as part of risk assessments of pathogen infection and is one of the attributes of the “human health” water quality value in the NOF.

There are currently no sediment attributes in the NPS-FM. Regional councils are able to establish their own attributes and limits and objectives if managing sediment is of particular importance to that community.

For this study, attributes for sediment and *E. coli* were selected that reflect values that are important to people in the Northland region. These values primarily relate to the ability to swim in rivers and in the harbour, secondary contact uses (such as wading or fishing) and other amenity or aesthetic values, such as the clarity of the water. The estimated impact on these attributes from applying a range of different mitigations was assessed through the catchment economic model.

1.2.1 *E. coli* attributes

The two NOF *E. coli* attributes are used to assess *E. coli* in freshwater environments in the Whangarei Harbour catchment. The *E. coli* median concentration is used for representing secondary contact in streams and rivers. This is an attribute in the National Objectives Framework (NOF). To meet the minimum required state, people should only be exposed to a moderate risk of getting sick (less than 5 percent risk) from activities with some immersion and some ingestion of water (such as wading and boating).

To represent the value that people obtain from being able to swim in rivers in the Whangarei catchment, the 95th percentile NOF target is used. For people to be able to swim in a water body, *E. coli* levels should be less than 540 *E. coli* per 100 millilitres at the 95th percentile (which means there is a less than 1 percent risk of getting sick from swimming).

Microbial loads in the upper harbour are also of concern to the council. For this study, it was decided that a terminal-reach[1] annual *E. coli* loading be used as a proxy for overall microbial contamination risk. This includes point source loadings. This is not a NOF target, but provides an indication of bacterial loads into the harbour. Changes to the *E. coli* load at the harbour reach are analysed for each of the policies that control sediment and *E. coli* loading to the harbour.

1.2.2 Sediment attributes

As there are no nationally established attributes for monitoring sediment, a workshop was held with experts to determine freshwater and estuary sediment attributes for assessment in

[1] At the location just before the river debouches into the harbour.

this study. The use of freshwater sediment attributes in this study are also informing the development of sediment attributes for the NOF.

It was decided to use an annual-average sedimentation rate (AASR) as the single estuary sediment attribute in the Whangarei study, defined as:

*Mass of sediment deposited per year/(settled-sediment density*area over which sediment deposits).*

The AASR is considered to be a good candidate for a master attribute that is indicative of a wide range of sediment effects in estuaries, including that the AASR is unambiguous, readily measurable (by, for example, repeat bathymetric surveys or sedimentation plates) and easy to relate to catchment sediment inputs (Green, 2013).

The following three attributes are used in the study to assess the impact of suspended fine sediment in freshwater bodies. These are:

- suspended sediment concentration: the ratio of the mass of dry sediment in a water–sediment mixture to the volume of the mixture;
- water clarity: the distance of water through which an object can be clearly seen;
- euphotic depth: the distance of water through which light travels and becomes attenuated to 1 percent of the surface light intensity. This distance defines the euphotic zone in which there is sufficient light for photosynthesis and periphyton and macrophytes to be sustained.

Embeddedness is used as an attribute for deposited fine sediment trapped in the channel gravel. Embeddedness is assumed to be equal to the suspended sediment concentration at the discharge when bedload transport stops, where that discharge is about one-quarter of the mean annual flood (Clausen and Plew, 2004).

1.3 WHANGAREI HARBOUR CATCHMENT MODELLING

NIWA provided estimates of baseline *E. coli* loads in the Whangarei Harbour catchment using the Catchment Land Use for Environmental Sustainability (CLUES) model, and Landcare Research provided estimates of baseline sediment loads in the catchment using SedNetNZ. A methodology for translating these loads into the various attributes outlined above was also provided to enable an assessment of the impact of different mitigations on these attributes in the catchment economic model.

A harbour sedimentation budget was produced by NIWA to show how catchment sediment loads deposit in four depositional basins in the harbour. The budget was used to assess the impact of different mitigations on the annual average sedimentation rate in the harbour.

1.3.1 Catchment economic model

The *E. coli* and sediment baseline loads, and the harbour sediment budget, were inputs into a catchment economic model that assessed the effect of the various mitigations on sediment and *E. coli* loads in rivers and streams in the Whangarei Harbour catchment and the Whangarei Harbour itself.

The catchment economic model is based on Landcare Research's economic land-use model, the New Zealand Forest and Agriculture Regional Model (NZ-FARM). NZ-FARM is designed for detailed modelling of land uses at a catchment scale. The Whangarei Harbour catchment version of NZ-FARM includes several farm- or parcel-level management options for managing sediment and *E. coli* loads. These include implementing farm plans, fencing streams and constructing wetlands.

The version of the model used for this study can track changes in land use, land management, agricultural production, and sediment and *E. coli* loads bv imposing policy options that range from having landowners implement specific mitigation practices to identifying the optimal mix of land management to meet a particular target. The model is parameterised such that responses to policy are not instantaneous but instead assume a response that landowners are likely to take over a 10-year period.

While the list of feasible farm management options is extensive, the study does not include all possible options to mitigate losses from diffuse sources into waterways. The results from NZ-FARM are reliant on input data (for example, farm budgets, mitigation costs and contaminant loss rates) from external sources and may vary if alternative data are used. NZ-FARM also does not account for the broader impacts of changes in land use and land management beyond the farm gate.

It is not intended that the catchment economic model define or analyse any specific policy or reduction target. Thus the scenarios presented in this report should be taken as illustrative examples of how the model works and can be used in future analyses, as opposed to a rigorous analysis of a proposed policy or rule change.

1.4 POLICY SCENARIOS

MPI and NRC met with experts to determine the range of mitigation scenarios to be included in the analysis. Fifteen different mitigation scenarios were modelled. The mitigations include (1) practice-based (or management) approaches, such as fencing streams for stock exclusion, farms plans or the use of wetlands; and (2) target-based (or environmental outcome) approaches that include reducing erosion to reach a harbour-wide sedimentation target or decreasing *E. coli* in important sites to achieve primary or secondary recreation targets.

The management action scenarios investigate the maximum amount of reductions that could be achieved when implementing certain mitigation options. The environmental outcome scenarios investigate the impact of setting a specific reduction target and then allowing landowners to collectively select the set of mitigation options that will meet the limit.

1.5 BASELINE DATA

Before conducting the analysis of mitigation scenarios, a baseline was established. The baseline assumes no sediment or *E. coli* mitigation practices or policies have been implemented (including existing farm plans or stream fencing).

Total net farm income from land-based operations with the current land-use mix is estimated at $16.6 million per year or $548 per hectare for all land and $964 per hectare for land that is currently earning revenue from farming and forestry. Total sediment load is almost 31 400 tonnes, of which more than 85 percent comes from landmass erosion. This is about 30 percent of the total sediment deposited into the Whangarei Harbour. The total stream and harbour *E. coli* loads are estimated to be 84 peta[2] and 293 peta per year, respectively.

[2] Peta = 10^{15} *E. coli*

1.6 RESULTS OF THE ANALYSIS

1.6.1 Catchment-wide results

The extent of possible reductions in contaminant loads is limited in this analysis because only 46 percent of the Whangarei Harbour catchment is in pasture, with a significant proportion classified as native or urban. This means management options that only target pastoral enterprises will not be enough to achieve large reductions in environmental contaminants.

Afforesting all land (including Whangarei city itself) if not a plausible scenario but was included to show the maximum possible reductions in sediment and *E. coli* loads that could be achieved. It provides a benchmark for assessing the other mitigation options. Afforesting all land would reduce sediment loads by 49 percent and *E. coli* loads by 73 percent. Even with this reduction, it would not be possible to meet the NPS-FM *E. coli* target for primary contact recreation, although many of the sites could achieve the secondary contact recreation target.

The choice of mitigations needs to be targeted to the particular land uses in the main areas of importance in a catchment. For the Whangarei Harbour catchment, the most cost-effective approach focuses effort where particular hotspots of sediment and *E. coli* occur. This is upstream of sites with important water quality objectives that use a combination of fencing, farm plans and wetlands, with landowners deciding on the optimal combination of mitigations for their farm.

In considering each mitigation on its own:

- Constructing wetlands and sediment ponds is estimated to be the most effective option (besides afforestation), because it is the only mitigation that can be applied to all land uses. It is also the only mitigation option that has a positive impact on the sediment attributes of water clarity and euphotic depth in all three measured sites in the catchment. However, co-ordination and cost constraints could limit uptake of this management option.
- Fencing all pasture has a limited effect on sediment loads, because only a small proportion of the catchment's sediment load comes from stream banks. As a result, the greatest impact of this management option is on *E. coli* loads in streams, which are estimated to be reduced by more than 50 percent relative to the baseline.
- Implementing farm plans aimed at reducing sediment from hotspots on pastoral farms also has a limited impact because most of the pasture in the catchment is not located at the top of the catchment where there are high levels of landmass erosion.

Catchment-wide policies that only target reductions in either *E. coli* or sediment can have a noticeable effect on reducing the non-targeted contaminant as well but not necessarily to the same degree. Therefore, mitigations that focus on simultaneously reducing both *E. coli* and sediment are likely to be the most cost-effective option. This also highlights that the specific location of these mitigations within the catchment can have an effect on other attributes that are not necessarily targeted by the policy.

1.6.2 Attribute impacts

A wide range of impacts to water clarity, euphotic depth and suspended sediment concentration are evident at the three sites where measurements could be taken in the Whangarei Harbour catchment. Changes in sediment loads were estimated to have a noticeable effect at the Ōtāika River site because it is surrounded by various pastoral and other land uses that could implement a range of mitigation practices.

Attributes in the Ōtāika sub-catchment are estimated to have the largest improvement because it is situated in a sub-catchment with a significant amount of sheep and beef farming. As a result, water clarity and euphotic depth could increase by as much as 77 percent and 35 percent respectively, if the maximum mitigation was put in place.

However, the two other sites were located in areas of the catchment mostly comprising native bush or urban land that produced minimal erosion. Thus, these sites only had estimated changes in the freshwater sediment attribute levels in the few scenarios where there was significant wetland mitigation in their vicinity.

Nearly all scenarios estimated a noticeable reduction in the harbour sediment attribute included in the Whangarei Harbour study, the AASR. Estimates varied widely across the four deposition basins, though, because they are all affected differently in terms of the amount of sediment they receive annually from both land and marine sources. Thus, the suggested "high" attribute state of one millimetre per year may not be achievable for all harbour basins.

Implementing mitigation practices in the Whangarei Harbour catchment can lead to reductions in *E. coli* concentration that allow many, and sometimes all, of the important sites in the catchment to reach at least the "B" band of 540 colony forming units (cfu) per 100 millilitres for secondary contact recreation (this is based on a median estimate). Seven of the 11 sites achieved the "A" band of 260 cfu per 100 millilitres using the median estimate if optimal combinations of fencing, farm plans and wetlands were used to try and reach the secondary contact "A" band target.

Achieving *E. coli* targets for primary contact recreation is not possible in the Whangarei Harbour catchment. Even if the catchment was completely covered in forest, it would not be possible to meet the NPS-FM target for primary contact recreation (a maximum of 540 cfu per 100 millilitres) in any of the 11 key sites. This target is based on 95th percentile measurements. Additional work is required to assess if there are other methods to estimate 95th percentile concentrations in the catchment, perhaps under different flow assumptions or time constraints (for example, only measure in the summer months when people swim).

1.7 LIMITATIONS OF THE STUDY

NZ-FARM has been developed to assess economic and environmental impacts over a wide range of land uses, but it does not account for all sectors of the economy. The economic land-use model should be used to provide insight on the relative impacts and trade-offs across a range of policy scenarios (for example, practice versus outcome-based targets), rather than for explicitly modelling the absolute impacts of a single policy scenario. Thus, it should be used to compare impacts across various scenarios or policy options. NZ-FARM also does not account for the broader impacts of changes in land use and land management beyond the farm gate.

The parameterisation of the model relies on biophysical and economic input data from several different sources. Therefore, the estimated impacts produced by NZ-FARM should be used in conjunction with other decision support tools and information not necessarily included in the model to evaluate the "best" approach to manage sediment and *E. coli* in the Whangarei Harbour catchment.

The model only includes data and mitigation practices for representative farms for the Whangarei Harbour catchment that were parameterised based on their physical characteristics (for example, land-use capability, slope and so on). It does not explicitly model the economic impacts on a specific farm in the catchment. As a result, some landowners in the catchment may actually face higher or lower costs than what are modelled using this representative farm approach.

The quality and depth of the economic analysis depend on the datasets and estimates provided by biophysical models like SedNetNZ and CLUES, farm budgeting data based on information published by MPI and industry groups, and spatial datasets such as maps depicting current land use and sub-catchments or water management zones. A range of assumptions were also made in the baseline estimates.

The model only includes management practices deemed feasible and likely to be implemented in a catchment as a result of *E. coli* and sediment reduction policies, given the current state of knowledge and technology available. It does not account for new and innovative mitigation options that might be developed in the future as a result of incentives created under the policy.

Each management practice included in the model is assumed to have a fixed relative rate of effectiveness for reducing sediment and *E. coli* loads (for example, 50 percent of baseline loads). In reality, the actual impact of a given practice is likely to vary, depending on where, when and how well the practice is implemented.

2 Introduction

Sediment has been highlighted as an important water quality challenge for the Northland region. Previous sediment studies indicate that sediment loads in Kaipara are substantially higher than other North Island estuaries while Whangarei is in the mid-range. Sub soils derived from streambank erosion, gullying and slips are major sources of sediments deposited in stream beds and at river deltas in the upper harbour. Native forest and pasture are the other primary sources of sediment. The contributions from pasture and sub soils are likely to reflect bank erosion from stock having direct access to streams rather than erosion from flat paddocks (Swales et al, 2013).

E. coli also presents a challenge in rivers. This affects the ability of people to safely swim in rivers and engage in fishing and other secondary contact recreation activities.

The Ministry for Primary Industries (MPI) and the Ministry for the Environment (MfE) worked with the Northland Regional Council (NRC) to conduct a sediment and *E. coli* study in the Whangarei Harbour catchment as part of a joint venture between MPI, MfE and the council.

Because some management practices exist, such as riparian planting and stock exclusion, that are effective for managing both sediment and *E. coli*, economic modelling can help identify the cost-efficient mitigation options and target locations to reduce the loads of both contaminants.

2.1 WHANGAREI HARBOUR CATCHMENT

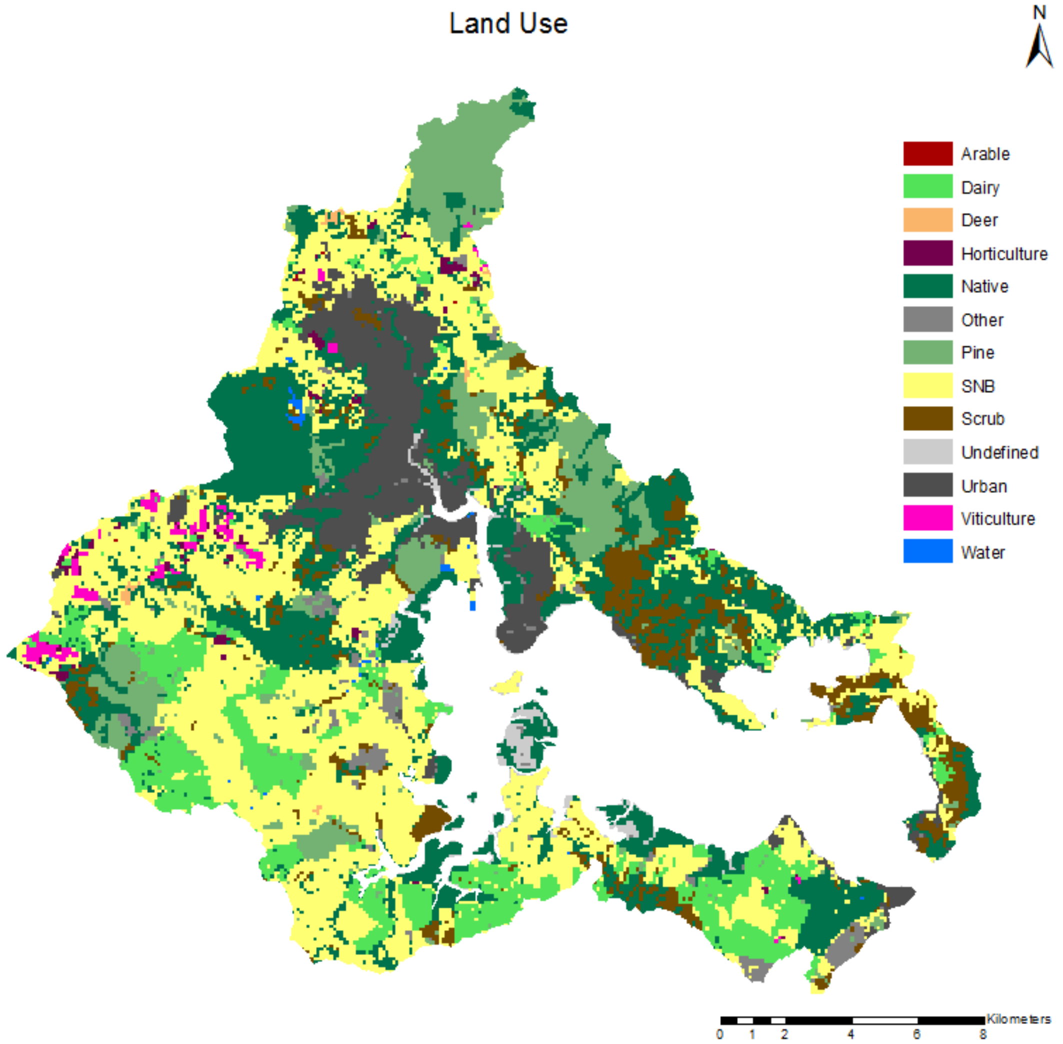
The Whangarei Harbour catchment is located on the south-east coast of Northland. The catchment covers approximately 300 square kilometres and drains through a number of rivers and streams to a large estuarine harbour of nearly 100 square kilometres. Population growth in the harbour catchment is increasing and will continue to do so. This growth and associated changes in land use will place pressure on the harbour, particularly in the upper areas where water quality is often degraded. Figure 1 shows the Whanagarei Harbour catchment within the Northland region.

Figure 1: Northland and the Whangarei Harbour catchment

Figure 2 and Figure 3 provide a graphical illustration of land use across the Whangarei Harbour catchment. Baseline land use areas for the catchment model are based on a 2011 GIS-based land use map created by Landcare Research using the latest information from Agribase and the NZ Land Cover Database version 2 (LCDBv2). Over a third of the land area comprises sheep and beef farms. A quarter of the catchment is native forest and 9 percent is urban.

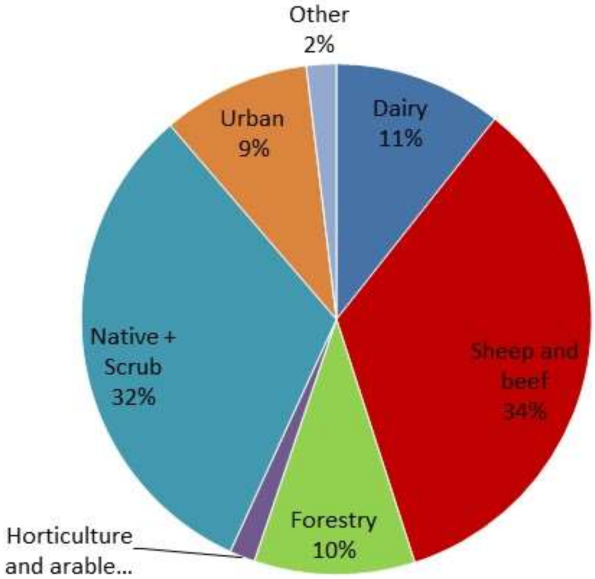
Note that because only 46 percent of the total catchment area is in pasture, some of the farm-based mitigation options explored in this study may not have a large effect compared to more rural catchments that are primarily grassland. This is the case for the Whangarei Harbour catchment, where a noticeable level of both *E. coli* and sediment are found to come from non-pastoral land uses.

Figure 2: Land use in the Whangarei Harbour catchment



Note: SNB = Sheep and beef

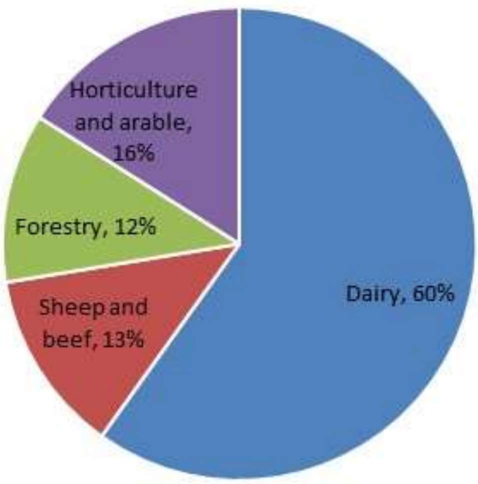
Figure 3: Proportion of land use area in the Whangarei Harbour catchment



SedNetNZ and SPARROW

Figure 4 shows the sources of net revenue in the catchment. Most of the catchment's revenue comes from the dairy industry.

Figure 4: Catchment net farm revenue



Source: New Zealand Forest and Agriculture Regional Model

2.2 OVERVIEW OF THE STUDY

The aim of the Whangarei Harbour sediment and *E. coli* study was to develop a model that integrates science and economics to assess the potential economic costs of meeting a variety of attribute states for sediment and *E. coli* in the Whangarei Harbour and freshwater environments that drain into the harbour.

The study is also intended to be a useful case study to inform further work on sediment attributes for the National Objectives Framework (NOF). In addition, the study has a broader goal of helping to further develop national understanding of cost-effective management of sediment and *E. coli*, especially since both contaminants have typically received less analysis at the catchment-scale, relative to nitrogen and, to a lesser extent, phosphorus.

The study has two main objectives:

1. Develop models to assess catchment sediment and *E. coli* loads and determine how to express these loads as freshwater attributes.
2. Incorporate the sediment and *E. coli* models developed in Objective 1 into a catchment economic model to identify cost-effective ways of managing sediment and *E. coli* loads in freshwater rivers and streams and in the Whangarei Harbour itself.

The study comprised five workstreams.

1. Attributes

This involved finalising the estuary and freshwater sediment attributes, and the freshwater and estuary *E. coli* attributes. The National Institute of Water and Atmospheric Research (NIWA) was contracted to deliver this component.

2. Whangarei Harbour catchment modelling

The workstream involved SedNetNZ sediment modelling and Catchment Land Use for Environmental Sustainability (*E. coli*) modelling to determine baseline sediment and *E. coli* loads in the Whangarei Harbour catchment. NIWA provided the *E. coli* modelling and Landcare Research the sediment modelling.

3. Whangarei Harbour sediment budget

This involved the development of an annual-average sediment budget for the Whangarei Harbour. NIWA was contracted to deliver this component.

4. Mitigation costs and efficiencies

A workshop was held to agree on and specify mitigation (sediment and *E. coli*) costs and efficiencies to be included in the economic model.

5. Catchment economic model

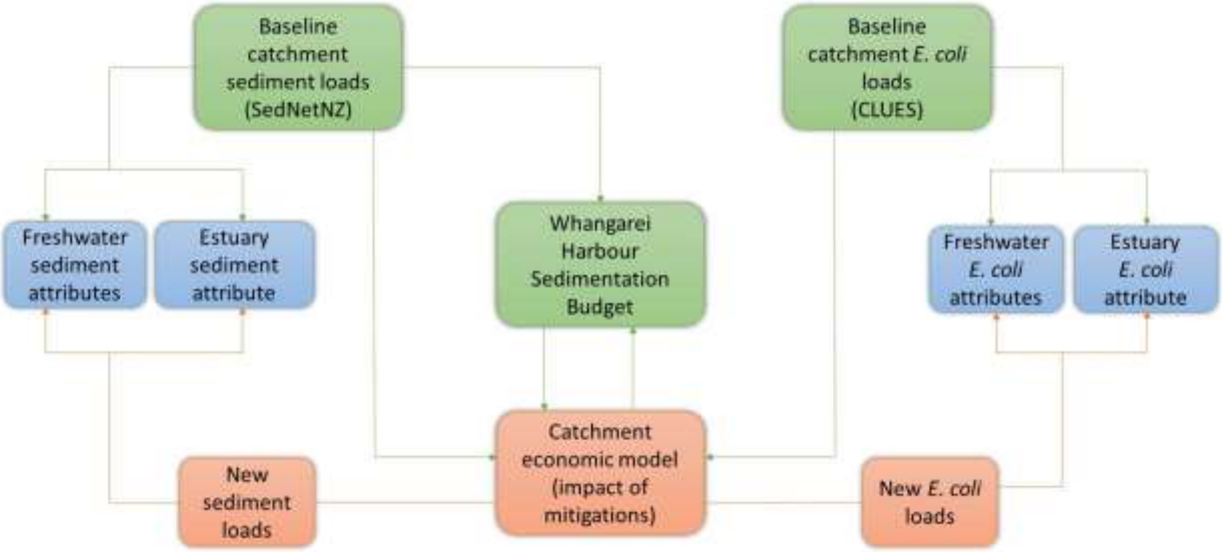
The *E. coli* and sediment baseline loads and the harbour sediment budget were inputs into a catchment economic model that assessed the impact of various mitigations on sediment and *E. coli* loads in rivers and streams in the Whangarei Harbour catchment and the Whangarei Harbour itself.

The catchment economic model is based on Landcare Research's economic land-use model, the New Zealand Forest and Agriculture Regional Model (NZ-FARM). NZ-FARM is designed for detailed modelling of land uses at a catchment scale. The Whangarei Harbour catchment version of NZ-FARM includes several farm- or parcel-level management options for managing sediment and *E. coli* loads. These include implementing farm plans, fencing streams and constructing wetlands.

While the list of feasible farm management options is extensive, the study does not include all possible options to mitigate losses from diffuse sources into waterways. The results from NZ-FARM are reliant on input data (for example, farm budgets, mitigation costs and contaminant loss rates) from external sources and may vary if alternative data are used. NZ-FARM also does not account for the broader impacts of changes in land use and land management beyond the farm gate.

Figure 5 shows the various components of the study and how they are linked.

Figure 5: Components of the Whangarei Harbour study



Note: CLUES = Catchment Land Use for Environmental Sustainability

3 Determining sediment and *E. coli* attributes

3.1 NATIONAL POLICY STATEMENT FOR FRESHWATER MANAGEMENT

The National Policy Statement for Freshwater Management (NPS-FM) 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 the life-supporting capacity, ecosystem processes and indigenous species of freshwater. It also requires protection of (secondary) contact recreation.

Regional councils are required to set freshwater objectives by 2025 that reflect national and local values; set flow, allocation and water quality limits to ensure freshwater objectives are achieved; address over-allocation; manage land use 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 relationships between values, attributes and states in a range of freshwater environments are codified in the NOF. Estuaries and coastal systems are specifically excluded from consideration in the NPS-FM, but they must be "given regard to" when setting limits for freshwater.

3.2 ATTRIBUTES FOR THE WHANGAREI HARBOUR STUDY

For this study, attributes for sediment and *E. coli* were selected to reflect values that are important to people in the Northland region. These values primarily relate to the ability to swim in rivers and in the harbour, secondary contact uses (such as wading or fishing) and other amenity or aesthetic values (such as the clarity of the water). The estimated impact on these attributes from applying a variety of different mitigations was assessed through the catchment economic model.

A significant challenge for both the NOF and the Whangarei Harbour study is to define attributes in ways that account for the natural variability of physical and ecological processes. This section outlines the attributes selected for inclusion in the Whangarei Harbour study.

3.2.1 *E. coli* attributes

The *E. coli* median concentration is used for representing secondary contact in streams and rivers. This is an attribute in the NOF. To meet the minimum required state, people should only be exposed to a moderate risk of getting sick (less than 5 percent risk) from activities with some immersion and some ingestion of water (such as wading and boating).

To represent the value that people obtain from being able to swim in rivers in the Whangarei catchment, the 95th percentile NOF target is used. For people to be able to swim in a water body, *E. coli* levels should be less than 540 *E. coli* per 100 millilitres at the 95th percentile (which means there is a less than 1 percent risk of getting sick from swimming).

As shown in Table 1, an "A" attribute state for both primary and secondary contact recreation is when concentrations are less than or equal to 260 *E. coli* per 100 millilitres at respective percentiles, while the "B" state is for concentrations between 260 *E. coli* and 540 *E. coli* per 100 millilitres. Secondary contact also has a "C" state between 540 *E. coli* and 1000 *E. coli* per 100 millilitres at median flows. Any concentrations greater than the National Bottom Line of 1000 *E. coli* per 100 millilitres at median flows is considered a "D" state.

Table 1: Attribute state for various *E. coli* concentrations (colony forming units per 100 millilitres)

A	B	C	D
Less than or equal to 260	Between 260 and 540	Between 540 and 1000	Greater than 1000

For the estuary, a terminal-reach[3] annual *E. coli* loading is used as a proxy for overall microbial contamination risk in the upper harbour. This includes point source loadings. Changes to the *E. coli* load at the harbour reach are analysed for each of the policies that control sediment and *E. coli* loading to the harbour.

A more complete analysis would include Enterococci loading, which is related to marine bathing water quality, and possibly pathogens related to human health risks. However, suitable data or models were not available for estimating these loadings, nor were the resources available to run dynamic estuary models that would be required for quantitative microbial risk assessment.

3.2.2 Estuary sediment attributes

It is possible to distinguish between the effects on estuarine ecosystem health of deposited sediments and the effects of suspended sediments. For example, high concentrations of fine terrigenous-sediment particles suspended in the water column reduce the feeding efficiency of suspension-feeding bivalves and the visual water clarity and light penetration into the water column. Reductions in light penetration reduce the amount of light available for primary production, and reductions in visual clarity affect the ability of visual predators to feed.

Sediment deposition may exert direct effects on benthic biota through smothering and indirect effects by changing the nature of the seabed. The latter is typically manifested as a progressive muddying of the seabed, which is negatively correlated with species distribution, abundance and richness. Increased mud content of the seabed also affects ecosystem functioning and services, such as nutrient assimilation and remineralisation.

The natural temporal variability of suspended sediment in estuaries is considered to be an insurmountable obstacle, at this point, to formulating a suspended sediment attribute for use in this study. Even if certain conceptual issues were to be resolved, an event-scale catchment sediment model would need to be used to evaluate the attribute. The SedNetNZ catchment sediment model is an annual-average model, which prevents the evaluation of event-scale attributes. Event-scale models exist, but they are typically expensive to run.

Two good candidates for an attribute that is indicative of the effects of deposited sediment on estuarine ecosystem health are the mud content of the surface layer of the seabed, expressed as a percentage, and event sediment-deposition thickness (millilitres, with an associated frequency of occurrence).

The SedNetNZ model predicts annual-average terrigenous-sediment inputs to the Whangarei Harbour not sediment inputs during individual events. Therefore, it was not possible to evaluate event sediment deposition within the modelling framework of the study.

Assuming a bed-sediment mixing length and calculating the change in seabed mud content associated with the accumulation of fine terrigenous sediment would have provided a useful attribute that is directly indicative of the effects of deposited sediments. However, this also is outside the scope of the modelling undertaken as part of the project.

[3] At the location just before the river debouches into the harbour.

It was decided to use an annual-average sedimentation rate (AASR) as the single estuary sediment attribute in the Whangarei study, defined as:

*Mass of sediment deposited per year/(settled-sediment density*area over which sediment deposits)*.

Green (2013) showed how a catchment–estuary sediment budget could be manipulated to calculate catchment sediment load limits that will achieve a target AASR in an estuary. Green also discussed whether managing for just an AASR would reduce the broad spectrum of adverse sediment effects and deliver the types of environmental outcomes desired.

Green (2013) argued that one of the main advantages of managing to a simple parameter, such as an AASR, is it is relatively easy to measure and explain progress towards achievement. Since then, the concept of the "master attribute" has been advanced and gained traction. The idea is to choose a target for the master attribute, and then base the calculation of the catchment load limits on the master-attribute target. It is expected that a range of desired outcomes will be attained if the master-attribute target is achieved. The master attribute may function as the "headline" measure of progress, but the monitoring of a range of other attributes would still be required to demonstrate progress towards achieving environmental outcomes.

NIWA considered the AASR to be a good candidate for a master attribute that is indicative of a wide range of sediment effects in estuaries, including that the AASR is unambiguous, readily measurable (by, for example, repeat bathymetric surveys or sedimentation plates) and easy to relate to catchment sediment inputs. Furthermore, data are available on reference conditions (the AASR before catchment deforestation), and research being conducted at the University of Auckland and NIWA is in progress relating the AASR to ecological health.

Using the AASR as a sediment attribute might not work for every estuary. There will also probably be some upper limit to the percentage of the catchment sediment runoff that is exported to the sea above which the AASR would not be valid as a sediment attribute.

The AASR has been used as the single estuary sediment attribute in this study on the basis that it is reasonable to assume the AASR is indicative of a wide range of sediment effects in the Whangarei Harbour. If the percentage of sediment to the harbour is high then the choice of AASR as an estuary sediment attribute will be invalid. This assumption was tested in the construction of the Whangarei Harbour sediment budget, which found that around 55 percent of the total catchment sediment runoff is deposited in the four depositional basins analysed (see Section 6). This suggests the AASR is an appropriate attribute to assess sediment deposition in the Whangarei Harbour.

3.2.3 Freshwater sediment attributes

Fine sediment is a natural feature of rivers (Suttle et al, 2004). However, human activities, such as forest clearance and agriculture, have increased the amount of fine sediment delivered to rivers. Affected freshwater organisms include fish, benthic invertebrates and algae.

Overall, ecological effects of suspended fine sediment in streams and rivers have been less extensively researched than those of deposited fine sediment. Physical effects of suspended sediment include reduced visual water clarity and reduced light penetration (euphotic depth).

Deposited fine sediment can adversely affect benthic invertebrates, fish and benthic algae. Most streams running through pastoral land are affected by multiple stressors acting simultaneously, and recent research in New Zealand has shown that deposited fine sediment interacts with other agricultural stressors when affecting stream communities Townsend et al, 2008; Matthaei et al, 2010; Wagenhoff et al, 2011, 2012, 2013; Piggott et al, 2012, 2015a, 2015b; and Lange et al, 2014).

Interacting stressors include nutrient enrichment, flow reduction (due to water abstraction) and raised water temperature (due to the removal of shading riparian vegetation), and such interactions occur both for benthic invertebrates and benthic algae. However, because of the pervasiveness and strength of its effects, deposited fine sediment can be regarded as a "master stressor" for streams running through pastoral land in New Zealand: its effects are often negative in their own right, and interactions with other stressors make these effects even worse.

Sediment concentration

Sediment concentration, *s*, is defined as the ratio of the mass of dry sediment in a water–sediment mixture to the volume of the mixture. Common units are grams per cubic metre or milligrams per litre. It is commonly measured by weighing the sediment collected in a sample of surface water or a depth profile of water. Sediment concentration is highly variable, with high values during floods and low values during low flows. Therefore, its ecological impact is also variable.

The full distribution of suspended-sediment concentration (SSC) in a given river is typically obtained by applying a rating curve that relates river flow to SSC. Having determined SSC, it may then be used to estimate other sediment-related measures that are of more direct relevance to ecology, such as visual water clarity (relevant to visually hunting fish and birds) and euphotic depth (relevant to growth of freshwater periphyton and macrophytes on the river bed) (Julian et al, 2013; Davies-Colley et al, 2014).

Suspended-sediment load

Suspended-sediment load is the average mass of sediment that flows past a point in the river in a year. This is denoted by *L*. It has units of tonnes per year. It is normally estimated by summing up the sediment discharge over a number of years to get the total tonnes of sediment discharge and then dividing by the number of years. The sediment discharge is estimated by multiplying the water flow, *flow* (cubic metres per second), by the sediment concentration as estimated from the sediment concentration rating curve, which is a function of water flow.

Suspended-sediment load is what is modelled in the SedNetNZ. When land use changes or soil conservation works are implemented then SedNetNZ will predict a change in the suspended-sediment load of a river. The question addressed in the study is what influence will suspended-sediment load have on the time distribution of other important sediment attributes, such as turbidity, sediment concentration, water clarity, euphotic depth and embeddedness?

Turbidity

Turbidity, *turb,* is the cloudiness of water caused by scattering of light from suspended particles. As mentioned previously it affects the foraging ability of fish. It is measured with a nephelometer, which measures the intensity of light scattered at 90 degrees from a beam of light passing through a water sample.

The scattering attenuation of light through water is then given by exp(-*turb x*) where *turb* is the turbidity in Nephelometric Turbidity Units (NTU) and *x* is the distance travelled through the water. Turbidity is closely related to sediment concentration and is also highly variable and depends strongly on water flow. The turbidity at a site is therefore often characterised by a time distribution. Often, there will be more measurements of turbidity available than sediment concentration because turbidity can be measured immediately and on site, whereas, for sediment, concentration samples must be processed at a laboratory.

Water clarity

Water clarity, *WC*, is the distance of water through which an object can be clearly seen. The object may be a black target or a so-called Sechi disk (white disk), which is usually viewed horizontally through water using a simple viewer equipped with a 45-degree mirror. Like sediment concentration and turbidity, water clarity is highly variable and depends strongly on water flow. Water clarity is a direct measure of the immediate foraging range of fish.

Euphotic depth

Euphotic depth, *ED*, is a measure of light penetration. The distance defines the euphotic zone in which there is sufficient light for photosynthesis and periphyton and macrophytes may be sustained (Julian et al, 2013; Davies-Colley et al, 2014). Euphotic depth is rarely measured directly but may be inferred from measurements of turbidity and water clarity.

Some long-term monitoring river sites in New Zealand have turbidity metres, and relationships between SSC and water turbidity have been developed for these sites. The specific form of the relationship for any given river will depend on typical particle size, organic content and so on and is usually site specific. Based on such relationships, full distributions of the measures more important to freshwater ecology (for example, visual water clarity and euphotic depth) may be obtained.

For this study, turbidity is treated as a state variable from which other attributes may be derived. The relationship between discharge and turbidity is considered, and then between turbidity and SSC, water clarity and euphotic depth. The relationship between SSC, turbidity, visual clarity and euphotic depth is shown for the Hātea River in Table 2 and Figure 6.

Table 2: Relationship between suspended sediment concentration, turbidity, water clarity and euphotic depth in the Hātea River

Percentile	Flow (m^3/s)	Turbidity (NTU)	Suspended sediment (gm/m^3)	Water clarity (m)	Euphotic depth (m)
10	0.15	1.5	1.4	4.5	3.8
50	0.53	4.3	3.6	1.7	2.2
80	1.11	7.7	6.0	0.95	1.7
95	2.71	15.7	11.3	0.48	1.2

Note: gm/m^3 = grams per cubic metre; m = metres; m^3/s = cubic metres per second; NTU = Nephelometric Turbidity Units.

Figure 6: Suspended sediment concentration and visual clarity and euphotic depth in the Hātea River (50 percentile)

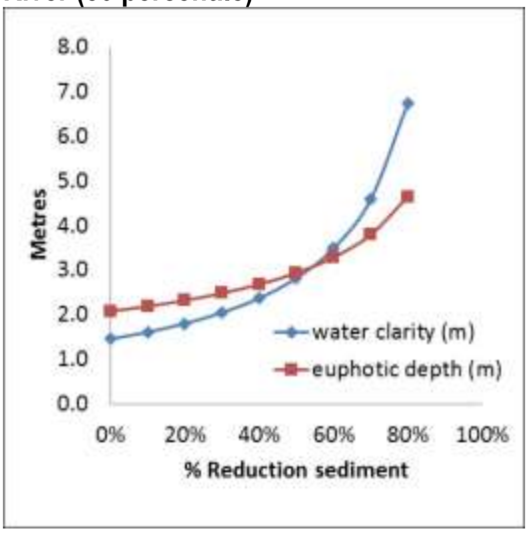
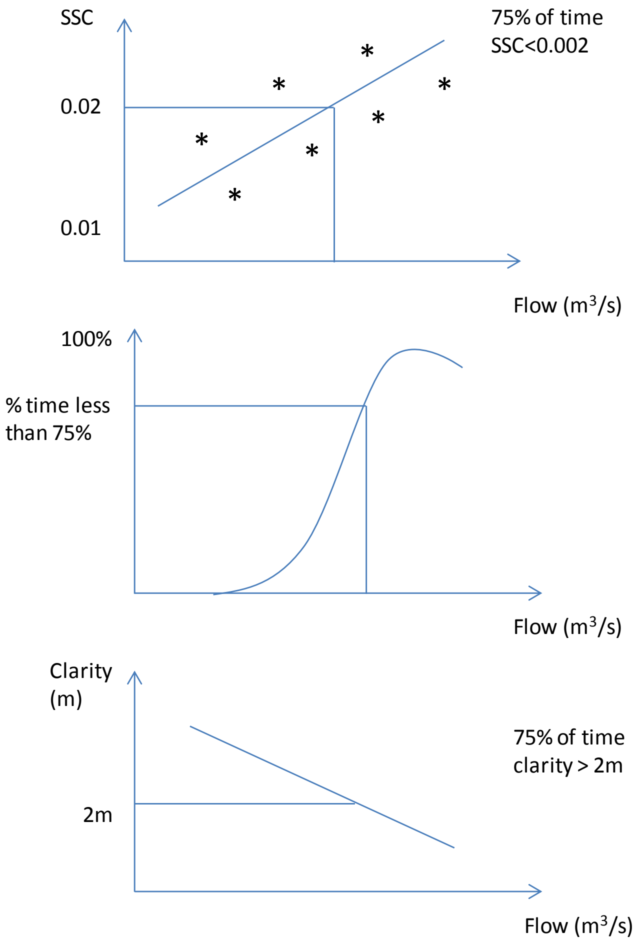


Figure 7 shows a specific example, in which 75 percent of the time the SSC is less than 0.002 grams per millilitre. Values of visual clarity and euphotic depth could also be expressed at the same percentile. For a second river, the 75-percentile concentration might be 0.0005 grams per millilitre, which would indicate that this second river was less turbid most of the time.

Using SSC as an attribute is attractive because it can be related to, first, the river sediment load (tonnes per year) through the sediment concentration rating curve and, second, visual water clarity and euphotic depth through site-specific relationships that can be developed from regular measurements. A one-parameter representation of the SSC distribution (for example, the 75th percentile) is used as the attribute that is indicative of the effects of suspended fine sediments. For the Whangarei Harbour study, it is necessary to be able to relate SSC to sediment load, since SedNetNZ predicts sediment loads. It is also important to be able to relate SSC to visual clarity and euphotic depth because these variables are meaningful to the freshwater ecology.

Figure 7: Example of relationship between suspended-sediment concentration and river flow and clarity



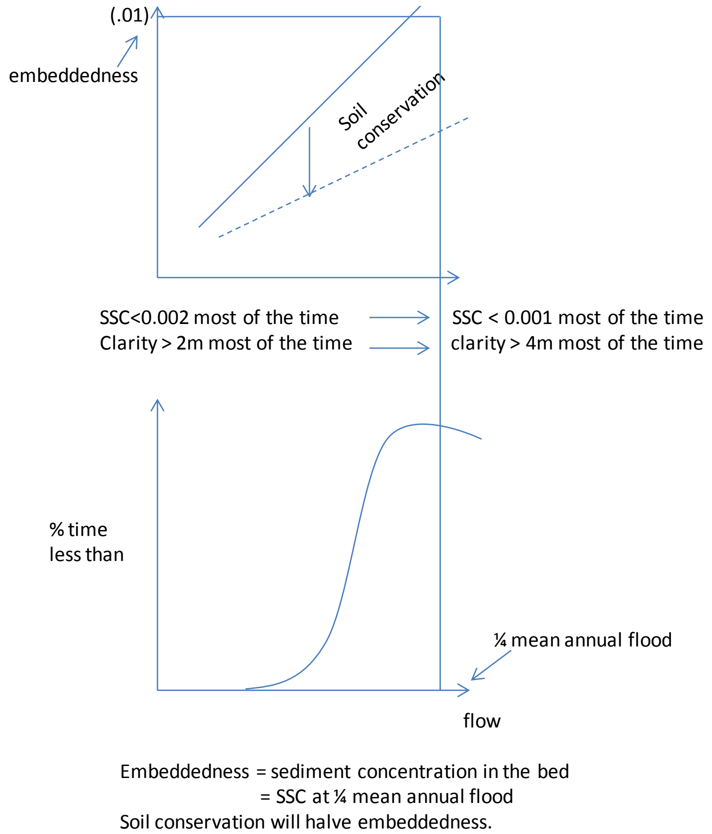
Notes: m^3/s = cubic metres per second; m = metres; SSC = suspended-sediment concentration. Top: Rating curve relating river flow and SSC. Middle: Example of how a time distribution of SSC versus river flow can be summarised with one parameter representing central tendency, in this case, the 75th percentile. Bottom: Expression of visual water clarity at the same percentile.

Embeddedness - deposited-sediment attribute for freshwater

For gravel-bed rivers, “embeddedness” (the concentration of fine sediment trapped by coarser particles in the riverbed; units of kilograms of sediment per cubic metre of water in the bed) could function as an attribute for deposited fine sediment. Like SSC, embeddedness can be related to other measures of deposited fine sediment that are relevant to river ecology.

The percentage cover of the riverbed by fine sediment cannot currently be related to catchment sediment loads. However, embeddedness can be related to catchment sediment loads using a result of Clausen and Plew (2004), who showed that embeddedness is equal to the SSC at the discharge when bedload transport stops, where that discharge is about one-quarter of the mean annual flood. The SSC at one-quarter of the mean annual flood is given by the rating curve relating SSC to flow, and the SSC rating curve in turn is controlled by the catchment sediment load. When river sediment loads are reduced by a certain percentage due to soil conservation work, the sediment concentration rating curve will shift down (Hicks et al, 2000) and embeddedness will reduce by the same relative amount (see Figure 8).

Figure 8: Embeddedness and the sediment concentration rating curve



Note: m = metres; SSC = suspended-sediment concentration. The top graph shows the hypothetical curve (solid line) relating SSC to river flow, and the bottom graph shows the flow duration curve. Fine sediment is trapped in coarser bed substrata when bedload transport stops at about one-quarter of the mean annual flood. Embeddedness (the concentration of fine sediment in the bed, expressed as kilograms of sediment per cubic metre of water in the bed) can be directly read off the rating curve (embeddedness = 0.01 kilograms per cubic metre in this example). When sediment loads are reduced by soil conservation work, the SSC rating curve shifts down (dashed curve in top graph), and embeddedness is reduced by the same relative amount (Hicks et al, 2000, have published data on SSC rating curves changing after major erosion events).

For the purpose of the Whangarei Harbour study, it is considered that embeddedness, defined as the SSC at one-quarter of the mean annual flood, is a useful attribute that is indicative of the effects of deposited fine sediments. However, further work is required to confirm the relationship between embeddedness and the SSC at one-quarter of the mean annual flood, and the extent to which fine sediments accumulate on streambeds between floods.

4 Whangarei Harbour catchment sediment modelling

This section describes how baseline sediment loads were modelled for the Whangarei Harbour catchment and outlines how the freshwater sediment attributes are evaluated. It provides details of how to translate a reduction in river sediment load into a change in five freshwater sediment attributes:

- turbidity;
- water clarity;
- euphotic depth;
- suspended sediment concentration; and
- embeddedness.

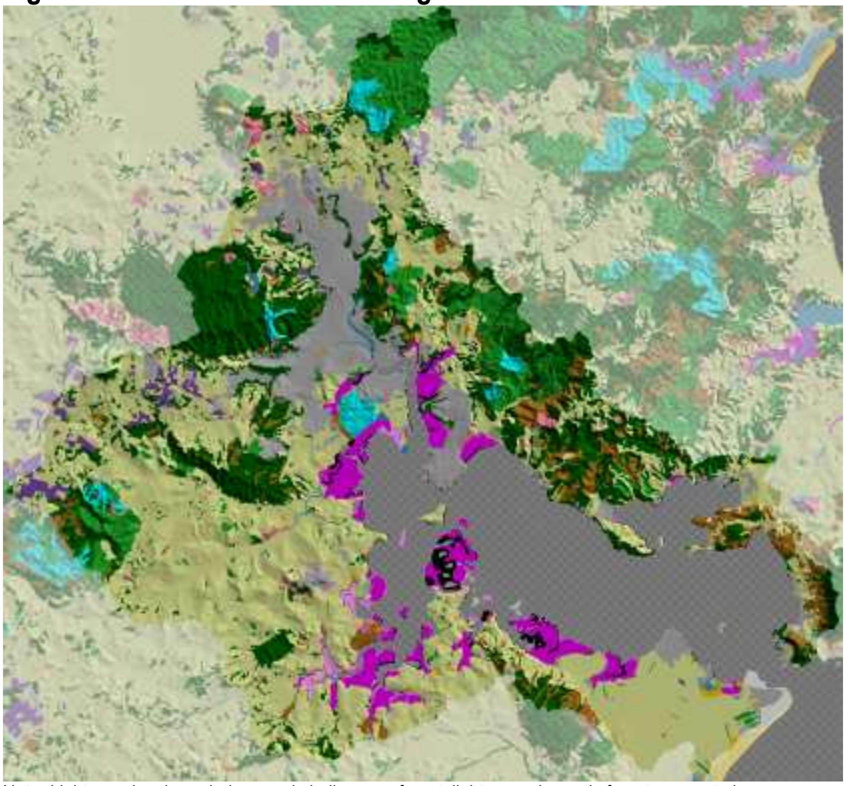
4.1 SEDIMENT LOADS IN THE WHANGAREI HARBOUR CATCHMENT

Landcare Research was sub-contracted by NIWA to undertake an analysis of baseline erosion rates and sediment loads in the Whangarei Harbour catchment using the SedNetNZ model (Dymond, 2015). The catchment erosion and sediment model simulates several erosion processes, sediment storages and transfers. For this analysis, SedNetNZ has been calibrated for the Whangarei Harbour catchment and downscaled to the farm scale.

SedNetNZ has been implemented for the Kaipara Harbour catchment. The model was implemented as four raster layers of landslide, earthflow, gully and surficial erosion, and a sub-catchment file (River Environment Classification level 2 (REC2) sub-catchments), which completes all the erosion processes with floodplain deposition and bank erosion. The large spatial rectangular extent of the Kaipara Harbour included the Whangarei Harbour catchment, so SedNetNZ was able to be implemented for the Whangarei Harbour catchment merely by clipping out the appropriate spatial extent from the Kaipara Harbour SedNetNZ implementation.

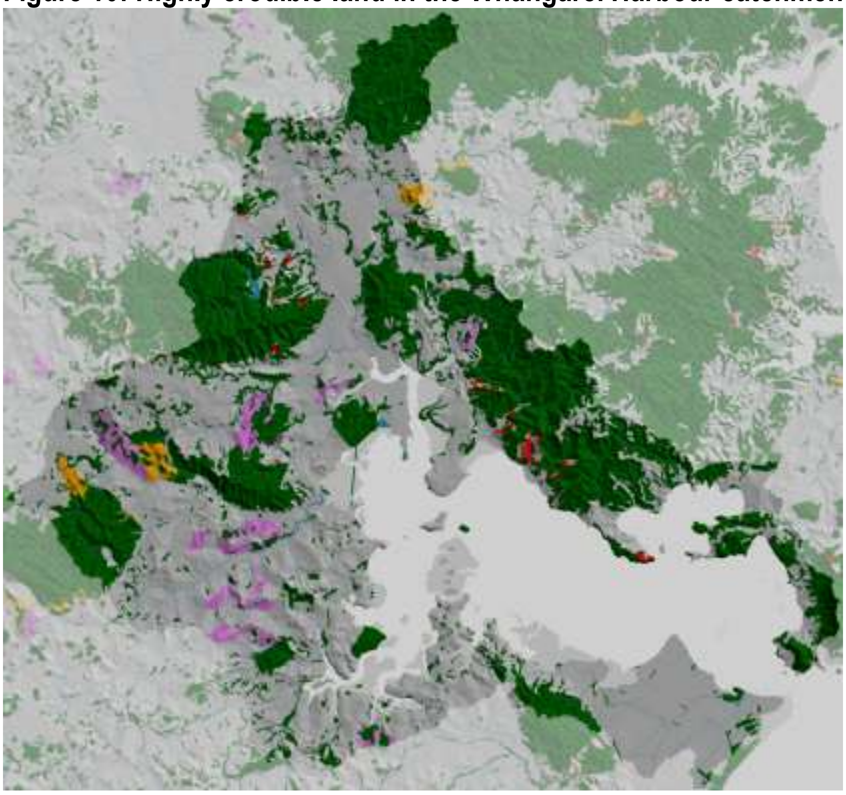
Land cover is a major driver of soil erosion. Figure 9 shows the land cover in the Whangarei Harbour catchment as given by the Land Cover Database (LCDB) 4.0. Figure 10 shows the intersection of land cover with erosion terrains (Dymond et al, 2010) to give the susceptibility of the land to mass-movement erosion. Significant areas of earthflow and gully erosion need soil conservation work and there are also areas susceptible to landsliding. Figure 11 shows the REC2 sub-catchments for which sediment budgets are constructed, and Figure 12 shows the mean total erosion for each sub-catchment. Figure 13 shows the reporting zones as constructed in the Whangarei Harbour study and their sediment loads to the Whangarei Harbour as predicted by SedNetNZ.

Figure 9: Land cover in the Whangarei Harbour catchment



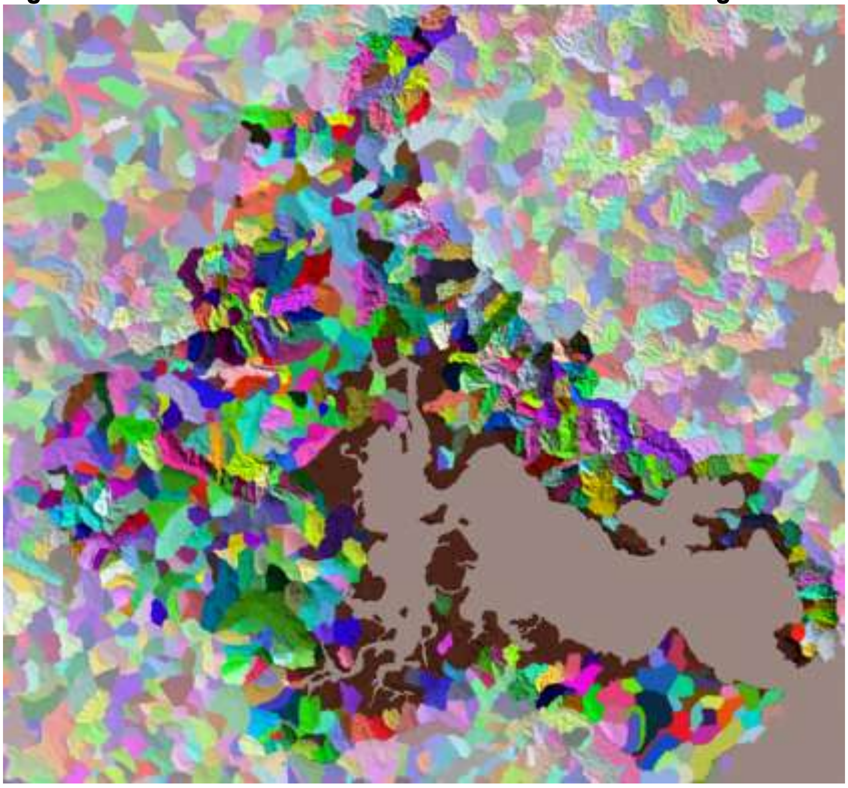
Note: Light grey is urban; dark green is indigenous forest; light green is exotic forest; magenta is mangroves; blue is harvested exotic forest; brown is mānuka and kānuka; yellow is pasture; purple is orchards and vineyards and pink is indigenous shrublands.

Figure 10: Highly erodible land in the Whangarei Harbour catchment



Note: Red shows land susceptible to landsliding; magenta shows land susceptible to earthflow erosion, gold shows land susceptible to gully erosion, dark green shows forested land that protects the land from mass-movement erosion.

Figure 11: REC2 sub-catchments for which sediment budgets are constructed



Note: Dark brown areas adjacent to the coast show the infill required to match the true coast.

Figure 12: Mean total erosion of all processes (landsliding, earthflow, gully, surficial, net bank erosion and floodplain deposition) as modelled by SedNetNZ for each REC2 sub-catchment in the Whangarei Harbour catchment

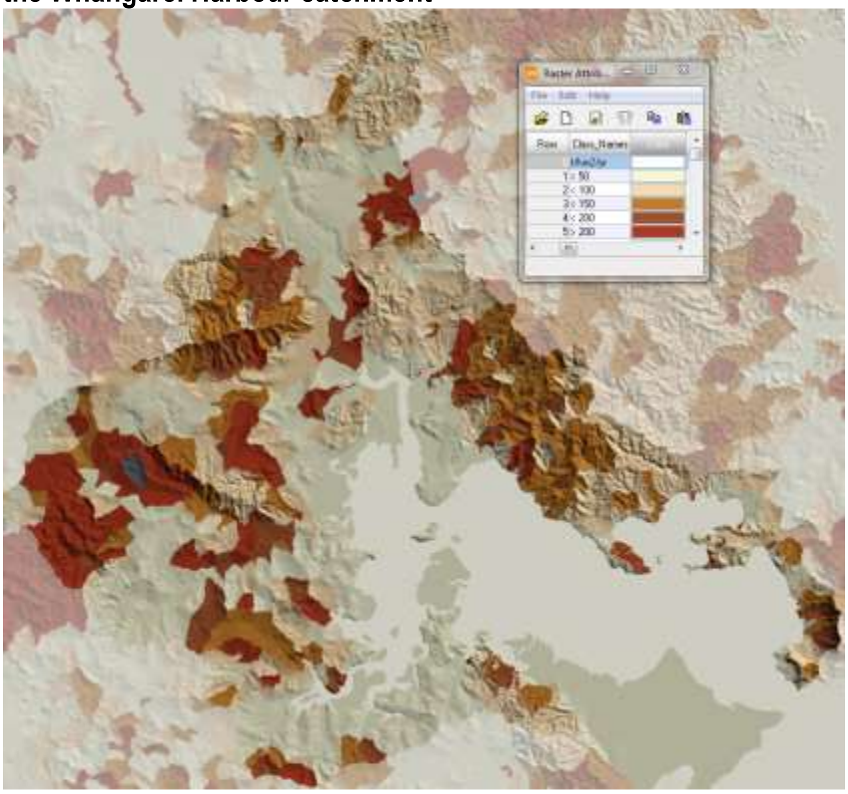
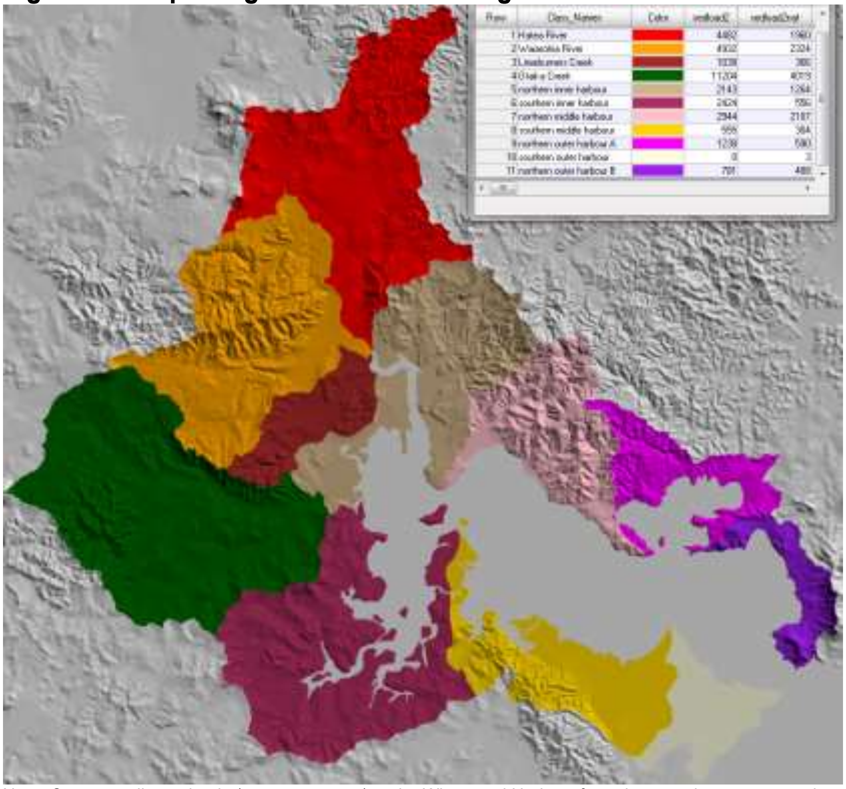


Figure 13: Reporting zones in the Whangarei Harbour catchment and current sediment loads



Note: Current sediment loads (tonnes per year) to the Whangarei Harbour from the reporting zones are shown in column "sedload2". Historic sediment loads before human settlement are shown in column "sedload2nat".

Sources of sediment are estimated for both hill–landmass and streambank erosion. The sum of these two sources is then aggregated to estimate total erosion for each REC2 sub-catchment, so that aggregated loads are consistent with the resolution of the *E. coli* load modelling.

SedNetNZ estimates that the total load in the catchment is more than 31 000 tonnes of sediment per year. About 86 percent of this is estimated to arise from hill and landmass erosion, while the remainder is from streambank erosion (see Figure 14 to Figure 16).

As the pie chart in Figure 14 shows, the bulk of the sediment is estimated to come from sheep and beef (36 percent), native land (36 percent), and pine plantations (13 percent). A large amount of sediment comes from forested areas because they are generally located on less productive areas with steeper slopes relative to the rest of the catchment. If any part of the forested area was to be converted to pasture, the level of erosion could increase by several factors (Dymond et al, 2010).

Figure 14: Total sediment load by stream reach in the Whangarei Harbour catchment (tonnes per hectare per year)

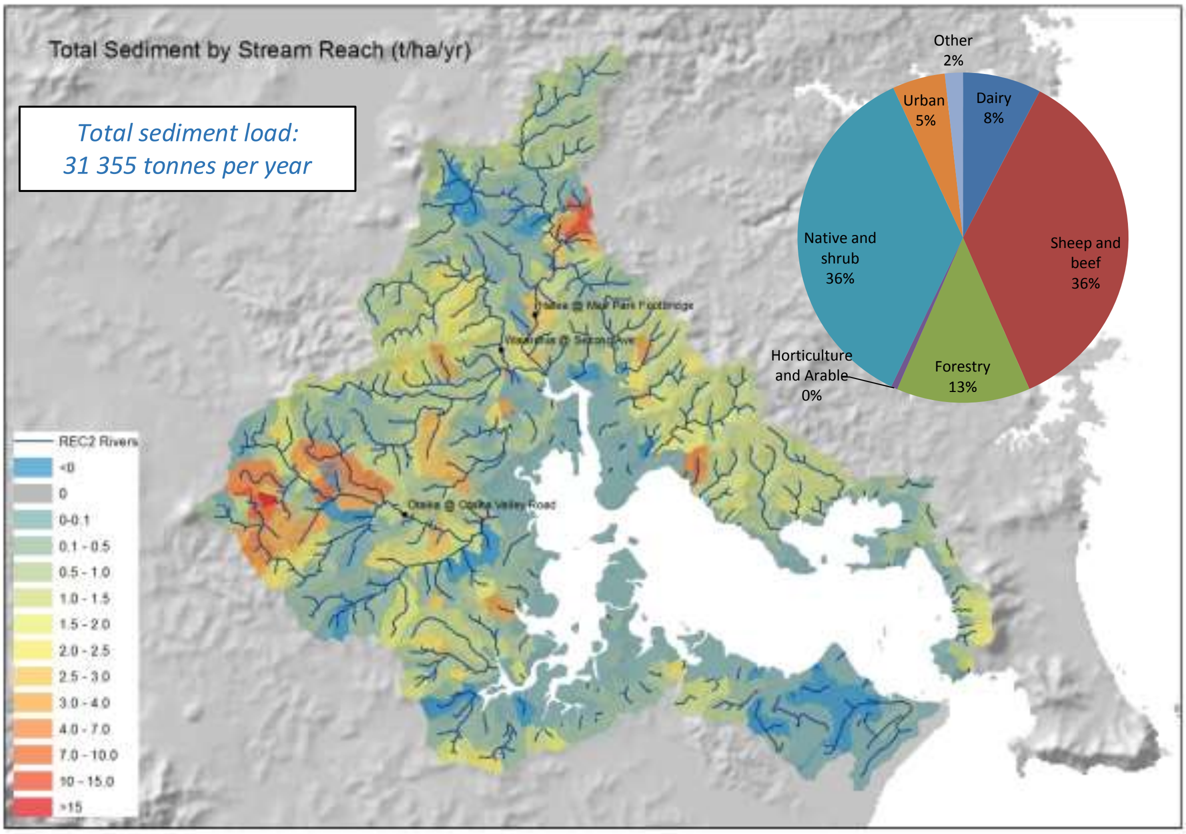


Figure 15: Total landmass sediment load by stream reach in the Whangarei Harbour catchment (tonnes per hectare per year)

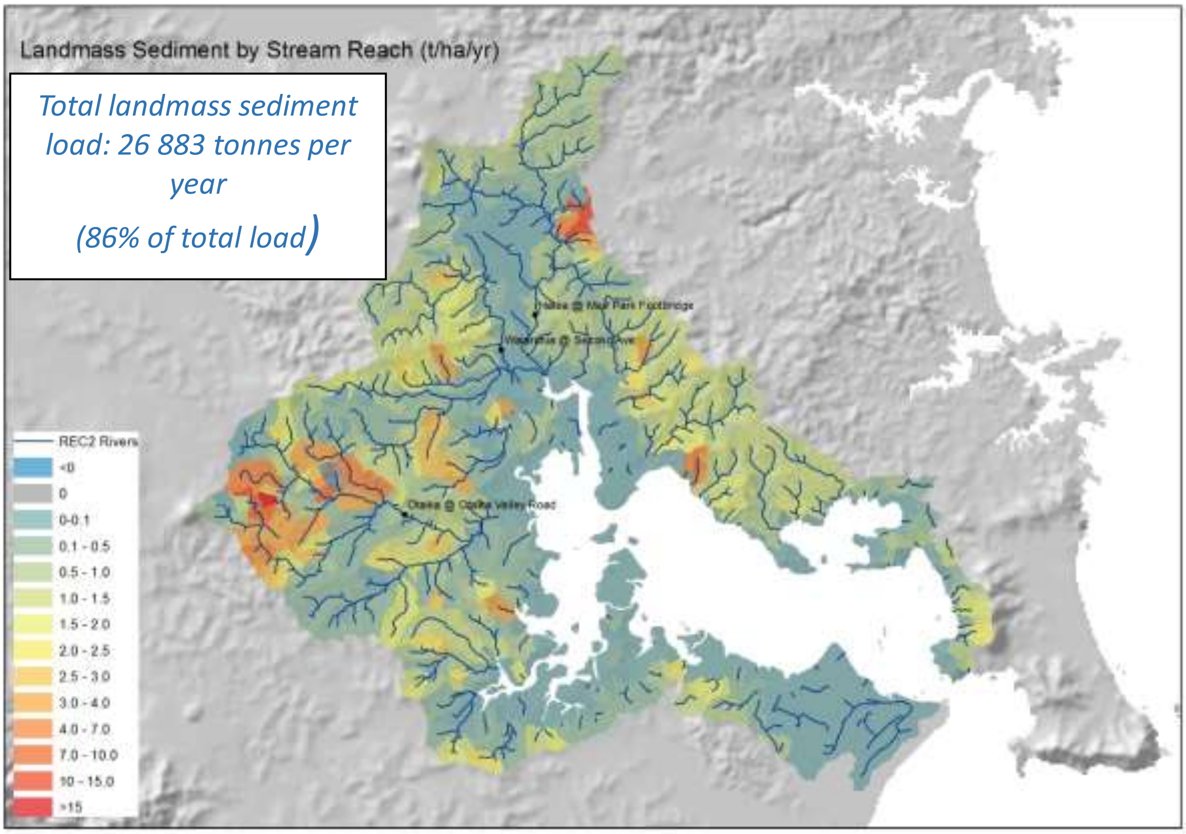
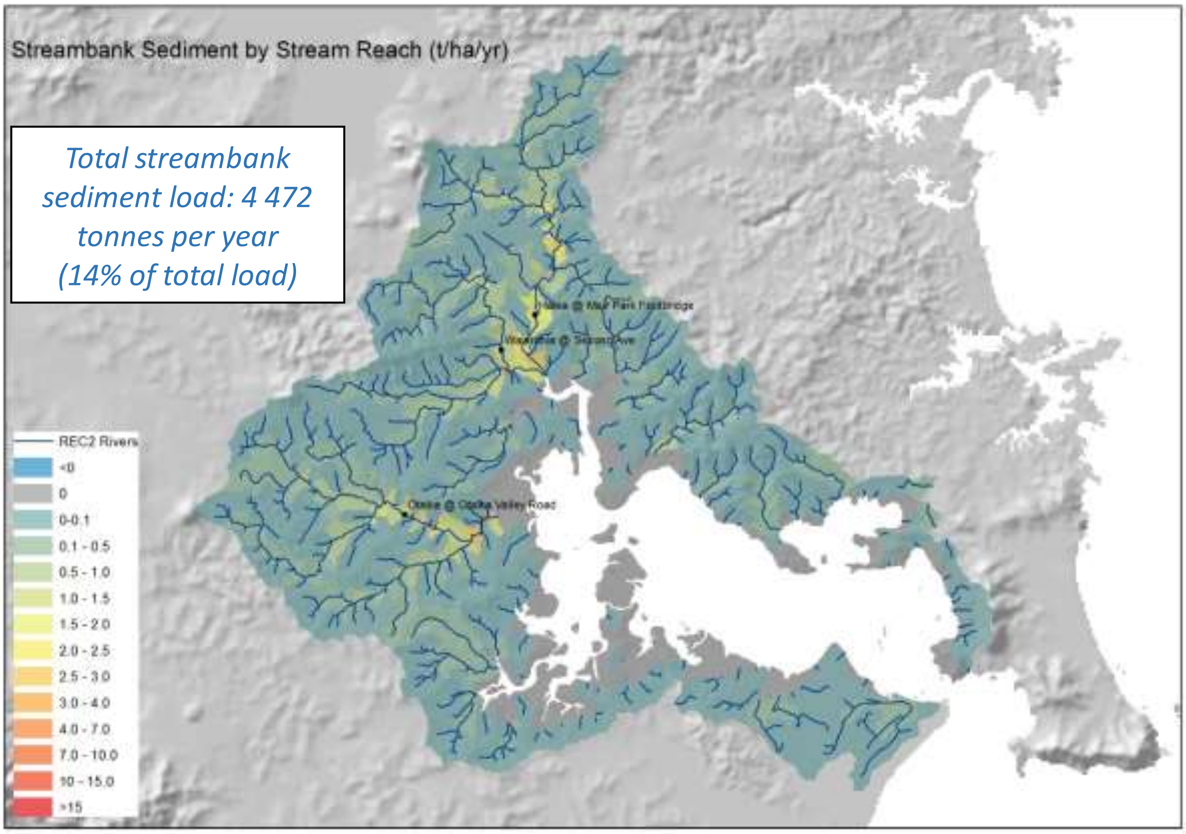


Figure 16: Total streambank sediment by stream reach in the Whangarei Harbour catchment (tonnes per hectare per year)



4.2 DATA

Annual sediment loads (tonnes per year) for 11 reporting zones are estimated for the current land cover and for pre-human vegetation (that is, indigenous forest everywhere). On average, the pre-human sediment loads are about 45 percent of the current sediment loads.

Only three sites exist in the Kaipara Harbour catchment where sediment loads have been measured. These are Kaipara at Waimauku, Kaukapakapa at Taylors and Hoteo at Gubbs (Curran-Cournane et al, 2013). Table 3 compares the measured sediment loads with those predicted by SedNetNZ. Modelled sediment load is about the same as measured for Kaukapakapa, 50 percent more for Hoteo and nearly twice as much for the Kaipara River. These ratios show reasonable agreement, given that the measurement records are only for several years, do not include major events yet and are based on surface sampling of sediment concentration, which will generally underestimate sediment loads. In general, a great deal of uncertainty occurs with sediment data. Results with +/– 50 percent uncertainty are quite normal.

Table 3: Comparison of measured sediment loads with those predicted by SedNetNZ

	Kaipara at Waimauku	Kaukapakapa at Taylors	Hoteo at Gubbs
Measured sediment load (tonnes per year)	5 200	4 700	19 800
Modelled sediment load (tonnes per year)	10 000	3 700	33 300

Temporal disaggregation[4] of sediment loads would normally be done through a sediment concentration rating curve. A measured time distribution of water flow may then be converted to a time distribution of sediment concentration. However, insufficient sediment concentration data are available for rivers in the Whangarei Harbour catchment to derive a robust sediment concentration curve. Also, the sediment concentration data are surface sampled rather than depth integrated and are not suitable for load estimates. Hence, disaggregation was achieved through the more numerous turbidity samples.

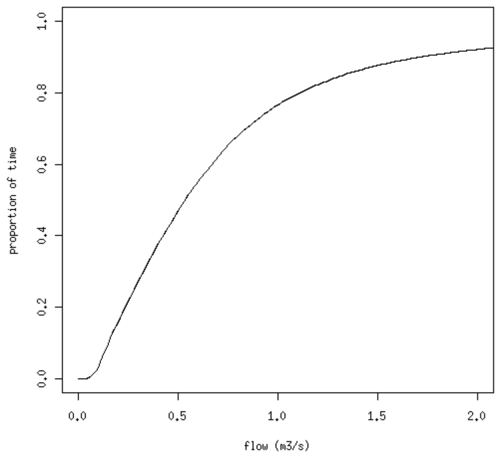
Only three water-level recorders are used in the Whangarei Harbour catchment that are rated for flow. From these recorders, hourly water flow, in cumecs (cubic metres per second), may be derived from the beginning to the end of the record (see Table 4). From these hourly records, it is possible to derive the time distribution of flow, that is, the fraction of time the river is below a given flow (see Figure 17 to Figure 19).

At sites near the water-level recorders, samples of turbidity and water clarity have been taken regularly (approximately monthly) since 2005 in the Hātea River and Waiarohia Stream, and since 2011 in the Otaika River, as part of the state of environment monitoring performed by the NRC. Samples of sediment concentration have been taken occasionally at the same time as the turbidity and water clarity samples.

Table 4: Number of turbidity, water clarity and sediment concentration samples collected from the Hātea River, Waiarohia Stream and Otaika River near water-level recorders

Water-level recorder	Length of flow record	No. of turbidity samples	No. of water clarity samples co-current with turbidity samples	No. of sediment concentration samples co-current with turbidity samples
Hātea at Whareora Road	1986–2014	71	62	6
Waiarohia at Lovers Lane	1979–2014	82	73	8
Otaika at Kay	2011–2015	30	30	11

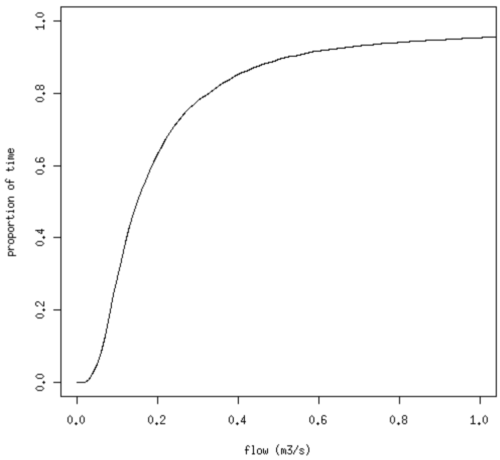
Figure 17: Time distribution of water discharge in the Hātea River at Whareora Road (1986–2014)



Note: m³/s = cubic metres per second; y axis shows fraction of time that the river is below water discharge on x axis.

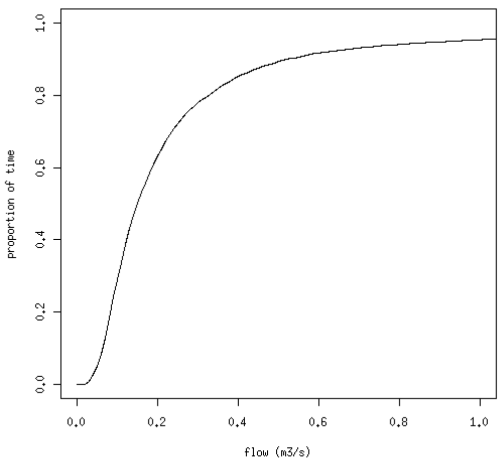
[4] Temporal disaggregation is the process of deriving high frequency data from low frequency data, and is closely related to benchmarking and interpolation.

Figure 18: Time distribution of water discharge in the Waiarohia River at Lovers Lane (1979–2014)



Note: m³/s = cubic metres per second; y axis shows fraction of time that the river is below water discharge on x axis.

Figure 19: Time distribution of water discharge in the Otaika River at Kay (2011—2015)



Note: m³/s = cubic metres per second; y axis shows fraction of time that the river is below water discharge on x axis.

4.2.1 Flow percentiles

Flow percentiles are simply read off the derived time distribution of flow. Low, medium, high and very high flows were characterised using 10, 50, 80 and 95th percentiles to represent these. Table 5 shows the flow percentiles.

Table 5: Flow percentiles in cubic metres per second of the Hātea, Waiarohia, and Otaika rivers.

	10%	50%	80%	95%
Hātea at Whareora Road	0.15	0.53	1.11	2.71
Waiarohia at Lovers Lane	0.06	0.15	0.33	0.92
Otaika at Kay	0.14	0.43	1.13	2.64

Note: River flow is below the flow percentile for the percentile of time; for example, the Hātea River flow is below 0.15 cubic metres per second for 10 percent of the time.

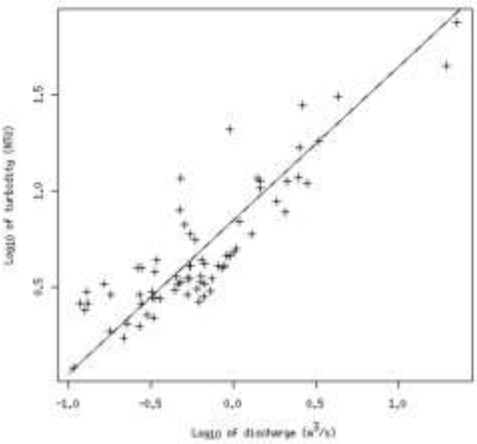
4.2.2 Turbidity percentiles

The 71 turbidity samples are not sufficient to derive an accurate time distribution. However, it is possible to derive a relationship between flow and turbidity and to use that relationship to associate turbidity percentiles with the accurate flow percentiles. It can be shown (see Appendix 1) that if the flow percentiles are given by x_i $(i = 1, 4)$ and turbidity y relates to flow x by $y = g(x)$ then the turbidity percentiles are simply $g(x_i)$ $(i = 1, 4)$.

Figure 20 to Figure 22 show the relationships of turbidity with flow for the Hātea River, Waiarohia Stream and Otaika River, respectively.

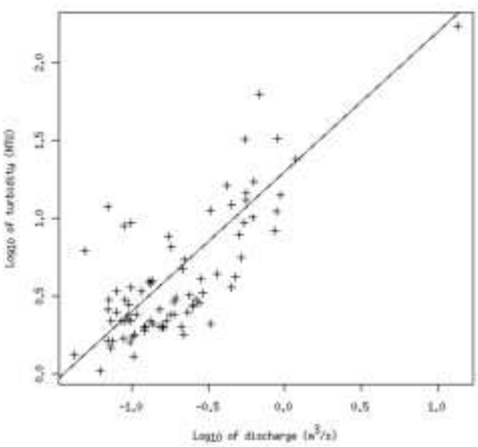
Table 6 shows the turbidity percentiles inferred from the relationships and the flow percentiles in Table 5.

Figure 20: Log-log plot of turbidity versus flow for the Hātea River at Whareora Road



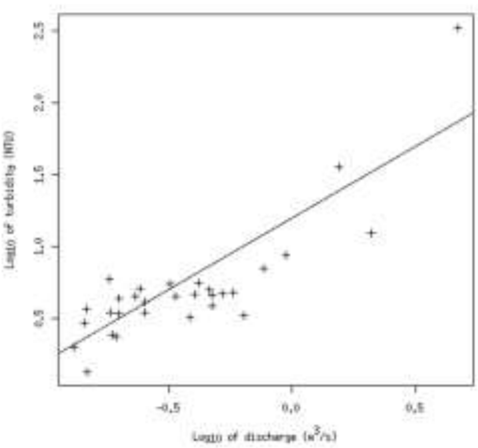
Note: m^3/s = cubic metres per second; NTU = Nephelometric Turbidity Units; fitted line is given by $\log_{10}(turbidity) = 0.8 \log_{10}(flow) + 0.85$.

Figure 21: Log-log plot of turbidity versus flow for the Waiarohia Stream at Lovers Lane



Note: m^3/s = cubic metres per second; NTU = Nephelometric Turbidity Units; fitted line is given by $\log_{10}(turbidity) = 0.9 \log_{10}(flow) + 1.3$.

Figure 22: Log-log plot of turbidity versus flow for the Otaika River at Kay



Note: m^3/s = cubic metres per second; NTU = Nephelometric Turbidity Units; fitted line is given by $\log_{10}(turbidity) = 1.0 \log_{10}(flow) + 1.2$.

Table 6: Turbidity percentiles (Nephelometric Turbidity Units) of the Hātea River, Waiarohia Stream and Otaika River

Percentile	Hātea River	Waiarohia Stream	Otaika River
10%	1.5	1.6	2.2
50%	4.3	3.6	6.8
80%	7.7	7.4	17.9
95%	15.7	18.5	41.8

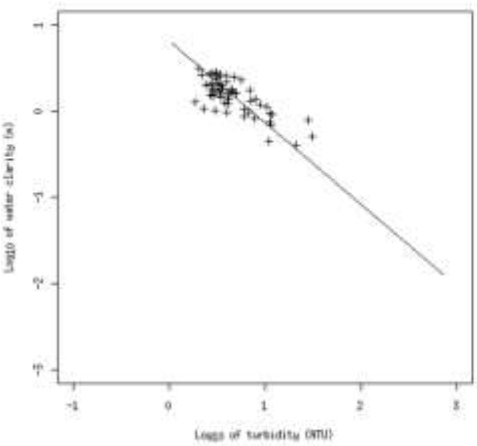
Note: Turbidity is below the turbidity percentile for the percentile of time; for example, turbidity in the Hātea River is below 1.5 Nephelometric Turbidity Units for 10 percent of the time.

4.2.3 Water clarity percentiles

The number of water clarity samples is not sufficient to derive an accurate frequency distribution. It is possible to derive a relationship between flow and water clarity; however, a much stronger relationship exists between turbidity and water clarity (as turbidity and water clarity are both functions of light scattering).

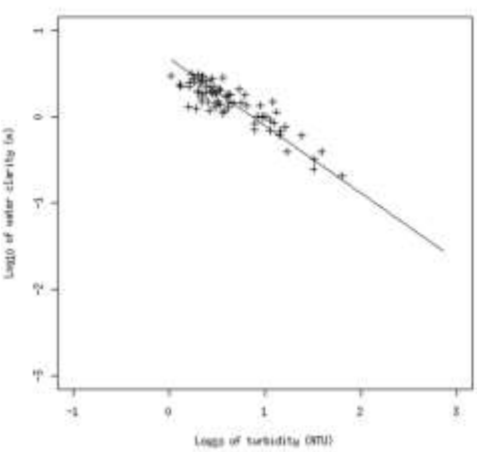
The relationship between turbidity and water clarity is derived and used to infer water clarity percentiles from the turbidity percentiles. Figure 23, Figure 24 and Figure 25 show the relationships of turbidity with water clarity for the Hātea River, Waiarohia Stream, and Otaika River. Table 7 shows the water clarity percentiles inferred from the relationships and the turbidity percentiles in Table 6.

Figure 23: Log-log plot of water clarity versus turbidity for the Hātea River at Whareora Road



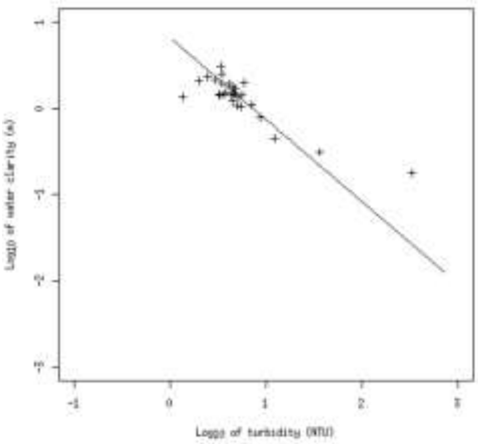
Note: m = metres; NTU = Nephelometric Turbidity Units; fitted line is given by $\log_{10}$(*water clarity*) = –0.95 $\log_{10}$(*turbidity*) +0.82.

Figure 24: Log-log plot of water clarity versus turbidity for the Waiarohia Stream at Lovers Lane



Note: m = metres; NTU = Nephelometric Turbidity Units; fitted line is given by $\log_{10}$(*water clarity*) = –0.78 $\log_{10}$(*turbidity*) +0.6)

Figure 25: Log-log plot of water clarity versus turbidity for the Otaika River at Kay



Note: m = metres; NTU = Nephelometric Turbidity Units; fitted line is given by $\log_{10}$(*water clarity*) = –0.95 $\log_{10}$(*turbidity*) +0.82)

Table 7: Water clarity percentiles (metres) of the Hātea River, Waiarohia Stream and Otaika River

Percentile	Hātea River	Waiarohia Stream	Otaika River
10%	4.5	3.3	3.12
50%	1.7	1.8	1.1
80%	0.95	1.0	0.42
95%	0.48	0.49	0.19

Note: Water clarity is greater than the water clarity percentile for the percentile of time; for example, water clarity in the Hātea River is greater than 4.5 metres for 10 percent of the time.

4.2.4 Euphotic depth percentiles

There are no samples of euphotic depth from which to estimate percentiles. However, Davies-Colley and Nagels (2008) found that attenuation coefficients were approximately the square root of turbidity, *turb*, for New Zealand rivers.

Euphotic depth is defined as the depth at which light radiance is attenuated to 1/100 of that at the surface. This equates to an exponential attenuation of 4.6 (that is, exp(–4.6) = 0.01), which equates to the euphotic depth times the square root of turbidity. Euphotic depth ED may then be approximated by:

$$ED = 4.6/sqrt(turb) \quad (1)$$

The percentiles of euphotic depth may then be estimated directly by applying equation (1) to the turbidity percentiles in Table 6. The results are shown in Table 8.

Table 8: Euphotic depth percentiles (metres) of the Hātea River, Waiarohia Stream and Otaika River

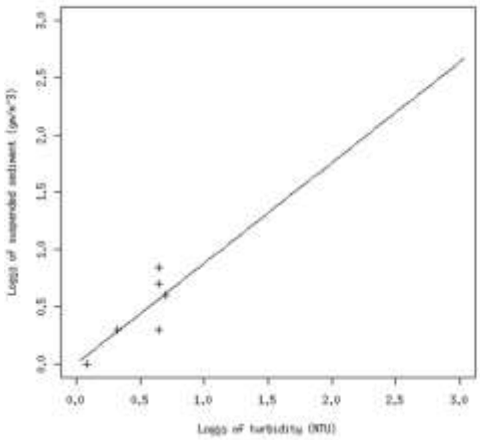
Percentile	Hātea River	Waiarohia Stream	Otaika River
10%	3.8	3.6	3.1
50%	2.2	2.4	1.8
80%	1.7	1.7	1.1
95%	1.2	1.1	0.7

Note: Euphotic depth is above the euphotic depth percentile for the percentile of time; for example, euphotic depth in the Hātea River is above 3.8 metres for 10 percent of the time.

4.2.5 Sediment concentration percentiles

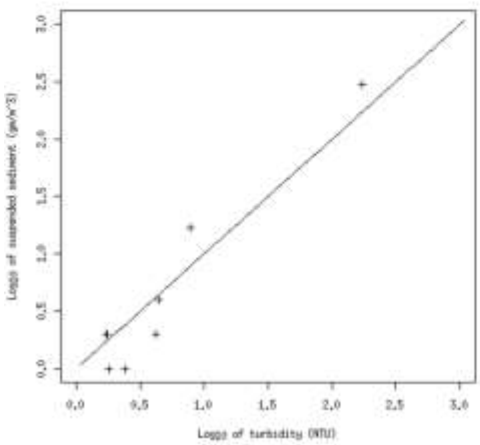
The number of sediment concentration samples is small so it is difficult to estimate percentiles of these. However, there are usually strong relationships between sediment concentration and turbidity, so the sediment concentration percentiles may be inferred from the turbidity percentiles. Figure 26 to Figure 28 show the relationships of turbidity with sediment concentration. Table 9 shows the inferred sediment concentration percentiles.

Figure 26: Log-log plot of suspended sediment concentration versus turbidity for the Hātea River at Whareora Road



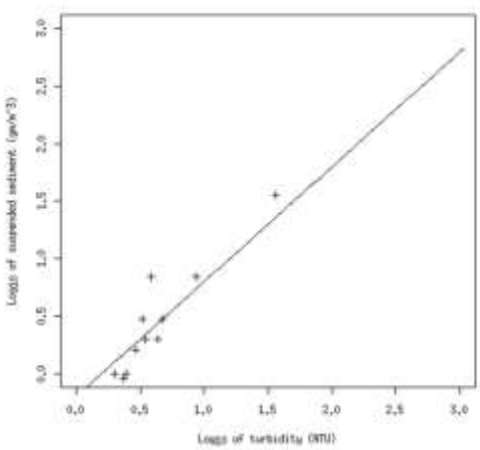
Note: gm/m^3 = grams per cubic metre; NTU = Nephelometric Turbidity Units; fitted line is given by $\log_{10}$(*suspended sediment*) = 0.88 $\log_{10}$(*turbidity*).

Figure 27: Log-log plot of suspended sediment concentration versus turbidity for the Waiarohia Stream at Lovers Lane



Note: gm/m^3 = grams per cubic metre; NTU = Nephelometric Turbidity Units; fitted line is given by $\log_{10}$(*suspended sediment*) = $\log_{10}$(*turbidity*).

Figure 28: Log-log plot of suspended sediment concentration versus turbidity for the Otaika River at Kay



Note: gm/m^3 = grams per cubic metre; NTU = Nephelometric Turbidity Units; fitted line is given by $\log_{10}$(*suspended sediment*) = $\log_{10}$(*turbidity*) –0.2.

Table 9: Suspended sediment concentration percentiles (grams per cubic metre) of Hātea River, Waiarohia Stream and Otaika River

Percentile	Hātea River	Waiarohia Stream	Otaika River
10%	1.4	1.6	1.4
50%	3.6	3.6	4.3
80%	6.0	7.4	11.3
95%	11.3	18.5	26.3

Note: Sediment concentration is below the sediment concentration percentile for the percentile of time; for example, sediment concentration in the Hātea River is below 1.4 grams per cubic metre for 10 percent of the time.

4.2.6 Embeddedness

Green and others (2015) characterised embeddedness as the concentration of fine sediment trapped in channel gravel expressed as a mass per unit volume of water in channel gravel (grams per cubic metre). Clausen and Plew (2004) showed that, for New Zealand rivers, the discharge at which channel gravel stops moving is approximately equal to one-quarter of the mean annual flow, therefore, it follows that:

$$\boldsymbol{EB} = \boldsymbol{S}(\,\boldsymbol{T}\left(\frac{\boldsymbol{MAF}}{\boldsymbol{4}}\right)) \qquad \textbf{(2)}$$

where *EB* is embeddedness, *MAF* is the mean annual flood in cubic metres s^{-1}, *S* is the function that gives sediment concentration (grams m^{-3}) from turbidity (NTU) and *T* is the function that estimates turbidity as a function discharge (metres s^{-1}).

The Waiarohia Stream has a gravel-based bed, and so embeddedness may be estimated for it (the Otaika and Hātea Rivers do not have a gravel-based bed). The mean annual flood of the Waiarohia Stream at Lovers Lane is 30 cubic metres per second, hence the discharge at which gravel stops moving on the falling limb of a flood hydrograph is 7.5 cubic metres per second. The turbidity at 7.5 cubic metres per second is given by Figure 21 as 122 NTU. Then Figure 27 gives a sediment concentration of 122 grams per cubic metre at an NTU of 122. Therefore, the embeddedness of the Waiarohia Stream at Lovers Lane is given by 122 grams of sediment per cubic metre of water.

4.3 CHANGES IN ATTRIBUTES FROM A CHANGE IN RIVER SEDIMENT LOAD

This section provides an overview of how to translate a reduction in river sediment load into a change in the freshwater sediment attributes of sediment concentration, turbidity, water clarity, euphotic depth and embeddedness. The catchment economic model (discussed in Section 7) applies various mitigations to estimate the effect on sediment load and the associated attributes.

4.3.1 Reduction in sediment concentration

Sediment load is the summation of sediment discharge over time so load is strongly related to concentration:

$$\boldsymbol{L} = \boldsymbol{10^6}(\textstyle\sum_j \boldsymbol{q_j}.\boldsymbol{s_j})/\boldsymbol{N} \qquad \textbf{(3)}$$

where *L* is the sediment load in tonnes per year $^{-1}$, q_j is the river discharge in cubic metres s^{-1} at time interval *j*, s_j is the suspended sediment concentration in grams m^{-3} at time interval *j*, $\sum$ is the summation over *N* years of record, and 10^6 is a conversion factor for converting grams to tonnes.

In many rivers there is a strong relationship between discharge, *q*, and the suspended sediment concentration, *s*:

$$s = R(q) \quad (4)$$

This is called the sediment concentration rating curve and is often used for estimating sediment loads in rivers.

Substitution of equation (4) into (3) gives:

$$L = 10^6 \sum_j q_j . R(q_j) / N \quad (5)$$

Equation (5) may be rewritten in distribution form as:

$$L = 10^6 \sum_i \; q_i R(q_i) H(q_i) / N \quad (6)$$

where $H(q_i)$ is the proportion of time discharge records fall in the increments of flow or "bins" q_i to $q_i + \Delta q$ during the N years of record (that is, discharge frequency), and summation is over the number of discharge bins.

If soil conservation reduces sediment load, L, then the right-hand side of equation (6) must also reduce. Discharge frequency will not change over a period of decades, and so it is the sediment concentration rating curve that must reduce.

Two instances of changes in sediment concentration rating have been observed in New Zealand: the Motueka River (Basher et al, 2011) and Waipaoa River (Hicks et al, 2000). In both cases, the rating curve moved parallel upwards in log-log space, indicating that sediment concentrations moved up by the same relative amount throughout the discharge range. We assume the same here, that is, when sediment loads are reduced by a fraction, p, then the sediment concentration rating curve is also reduced by p throughout the discharge range.

As an example, it is assumed that the catchment-wide soil conservation reduces sediment loads by 50 percent. Then the percentiles of sediment concentration given in Table 9 are reduced by 50 percent to give those in Table 10.

Table 10: Suspended sediment concentration percentiles (grams per cubic metres) of the Hātea River, Waiarohia Stream, and Otaika River after a reduction of sediment loads of 50 percent

Percentile	Hātea River	Waiarohia Stream	Otaika River
10%	0.7	0.8	0.7
50%	1.8	1.8	2.1
80%	3.0	3.7	5.7
95%	5.6	9.2	13.1

Note: Sediment concentration is below the sediment concentration percentile for the percentile of time; for example, sediment concentration in the Hātea River is below 0.7 grams per cubic metres for 10 percent of the time.

4.3.2 Reduction in turbidity

As shown in the previous section, reductions in sediment load following soil conservation, will result in the same reduction in sediment concentration. The reduction in turbidity, therefore, will depend on the relationships between turbidity and sediment concentration.

There is usually a linear relationship in log-log space:

$$log10(turb) = a \; log10(s) + b \quad (7)$$

This may be rewritten as:

$$turb = 10^b s^a \quad (8)$$

Therefore, if sediment concentration is reduced to a fraction q of what it was, then the turbidity will be reduced to:

$$\boldsymbol{turb'} = \boldsymbol{q^a.turb} \qquad (9)$$

and turbidity will be reduced to a fraction q^a of what it was. This assumes that the character of the sediment, such as particle size, remains the same as before.

Table 11 shows how the reduced turbidity percentiles may be estimated from the reduced sediment loads.

Table 11: Estimation of the decrease in turbidity percentiles from reduced sediment loads

	Hātea River	Waiarohia Stream	Otaika River
Value of *a* from figures 19, 20, 21	1.14	1.0	1.0
Reduced sediment load as fraction of old	*q*	*q*	*q*
Percentiles of sediment concentration as fraction of old	*q*	*q*	*q*
Percentiles of turbidity as fraction of old	$q^{1.14}$	*q*	*q*

4.3.3 Increase in water clarity

Water clarity is inversely linearly related to turbidity in log-log space (Figure 22, Figure 23 and Figure 24):

$$\boldsymbol{log10(wc) = -m\ log10(turb) + c} \qquad (10)$$

where m is a negative real number. This may be rewritten as:

$$\boldsymbol{wc = 10^c\ turb^{-m}} \qquad (11)$$

Therefore, if turbidity is reduced to a fraction p of what it was, then the water clarity will be increased to:

$$\boldsymbol{wc' = \frac{wc}{p^m}} \qquad (12)$$

Table 12 shows how the increased water clarity percentiles may be estimated from the reduced sediment loads.

Table 12: Estimation of increased water clarity percentiles from reduced sediment loads

	Hātea River	Waiarohia Stream	Otaika River
Value of *m* from figures 22, 23, 24	–0.95	–0.78	–0.95
Reduced sediment load as fraction of old	*q*	*q*	*q*
Percentiles of sediment concentration as fraction of old	*q*	*q*	*q*
Percentiles of turbidity as fraction of old	$q^{1.14}$	*q*	*q*
Ratio of new over old water clarity percentiles	1/(*q***1.14)**0.95	1/*q***0.78	1/*q***0.95

Table 13 gives an example of how to estimate increases to water clarity as a result of a 50 percent reduction in sediment loads.

Table 13: Estimation of increased water clarity percentiles from a 50 percent reduction in sediment loads

	Hātea River	Waiarohia Stream	Otaika River
Value of *m* from figures 22, 23, 24	–0.95	–0.78	–0.95
Reduced sediment load as fraction of old	0.5	0.5	0.5
Percentiles of sediment concentration as fraction of old	0.5	0.5	0.5
Percentiles of turbidity as fraction of old	0.454 (= $0.5^{1.14}$)	0.5	0.5
Ratio of new over old water clarity percentiles	2.12 (= 1/(0.454)**0.95 (i.e., 112% increase)	1.71 (= 1/0.5**0.78) (i.e., 71% increase)	1.93 (= 1/0.5**0.95 (i.e., 93% increase)

4.3.4 Increase in euphotic depth

Euphotic depth is a power relationship of turbidity as given by equation (1).Therefore, if turbidity is reduced to a fraction p of what it was, then the water clarity will be increased to:

$$\boldsymbol{ED' = ED/sqrt(p)} \quad \textbf{(13)}$$

Table 14 shows how the increased euphotic depth percentiles may be estimated from the reduced sediment loads.

Table 14: Estimation of increased euphotic depth percentiles from reduced sediment loads

	Hātea River	Waiarohia Stream	Otaika River
Value of *m* from figures 22, 23 and 24	–0.95	–0.78	–0.95
Reduced sediment load as fraction of old	*q*	*q*	*q*
Percentiles of sediment concentration as fraction of old	*q*	*q*	*q*
Percentiles of turbidity as fraction of old	$q^{1.14}$	*q*	*q*
Ratio of new over old euphotic depth percentiles	1/(*q***1.14)**0.5	1/*q***0.5	1/*q***0.5

Table 15 gives an example of how to estimate increases to euphotic depth percentiles from a 50 percent reduction in sediment loads.

Table 15: Estimation of increased euphotic depth percentiles from a 50 percent reduction in sediment loads

	Hātea River	Waiarohia Stream	Otaika River
Value of *m* from figures 22, 23, 24	–0.95	–0.78	–0.95
Reduced sediment load as fraction of old	0.5	0.5	0.5
Percentiles of sediment concentration as fraction of old	0.5	0.5	0.5
Percentiles of turbidity as fraction of old	0.454 (= $0.5^{1.14}$)	0.5	0.5
Ratio of new over old euphotic depth percentiles	1.48 (= 1/(0.454)**0.5 (i.e., 48% increase)	1.41 (= 1/0.5**0.5) (i.e., 41% increase)	1.41 (= 1/0.5**0.5) (i.e., 41% increase)

4.3.5 Decrease in embeddedness

Embeddedness is given by the sediment concentration at one-quarter of the mean annual flood. Hence, when sediment load becomes a fraction q of what it was (due to soil conservation works) then embeddedness becomes the same fraction q of what it was.

$$\boldsymbol{EB' = q.EB} \quad \textbf{(14)}$$

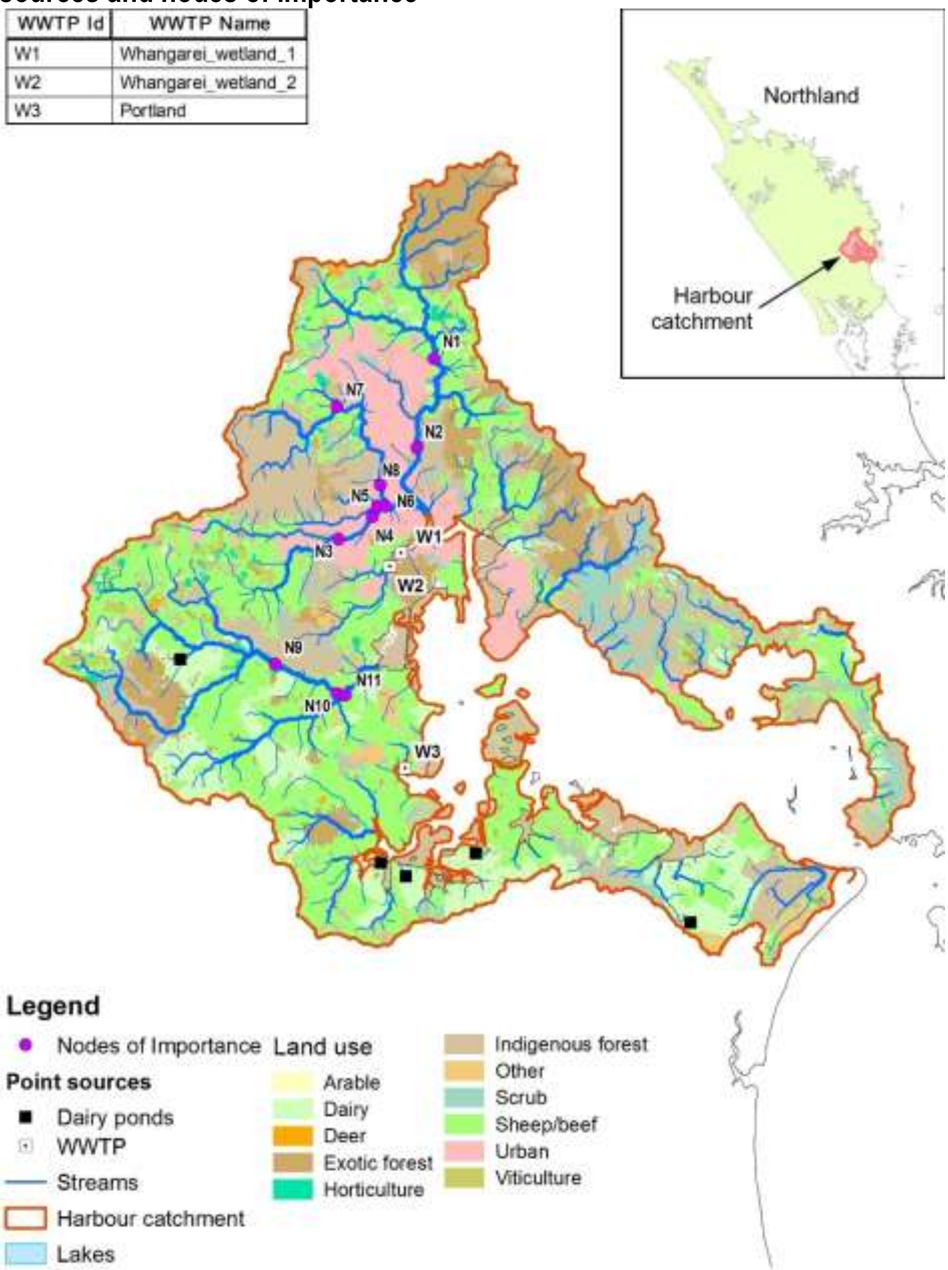
5 Whangarei Harbour catchment *E. coli* modelling

This section outlines the methodology used to estimate baseline *E. coli* loads in the Whangarei Harbour catchment.

A customised version of the CLUES (Elliott et al, 2005; Semadeni-Davies et al, 2011) was developed and calibrated to estimate *E. coli* loads in the Northland region, with a specific emphasis given to the Whangarei Harbour catchment. The model was calibrated to as many suitable sites in the region as possible, rather than just to those sites within the harbour catchment, to improve the model predictions for the harbour catchment.

Water quality modelling focused on 11 "nodes of importance" in the Whangarei Harbour catchment that were identified by the NRC, as well as *E. coli* loads entering the Whangarei Harbour (as shown in Figure 29).

Figure 29: Whangarei Harbour catchment showing streams of order ≥ 3, lakes, land use, point sources and nodes of importance



Note: WWTP: wastewater treatment plant.

The total size and distribution of each REC2 catchment in which each node of importance is located varies widely. This has an impact on the total effectiveness of implementing particular mitigation options to meet attributes for each of these nodes.

Table 16 shows the land use of the Whangarei Harbour catchment sites classified as nodes of importance.

Table 16: Landuse (hectares) of Whangarei Harbour catchment sites classified as nodes of importance

Node #	Site	Dairy	Deer	Pine	Grapes	Native	Other	Sheep and beef	Scrub	Arable	Horticulture	Urban	Total area
1	Whangarei Falls	0.0	0.0	0.0	0.0	3.1	0.0	5.3	0.0	0.0	0.3	5.1	14
7	Waiarohia at confluence with Waiarohia and Waikahitea	0.0	0.0	5.2	0.0	29.4	1.3	50.4	4.4	0.9	8.6	0.4	101
2	Hātea at Mair Park Footbridge	0.0	0.0	0.0	0.0	72.6	0.1	0.0	3.5	0.0	0.0	35.1	111
8	Waiarohia at Second Ave	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	52.1	52
6	Raumanga just before it joins the Waiarohia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.3	5
5	Kirikiri just before it joins the Raumanga	0.0	0.0	0.0	0.0	16.5	1.1	0.8	0.0	0.0	0.0	87.6	106
4	Raumanga at Bernard Street	0.0	0.0	0.3	0.0	6.0	0.0	0.0	0.0	0.0	0.0	41.6	48
3	Raumanga Stream at swimming pool below falls	0.0	0.0	0.0	0.0	11.9	0.0	0.0	0.0	0.0	0.0	12.4	24
9	Otaika at Otaika Valley Road	0.0	0.0	0.5	0.0	30.6	0.0	27.3	2.2	0.0	0.0	0.0	61
10	Otaika weir (Golden Bay surface water take)	0.6	0.0	0.0	0.0	24.1	0.0	50.6	0.1	0.0	0.0	0.0	75
11	Puwera just before it joins Otaika	0.0	0.0	0.0	0.0	0.0	0.0	9.9	4.1	0.0	0.0	0.0	14

Note: Red text indicates nodes with both *E. coli* and sediment attributes. All other sites measure *E. coli* only.

The CLUES model was identified as suitable for estimating *E. coli* loads and concentrations. CLUES has been set up on a regional basis and has been calibrated nationally. However, to update and improve the spatial representation of the catchment, the CLUES model was customised and recalibrated specifically for this application.[5] The customised CLUES model uses 2011 land use in the Northland region, which was provided by Landcare Research. The customised CLUES model was calibrated against measured *E. coli* loads, which were determined from *E. coli* concentrations and flow data from a number of sites in the region.

E. coli loads were calculated for catchments defined according to the sub-catchment classification. Of these sub-catchments, 655 were within the Whangarei Harbour catchment. Areas of land that discharged directly to the harbour were grouped into a single pseudo-catchment and treated as other catchments.

5.1 METHODOLOGY

The CLUES model determines mean annual loads of *E. coli*. The catchment of interest is broken into REC2 sub-catchments, and each sub-catchment has several land uses with associated yields, which are modified according to environmental factors such as rainfall.

[5] Customisation included the introduction of a slope term; adjustment of model parameters where appropriate to improve the fit of model predictions with measured loads; use of a formal method for assessing goodness-of-fit and the variability and inter-dependency of the adjusted model parameters.

These sources are accumulated and decayed down the stream network, with the addition of point source loading. This gives estimated loads for each stream reach in the catchment.

The various parameters in the model are determined by calibration to measured loads. Rather than using parameters from national calibration exercises, NIWA recalibrated the model for Northland using data from 25 suitable sites, including five sites in the Whangarei Harbour catchment. The resulting parameters were then applied to the Whangarei catchment.

After calibration, the loads for all the streams became known as the "current loads", because they are based on the current (2011) land use. The current loads estimated for 655 streams in the harbour catchment represent the baseline load used by the catchment economic model.

The predicted *E. coli* loads were converted to *E. coli* concentrations. A linear relationship between load and concentration is assumed, that is, if a mitigation option reduces loads by X percent, then current concentrations are assumed to reduce by X percent as well. This linearity assumption has not been validated with experimental data, because it would require long-term observations covering a period of substantial change. It is possible to envisage situations where the relationship may break down, such as under large climate shifts, timing of loading or large land-use changes. Nevertheless, this is a reasonable assumption, and significantly more detailed modelling and measurement would be required to improve upon it.

The economic model focuses on calculated concentrations at the nodes of importance. The current concentrations at those locations were determined from measurements where available or were estimated from the estimated current loads and flow rates.

The *E. coli* load to the Whangarei Harbour was also determined. While *E. coli* loads into the harbour are not being investigated by the catchment economic model, changes in harbour *E. coli* loads are still considered to be of interest as co-benefits from policies for controlling sediment loading to the harbour and *E. coli* concentrations in-stream. For example, fencing undertaken to reduce streambank erosion will also reduce *E. coli* losses from that farm.

5.1.1 Calibration sites and measured loads

Water quality sites were deemed suitable for model calibration if they had more than 50 *E. coli* observed data points with corresponding flow data. Mean annual loads for suitable sites were calculated for all of these sites using rating curve methods. The methods fit a rating curve to the relationship between concentration and flow, and then apply this relationship to continuous flow records over the period of interest (20 years, in this case).

Two separate load values were determined: a) using all flows (L_A); and b) using only flows below the 95th percentile of flows (L_{95}). The reasoning is that L_A is of interest for harbour loading, but L_{95} estimates have less error (because they omit the uncertain contributions from storms) and are more relevant to normal flow conditions.

To establish the variation in L_A and L_{95}, the ratio of the upper 90 percent confidence interval (CI) to the lower 90 percent CI was calculated for L_A (that is, (90 percent upper CI L_A) / (90 percent lower CI L_A)), and for L_{95}, using bootstrap resampling[6] of the concentration data. The results are given in Table 17. Because of the wide variation in the ratio for L_A, calibration of the customised CLUES was limited to L_{95}.

[6] Random sampling with replacement.

Table 17: The mean annual load ratio of the upper 90 percent confidence interval to the lower 90 percent confidence interval for the River Water Quality Monitoring Network sites

(90% upper CI L_A) / (90% lower CI L_A)			(90% upper CI L_{95}) / (90% lower CI L_{95})		
Range	**Mean**	**Standard deviation**	**Range**	**Mean**	**Standard deviation**
3.4–592.9	51.5	114.3	1.5–10.3	3.4	2.5

Note: L_A represents the load calculated for all flow conditions, and L_{95} represents loads calculated for flows less than the 95th percentile; CI is confidence interval.

The rating curve method requires a flow record, but flow data are not recorded at all water quality monitoring sites. For several water quality sites, a flow recorder was not in place at the actual site, but there was a suitable record within a reasonable distance to generate a synthetic flow record. These records were provided by the NRC. A rating curve method, based on Generalised Additive Modelling (GAM), was used to calculate measured loads, as used by Palliser and others (2015b). However if:

- no concentration-versus-flow rating curve was available for a site because there was no nearby flow site; or
- there was too much uncertainty in the calculated load, that is:
  - the standard deviation of the natural logarithms of bootstrap replicates for $L_{95} > 1$; or
  - (95 percent lower CI L_{95}) / (L_{95}) < 0.5; or
  - (95 percent upper CI L_{95}) / (L_{95}) > 2.0;

then the site was discarded. Twenty-five of 73 water quality monitoring sites in Northland satisfied three selection criteria and were selected for model calibration. Five of these sites fell within the Whangarei Harbour catchment.

Land areas around the harbour fringe

The REC network on which CLUES is based did not extend to the shoreline fringes of the Whangarei Harbour. This area (which NIWA called “pseudo-catchments”) is 3814 hectares in extent and represents 14 percent of the total area of the harbour catchment. There were 61 pseudo-catchments across the harbour catchment and their loads were obtained in a similar way to CLUES, that is, multiplying the area of each land use in a pseudo-catchment by its yield coefficient (peta[7] *E. coli* per hectare per year) and then summing the individual load estimates. The yields were obtained from the model calibration (discussed below). Unlike the rest of the customised CLUES catchment areas, the loads from these areas were assumed to discharge directly to the harbour unattenuated. Table 18 shows the calibration site data for Whangarei.

[7] Peta = 10^{15} *E. coli*

Table 18: Calibration site data in Whangarei

Water quality sites								Site from which flow was obtained		
Site name	Site ID	Period		Measured median concentration (cfu/100 ml) /period		Measured 95th percentile concentration (cfu/100 ml) /period		Site name	Site ID	Measured mean flow (L/s)
		20 yr	5 yr	20 yrs	5 yrs	20 yrs	5 yrs			
Hātea at Mair Park Footbridge	100194	90	67	302	259	7 270	6 306	Hātea at Whareora Road	5538	1 333
Raumanga Stream	103246	143	79	228	211	3 255	3 076	Raumanga at Bernard Street	5528	345
Waiarohia at Waikahitea confluence	107773	100	45	521	525	2 948	3 485	Waiarohia at Lovers Lane	5527	257
Waiarohia at Second Ave	108359	121	66	399	399	4 586	5 421	Waiarohia at Lovers Lane	5527	409
Otaika at Otaika Valley Road	110431	48	48	484	484	4 378	4 378	Otaika at Kay	5659	919

Note: concentration data over the past 20 years and past 5 years; flow data over the past 20 years; cfu = colony forming units; L/s = litres per second; mL = millilitres; yr = year.

5.1.2 Point sources

E. coli loads were estimated for wastewater treatment plants within the Whangarei Harbour catchment and for farm dairy effluent ponds across Northland. Within the Whangarei Harbour catchment, the model accounted for three municipal wastewater discharges and five dairy shed effluent ponds.

5.1.3 Model calibration

The model was calibrated by minimising the difference between the measured and predicted loads of 25 calibration sites in the form of the root mean square error (RMSE)[8] in natural log space. The RMSE was calculated using the following equation:

$$\textbf{RMSE} = \sqrt{\left(\sum (\boldsymbol{Ln}(\boldsymbol{Predicted\ load}) - \boldsymbol{Ln}(\boldsymbol{Measured\ load}))^2 / \boldsymbol{n}\right)} \qquad \textbf{(15)}$$

The calibration involved optimising various parameters used in the model to minimise the RMSE. Standard errors were also calculated for the parameters. The parameters that were optimised are described below.

Yield coefficients

The model included the loads from point sources and those from the land-use types. The loads from the land uses were calculated by multiplying the area of each land use by its yield coefficient (peta *E. coli* per hectare per year that is, 1015 *E. coli* per hectare per year). The yield coefficient for “urban” land use was set at 0.99 peta *E. coli* per hectare per year as established for the Waikato River and Waipa River catchments (Semadeni-Davies et al, 2015). The other land uses were grouped for yield coefficient purposes as follows:

- “deer” and “dairy” were assigned the same yield coefficient;
- “sheep and beef” had its own yield coefficient;

[8] The RMSE is used as a standard statistical metric to measure model performance in many fields, including meteorology, air quality, climate research and agriculture. It assumes the errors (= predicted – measured) are unbiased and follow a normal distribution.

- "non-pasture" included arable, exotic forest, horticulture, indigenous forest, other, scrub and viticulture land uses, which were assigned a common yield coefficient.

Examination of these three estimated or fitted yield coefficient values after optimisation indicated it was possible to have similar yield coefficients for deer and dairy as for sheep and beef, and for non-pasture as for sheep and beef. Because the model was unable to provide different yield coefficients for deer and dairy, and sheep and beef land uses, it was deemed expedient to combine the yield coefficients for deer and dairy and sheep and beef into one called "pasture", apply a single yield coefficient and re-optimise the coefficients. See Table 19 for the results.

Table 19: Re-optimisation of the yield coefficients and their standard errors

Land use	Yield coefficient (peta *E. coli* per hectare per year)	Standard error
Pasture = deer, dairy and sheep and beef	0.77	0.17
Non-pasture = arable, exotic forest, horticulture, indigenous forest, other, scrub and viticulture	0.13	0.07

Decay coefficients

There are two decay coefficients in the model – one associated with the decay of *E. coli* in streams and the other with its decay in lakes. Both optimised to approximately zero, so a value of zero was used, that is, there was no in-stream or in-lake decay.

Land-to-water delivery coefficients

Three land-to-water delivery coefficients – mean annual rainfall, mean Land Use Capability (LUC) soil drainage class and land slope – were investigated. Each of these modifies the diffuse source coefficient according to an exponential function of the relevant variable (such as rainfall). The addition of drainage and slope terms did not improve the model significantly, so they were removed from the final model. The calibrated exponent for rain was 2.0185 with a standard error = 0.7953 (where rainfall is in metres per year). The statistics for rainfall for each of the 25 calibration sites are given in Palliser and others (2015b).

The RMSE of the final modelled load (peta *E. coli* per year) equalled 0.56 and a R^2 value of 0.86. In non-log space, this means an error factor of exp(0.56) at the one standard error level. The RMSE, in non-log space, of the final modelled specific load (or yield, that is, peta *E. coli* per hectare per year) was 0.31, with an R^2 value of 0.62.

5.1.4 Calculating *E. coli* loads to the Whangarei Harbour

Four components were involved in calculating the load the harbour:

- load from terminal streams, that is, the loads from the 98 streams that discharge directly into the harbour;
- load from the pseudo-catchments around the shoreline fringes of the harbour;
- load from Portland Whangarei Wastewater Treatment Plant (WWTP);
- one farm dairy effluent pond near the shoreline was not close to a stream, so it was assumed that this pond discharged into the harbour.

To obtain the total *E. coli* loads, including all flows and not just those from the 95th percentile of flows, the ratio L_A/L_{95}, was calculated for each of the five calibration sites where suitable measured loads existed (see Section 5.1.1). The mean of these five ratios (26) was then multiplied by the predicted L_{95} for the 98 terminal streams to obtain their contribution to the total *E. coli* load to the harbour.

Similarly, the loads from the 61 pseudo-catchments were multiplied by the mean ratio to obtain their contribution to the total *E. coli* load to the harbour.

5.1.5 Calculating *E. coli* loads at the nodes of importance

Eleven sites (referred to as nodes of importance) within the Whangarei Harbour catchment are of particular interest to the NRC, in terms of the current median and 95th percentile concentrations (see Figure 29 above). Seven of the nodes of importance are monitored and six had sufficient measured data to calculate median and 95th percentile concentrations. Insufficient concentration data were available for one node, and no concentration data existed for four other nodes of importance.

The median and 95th percentile concentrations ($C_{median,pred}$ and $C_{95,pred}$) for each of these five sites were predicted as outlined below:

Predicted median concentrations for nodes without suitable measurements

The median concentrations were calculated using equation (16):

$$\boldsymbol{C_{median,pred}} = \frac{\boldsymbol{L_{95} \times R_1}}{\boldsymbol{Q_{mean}}} \qquad \textbf{(16)}$$

where $C_{median,pred}$ is the predicted median concentration, L_{95} is the load based on the 95th percentile of flows, Q_{mean} is the mean flow at the closest flow site (adjusted if necessary as described in Section 5.1.1 and R_1 is a ratio calculated from those six sites where measured median and 95th percentile concentrations exist. R_1 was calculated at those six sites using equation (17):

$$\boldsymbol{R_1} = \frac{\boldsymbol{C_{median,meas} \times Q_{mean}}}{\boldsymbol{L_{95}}} \qquad \textbf{(17)}$$

where $C_{median,meas}$ is the measured median concentration.

The locations of the five nodes of importance that did not have measured concentrations were examined to see if they were close to any that do. For those that were close to sites with measured concentrations, equation (1) was used to calculate $\boldsymbol{C_{median,pred}}$. For the remaining three nodes of importance that did not have measured concentrations and were not close to any that do, $\boldsymbol{R_1}$ was taken to be the average of those that do (1.1766) and used in equation (16) to calculate $\boldsymbol{C_{median,pred}}$.

Predicted 95th percentile concentrations for nodes without suitable measurements

The ratio:

$$\boldsymbol{R_2} = \frac{\boldsymbol{C_{95,meas}}}{\boldsymbol{C_{median,meas}}} \qquad \textbf{(18)}$$

was calculated for the six nodes of importance where measured median and 95th percentile concentrations exist. The mean value of this ratio for those six sites was then applied to the median concentration at the remaining sites to estimate the 95th percentile concentrations for these six sites, $C_{95,pred}$:

$$\boldsymbol{C_{95,pred}} = \boldsymbol{C_{median,pred}} \times \boldsymbol{R_2} \qquad \textbf{(19)}$$

5.2 RESULTS

5.2.1 Calibration

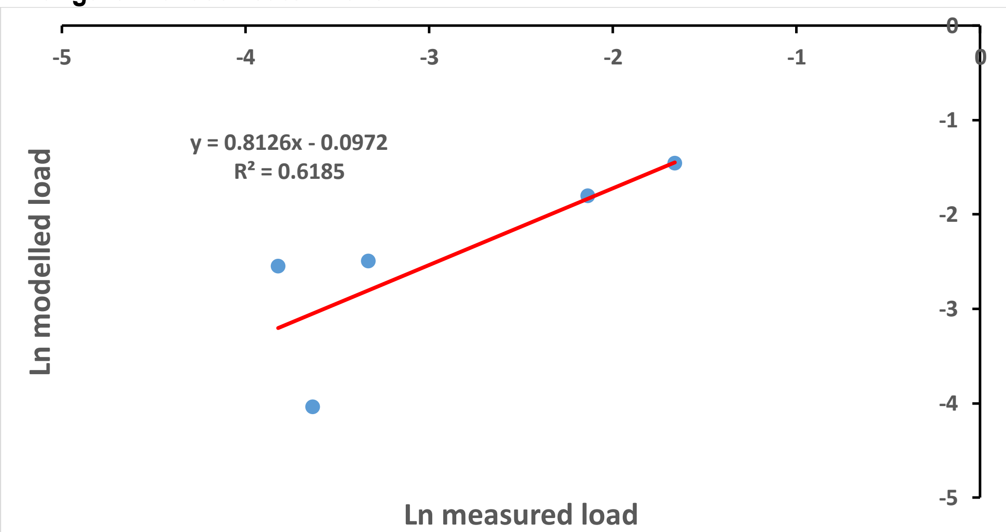
The calibration results are summarised in Table 20 below. Figure 30 shows the measured versus predicted *E. coli* loads for the five calibration sites in the Whangarei Harbour catchment, while Figure 31 shows the same results for *E. coli* yields.

Table 20: Measured and predicted (or modelled) *E. coli* loads at the calibration sites in the Whangarei Harbour catchment

Calibration site name, site ID	Mean load (peta per year)		Percentage load error[1]
	Measured	Predicted	
Hātea at Mair Park Footbridge, 100194	0.1893	0.2322	23
Raumanga Stream, 103246	0.0218	0.0780	257
Waiarohia at Waikahitea confluence, 107773	0.0263	0.0176	–33
Waiarohia at Second Ave, 108359	0.0357	0.0827	132
Otaika at Otaika Valley Road, 110431	0.1176	0.1645	40

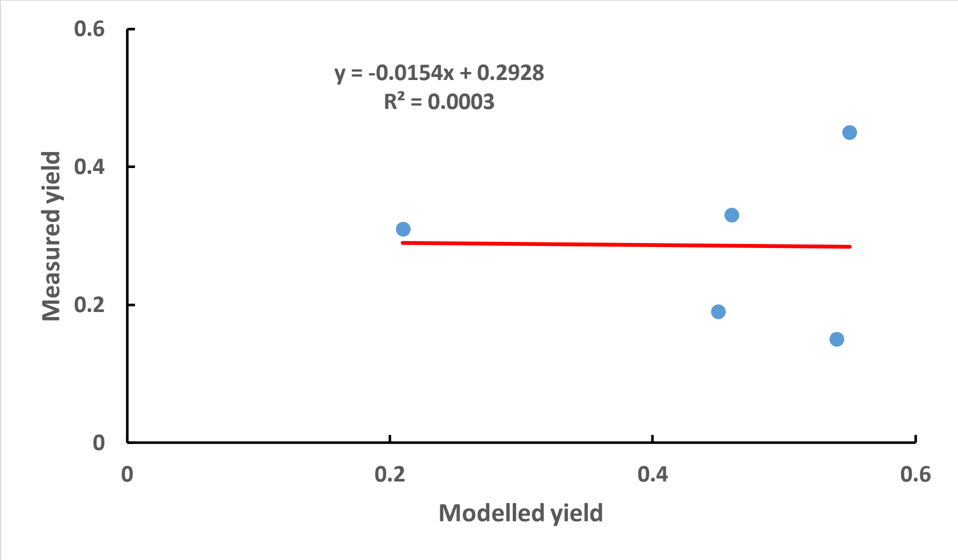
Note: [1] Equals (Predicted – Measured)/Measured.

Figure 30: Measured versus predicted *E. coli* loads for the five calibration sites in the Whangarei Harbour catchment



Note: Ln = log

Figure 31: Measured versus predicted *E. coli* yields for the five calibration sites in the Whangarei Harbour catchment



To better understand *E. coli* dynamics, concentrations, yields and land uses at the calibration sites were examined in detail. It was expected that catchments with higher proportions of pasture would have higher *E. coli* concentrations and catchments that were predominantly forested would have lower *E. coli* concentrations. However, as seen in Table 21, this was not always the case. For example, selected forested catchments in Northland exhibited *E. coli* concentrations that were larger than those predicted for catchments where pastoral land use was dominant.

Table 21: Concentrations, yields and land uses for the 25 calibration sites

Calibration site name, site ID	Measured median concentration over past 5 years (cfu/100 mL)	Mean yield (peta per hectare per year)		Predominant land uses (%t)
		Measured	Predicted	
Hātea at Mair Park Footbridge, 100194	259	0.45	0.55	Forest 43, Sheep and beef 34, Urban 15
Raumanga Stream, 103246	211	0.15	0.54	Sheep and beef 50, Forest 26, Urban 11
Waiarohia at Waikahitea confluence, 107773	525	0.31	0.21	Forest 82, Sheep and beef 12
Waiarohia at Second Ave, 108359	399	0.19	0.45	Forest 55, Urban 22, Sheep and beef 17
Otaika at Otaika Valley Road, 110431	484	0.33	0.46	Sheep and beef 44, Forest 31, Dairy 14

Note: cfu = colony forming unit; mL = millilitres; yields = measured loads (L_{95})/area; forest includes both exotic and indigenous.

Within the Whangarei Harbour catchment, the model predicted that the overwhelming bulk of the *E. coli* load was derived from streams flowing directly into the harbour, rather than the pseudo-catchment or point source discharges. These apparent anomalies cannot be explained at present but could be related to decay factors and possibly input from feral animals in forested areas.

Sources of uncertainty in the model include:

- water quality monitoring sites where there is no coincident flow site, so that flow data are used from a nearby site if there is one;
- lack of knowledge around *E. coli* land and stream dynamics;
- groundwater not included in the model, although it is unlikely this is a significant factor for *E. coli*;
- the measured loads, which are used for calibration, have considerable uncertainties. For example, bootstrapping of the load estimate showed considerable imprecision of the load estimate, such that the 90-percentile L_{95} value was 3.4 times the 10-percentile L_{95} value, on average. There may also be biases in the load estimates (a tendency to underestimate or over-estimate the measured load in relation to the actual true load) that the bootstrapping method does not evaluate. These sources of measurement limit the accuracy and precision of the model. For example, it would not be reasonable to expect the model residual error to be less than the uncertainty in the measurements.

5.2.2 *E. coli* loads to the Whangarei Harbour

Total loads (that is, not just those from the 95th percentile of flows) are shown in Table 22. Most of the load is coming from the terminal streams. Figure 32 provides a graphical illustration and Figure 33 shows what proportion of land use contributes to *E. coli* loads at the entrance to the harbour.

Total load from point sources
= (load from five FDE ponds) + (load from WWTPs)

= load from four FDE ponds that discharge into streams + load from one FDE pond that discharges directly into the harbour + load from Portland WWTP + load from Whangarei WWTP (wetland 1) + load from Whangarei WWTP (wetland 2)

= 0.0238 + 0.0058 + 0.0012 + 0.0.0195 + 0.0552

= 0.1055 peta per year.

Total load from diffuse sources = 294.3650 peta per year.

Table 22: Total predicted *E. coli* loads to the Whangarei Harbour

Source	Predicted total load (peta per year)
Terminal streams[1]	290.1900
Pseudo-catchments	4.4237
Portland Wastewater Treatment Plant	0.0012
One farm dairy effluent pond that discharges directly to the harbour	0.0090
TOTAL	**294.6239**

Note: [1] Includes 0.0747 peta per year from the Whangarei Wastewater Treatment Plant, and 0.0288 peta per year from the four farm dairy effluent ponds that discharge into streams.

Figure 32: *E. coli* load into the Whangarei Harbour by reach (peta *E. coli*)

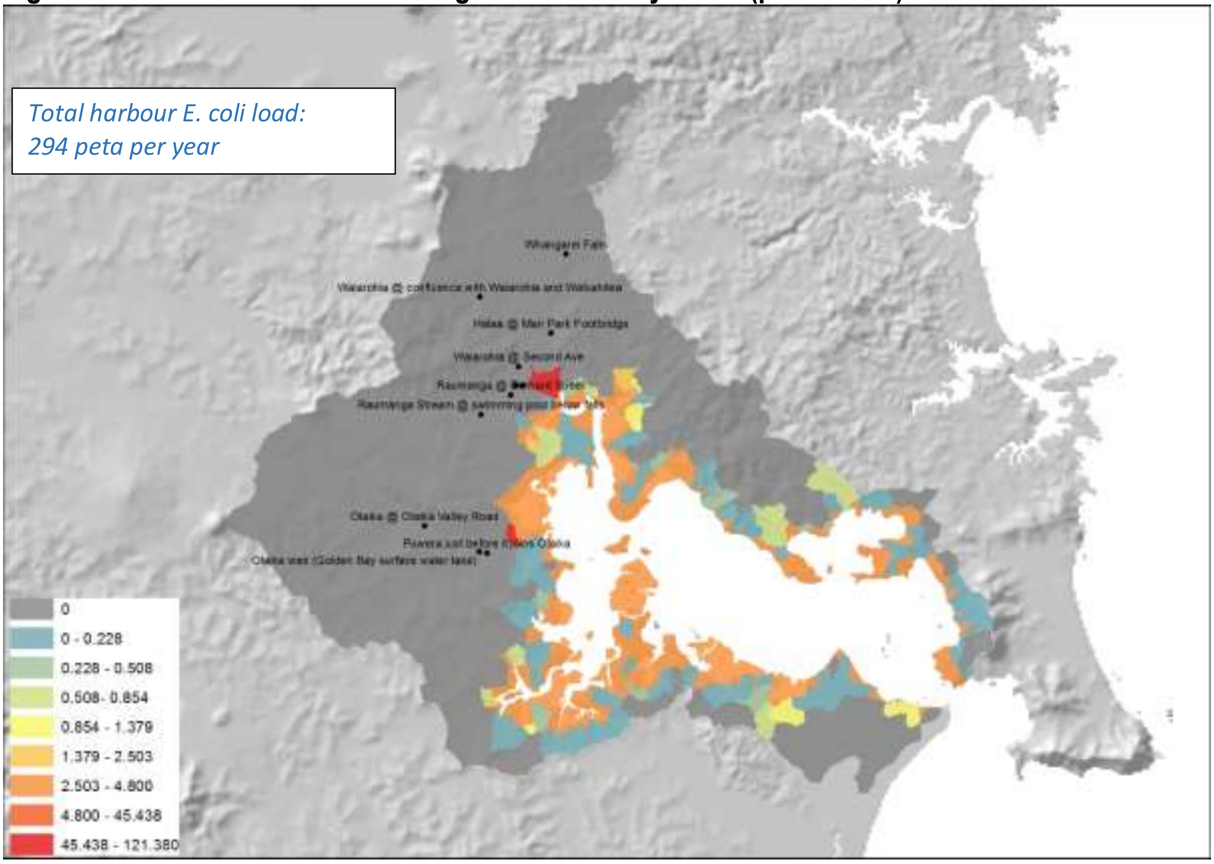
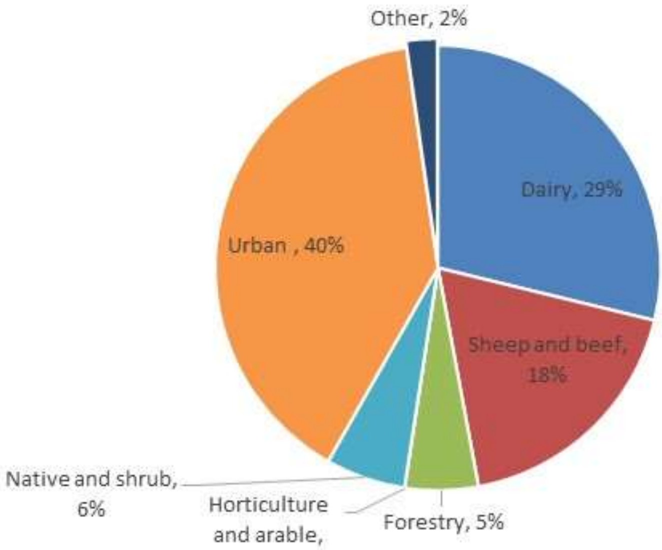


Figure 33: Source of *E. coli* into the Whangarei Harbour



5.2.3 *E. coli* concentrations at the nodes of importance

Concentrations predicted at the nodes of importance are summarised in Table 23, and Figure 34 provides a graphical illustration. Figure 35 shows what proportion of land use contributes to *E. coli* loads in freshwater environments at the nodes of importance. There is uncertainty with the method for getting concentrations from loads (see equations (16)and (19)), uncertainty around the relative contributions from pasture and forest, and poor model performance for some of the streams in the Whangarei catchment (for example, the Raumanga Stream).

Table 23: *E. coli* concentrations at the freshwater nodes of importance

Node #	Node of importance name	Site ID	Median concentration (cfu/100 ml)	95th percentile concentration (cfu/100 ml)
N2	Hātea at Mair Park Footbridge	100194	259	6 306
N3	Raumanga Stream at swimming pool below falls	103246	211	3 076
N1	Whangarei Falls	105972	439	2 003
N7	Waiarohia at confluence with Waiarohia and Waikahitea	107773	525	3 485
N8	Waiarohia at Second Ave	108359	399	5 421
N9	Otaika at Otaika Valley Road	110431	484	4 378
N4	Raumanga at Bernard Street	304709	903[a]	13 164
N5	Kirikiri immediately upstream the Raumanga	–	722	9 852
N6	Raumanga immediately upstream the Waiarohia	–	942	12 844
N10	Otaika weir (Golden Bay surface water take)	–	871	7 883
N11	Puwera immediately upstream Otaika	–	1 354	18 470

Note: [a] The nine concentration data points have a median concentration of 315 cfu per 100 mL; cfu = colony forming unit; mL = millilitres. Green text indicates measured concentrations, black text indicates concentrations as predicted in Section 5.1.5.

Figure 34: Total *E. coli* loads by reach at the freshwater nodes of importance (peta *E. coli*)

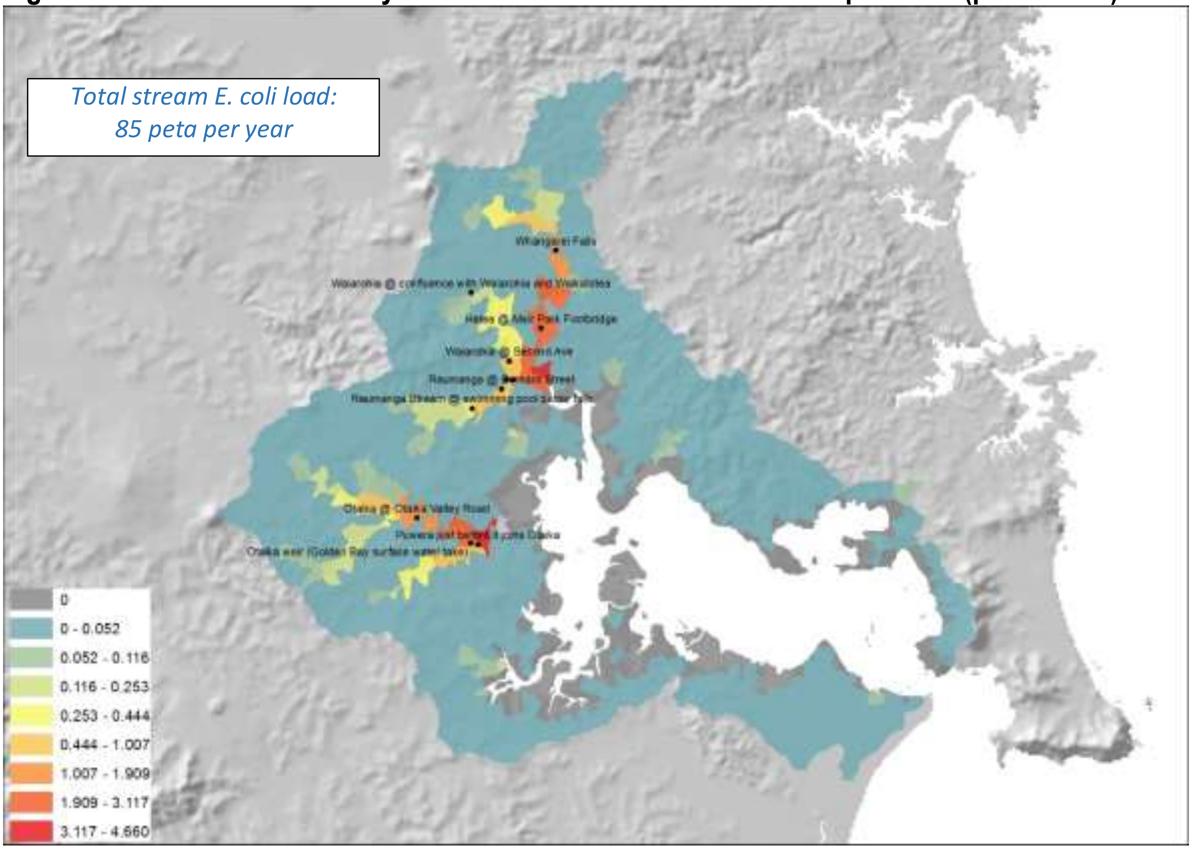


Figure 35: Source of *E. coli* loads in freshwater environments at the nodes of importance

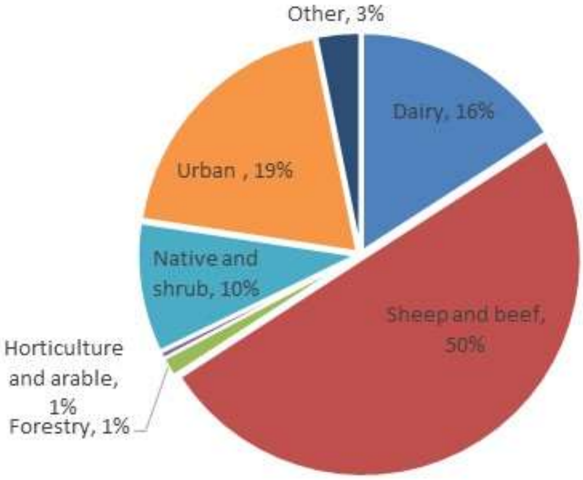
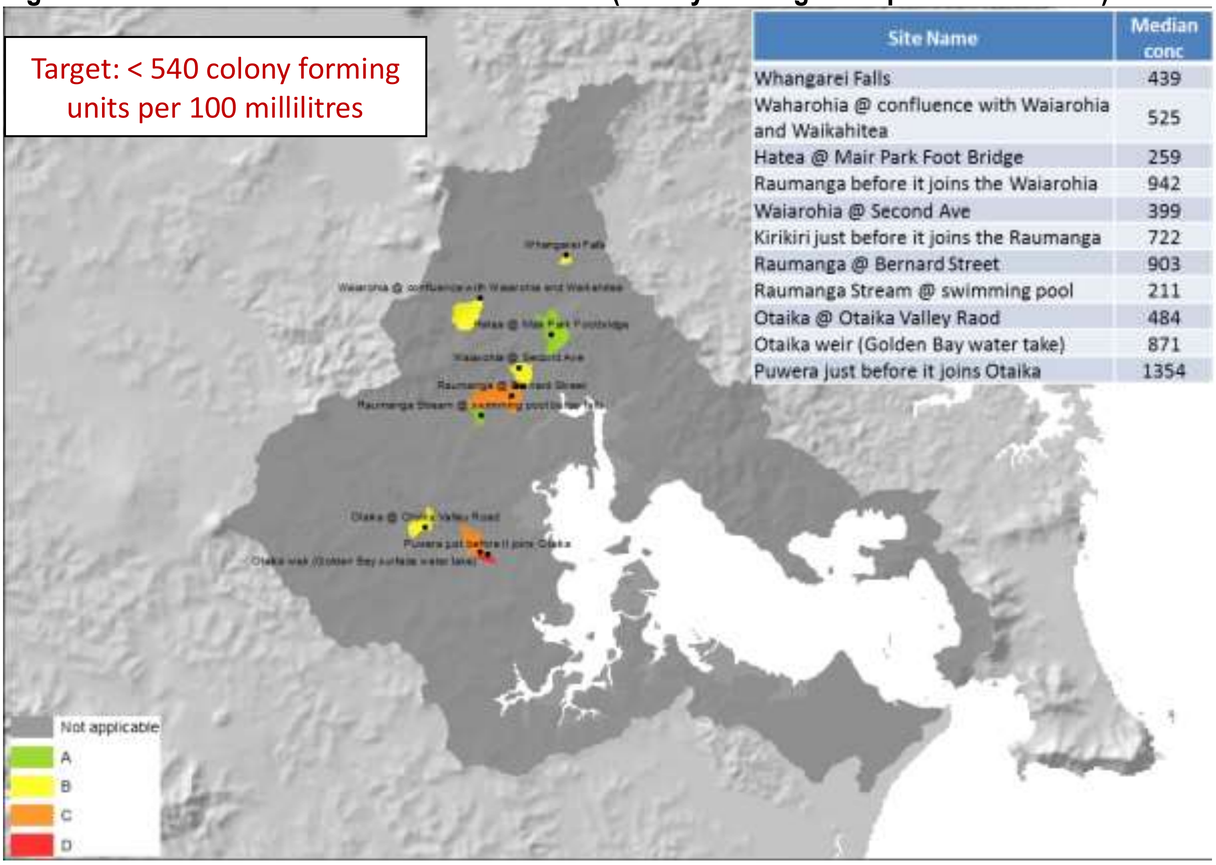


Figure 36 and Figure 37 show the baseline results for the two *E. coli* attributes: annual median and the 95th percentile for the 11 nodes of importance. Most sites meet the required standard for the annual median, but no sites meet the required band for swimming for the 95th percentile.

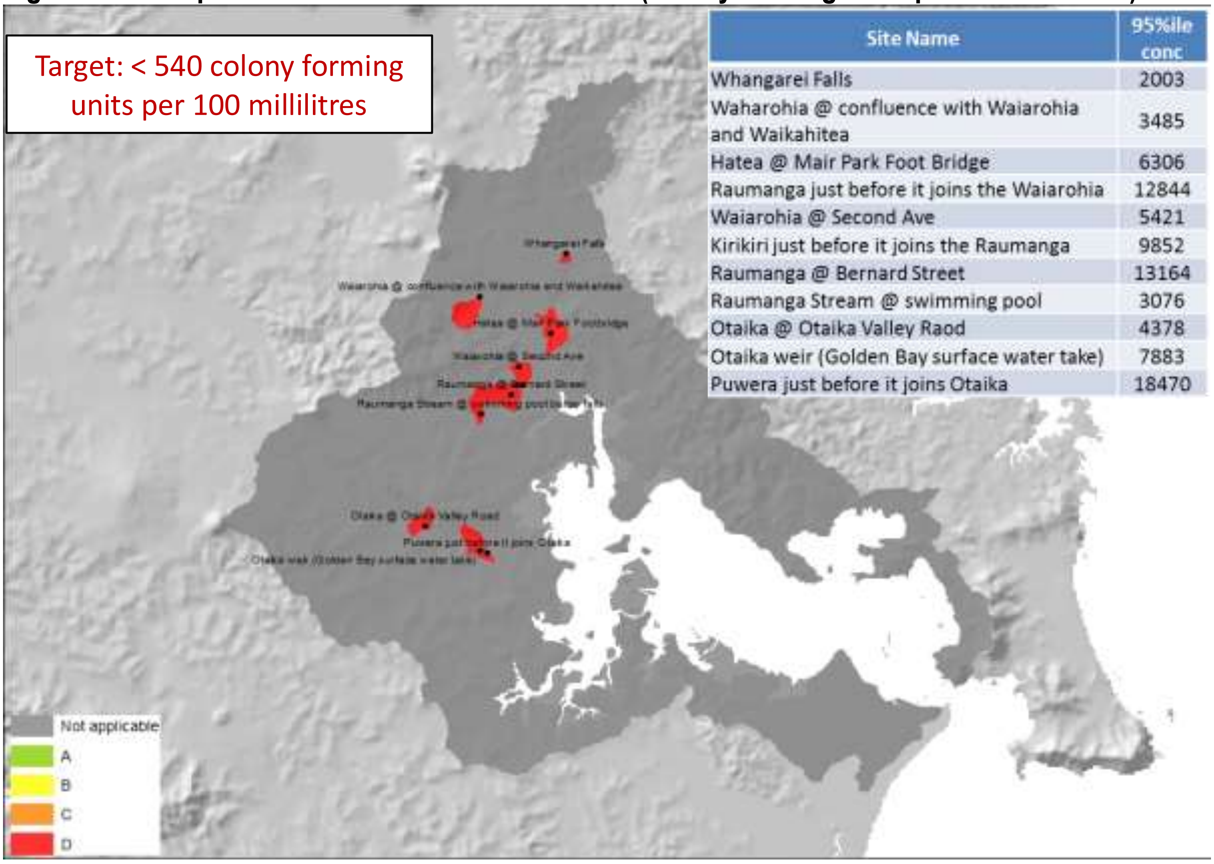
Figure 36: Annual median *E. coli* concentrations (colony forming units per 100 millilitres)



Site Name	Median conc
Whangarei Falls	439
Waharohia @ confluence with Waiarohia and Waikahitea	525
Hatea @ Mair Park Foot Bridge	259
Raumanga before it joins the Waiarohia	942
Waiarohia @ Second Ave	399
Kirikiri just before it joins the Raumanga	722
Raumanga @ Bernard Street	903
Raumanga Stream @ swimming pool	211
Otaika @ Otaika Valley Raod	484
Otaika weir (Golden Bay water take)	871
Puwera just before it joins Otaika	1354

Note: A, B, C and D are the *E. coli* NOF Bands. The C Band (1000 cfu per 100 millimetres) is the national bottom line.

Figure 37: 95th percentile of *E. coli* concentrations (colony forming units per 100 millilitres)



Site Name	95%ile conc
Whangarei Falls	2003
Waharohia @ confluence with Waiarohia and Waikahitea	3485
Hatea @ Mair Park Foot Bridge	6306
Raumanga just before it joins the Waiarohia	12844
Waiarohia @ Second Ave	5421
Kirikiri just before it joins the Raumanga	9852
Raumanga @ Bernard Street	13164
Raumanga Stream @ swimming pool	3076
Otaika @ Otaika Valley Raod	4378
Otaika weir (Golden Bay surface water take)	7883
Puwera just before it joins Otaika	18470

Note: A, B, C and D are the NOF *E. coli* bands. 540 cfu per 100 millilitres is the minimum acceptable state for activities involving full immersion.

6 Whangarei Harbour sediment budget

NIWA developed a sediment budget for the Whangarei Harbour. The budget is used to evaluate the impact of mitigations on the AASR in a number of individual depositional basins in the Whangarei Harbour. This section provides an overview of how the Whangarei Harbour sediment budget was constructed.

6.1 THEORY

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

$$\boldsymbol{D_e = \sum_{c=1}^{C} L_c F_{c,e}} \quad \textbf{(20)}$$

where:

- L_c is the total (that is, the sum of all sediment grainsizes) mass of sediment that is discharged into the harbour from sub-catchment c during the time period Γ, and there are C sub-catchments;
- $F_{c,e}$ is the total-sediment fate matrix, which is the fraction of the total sediment mass that is discharged from sub-catchment 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 sub-catchment sediment D_e by:

$$\boldsymbol{S_e = \frac{D_e + M_e}{\rho_e A_e \Gamma}} \quad \textbf{(21)}$$

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 equation (21) into (22), S_e is seen to be related to the sediment discharged from each sub-catchment L_c by:

$$\boldsymbol{S_e = \frac{(\sum_{c=1}^{C} L_c F_{c,e}) + M_e}{\rho_e A_e \Gamma}} \quad \textbf{22}$$

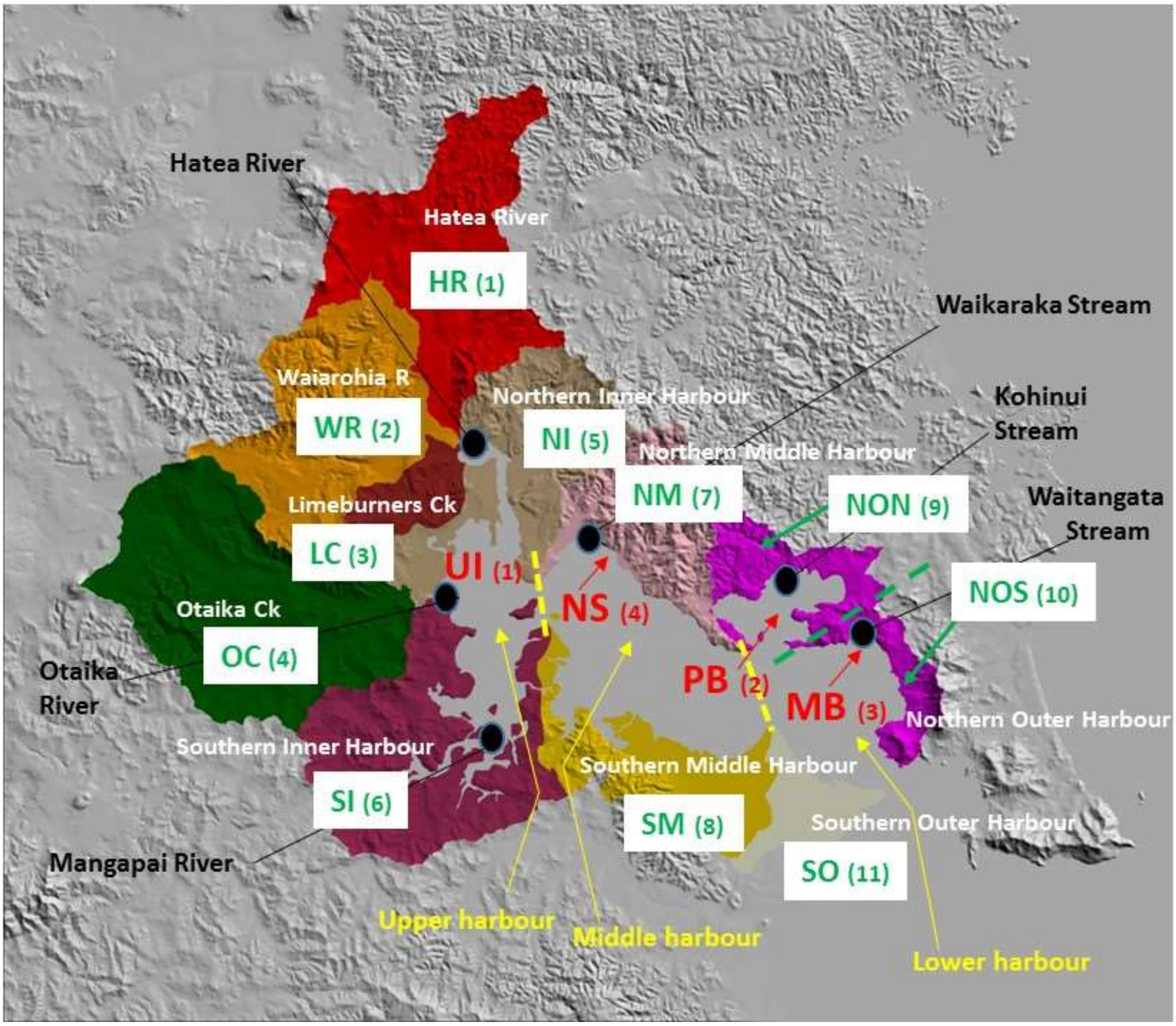
The time period Γ for this application will be one year; hence, S_e is the annual sedimentation rate.

6.2 CONSTRUCTION OF THE SEDIMENT BUDGET FOR THE WHANGAREI HARBOUR

Figure 38 provides a summary of the nomenclature used in the development of the Whangarei Harbour sediment budget.

Figure 38: Summary of the nomenclature used in the Whangarei Harbour sediment budget

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 **sub-catchment** 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



Note: UI = Upper harbour unvegetated intertidal flats; NS = Northern shore from Onerahi Peninsula east to Jacksons Bay; PB = Parua Bay; MB = Munro Bay.

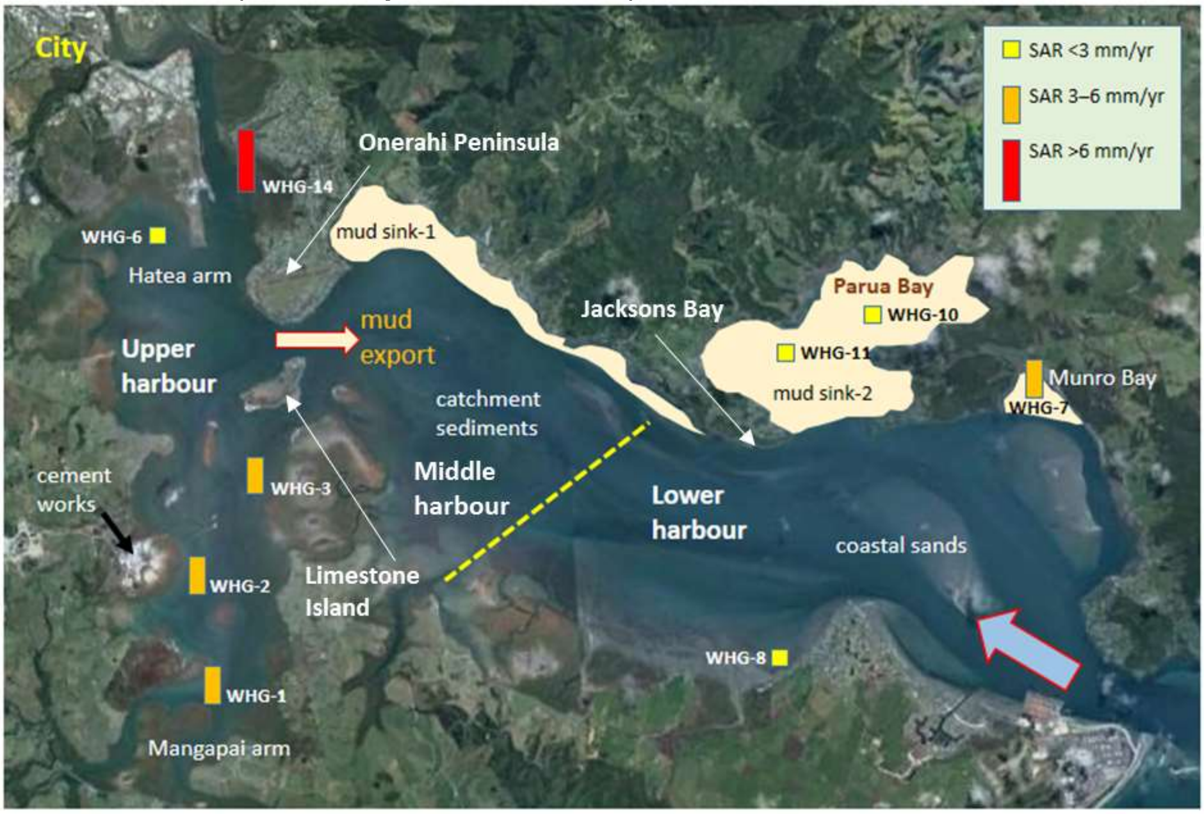
6.2.1 Depositional basins

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) identified three areas in the upper Whangarei Harbour (that is, west of Limestone Island) that deposit catchment sediments and three long-term "mud sinks" east of Onerahi Peninsula (see Figure 39).

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 millimetres per year 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 millimetres per year at the Ports of Auckland);
- upper harbour unvegetated intertidal flats, accreting at a spatially averaged rate of 4 millimetres per year;
- Parua Bay, in the lower harbour (Figure 39), where the intertidal flat is accumulating sediment (2.9 millimetres per year) at a similar rate to the central subtidal basin (2.2 millimetres per year);
- Munro Bay, in the lower harbour (Figure 39), 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 39).

Figure 39: Location map, including the locations of the three long-term mud sinks east of Onerahi Peninsula (identified by Swales et al, 2013)

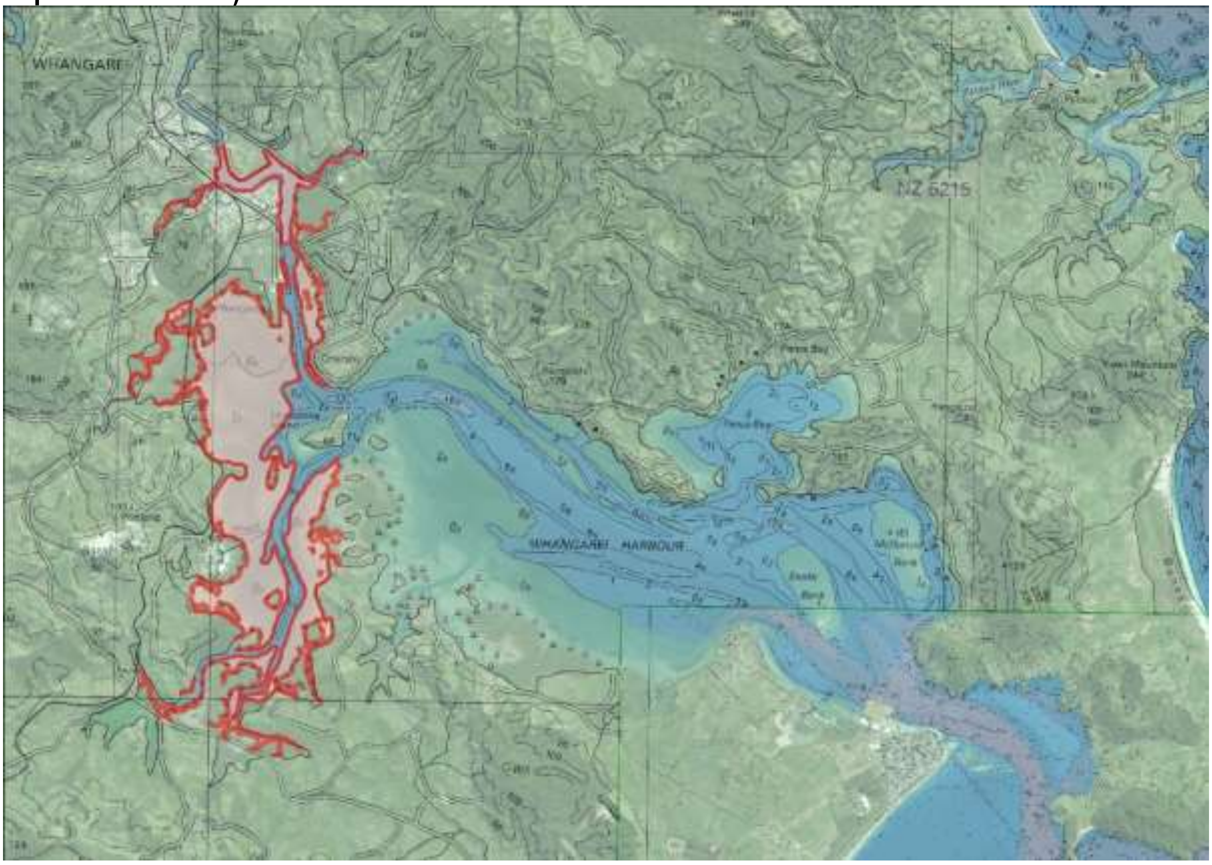


Source: Reproduced from Swales et al (2013).

Note: mm/yr = millimetres per year; WHG = Whangarei; SAR – sediment accumulation rate. 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 Whangarei Harbour study, we follow Swales et al (2013) 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 40 and the others are shown in Figure 39.

Figure 40: 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. The upper harbour mangrove and upper harbour saltmarsh habitats are disregarded because the sediment accumulation rate is thought to be controlled by the rate of sea-level rise in these basins, as described by Swales et al (2013).

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 24 lists the depositional basins and provides basic data for each basin. Notes follow the table.

Table 24: Whangarei Harbour depositional basins included in the study

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

Note: m^2 = square metres; mm/y = millimetres per year; t/m^3 = tonnes per cubic metre.

A (area of depositional basin)

- Swales et al (2013) reported the area of the upper harbour unvegetated intertidal flats, which corresponds to the **UI** depositional basin, as 2 660 000 square metres. This excluded 2.3 square kilometres of intertidal flat west of and between Knight Point (south of Limestone Island) and Onerahi Peninsula, where cores showed that sediment is not accumulating. This is shown in Figure 40.

- 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 Swales et al (2013) as the "mud sinks" in Figure 39 (the light-yellow areas).

S (sedimentation rate)

- Swales et al (2013) estimated the sediment accumulation rate averaged over **UI** as 4 millimetres per year 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) millimetres per year, respectively) and two cores in the Hātea Arm (WHG-6 and WHG-14; sediment accumulation rates of 2.8 (1830–2012) and 6.5 (1974–2012) millimetres per year, respectively).
- For **PB**, S = 2.5 millimetres per year is an intermediate value between the two lead-210 sediment accumulation rates reported by Swales et al (2013) (2.2 millimetres per year (1935–2012) and 2.9 millimetres per year (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 millimetres per year (1957–2012).
- S = 1.0 millimetres per year 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.

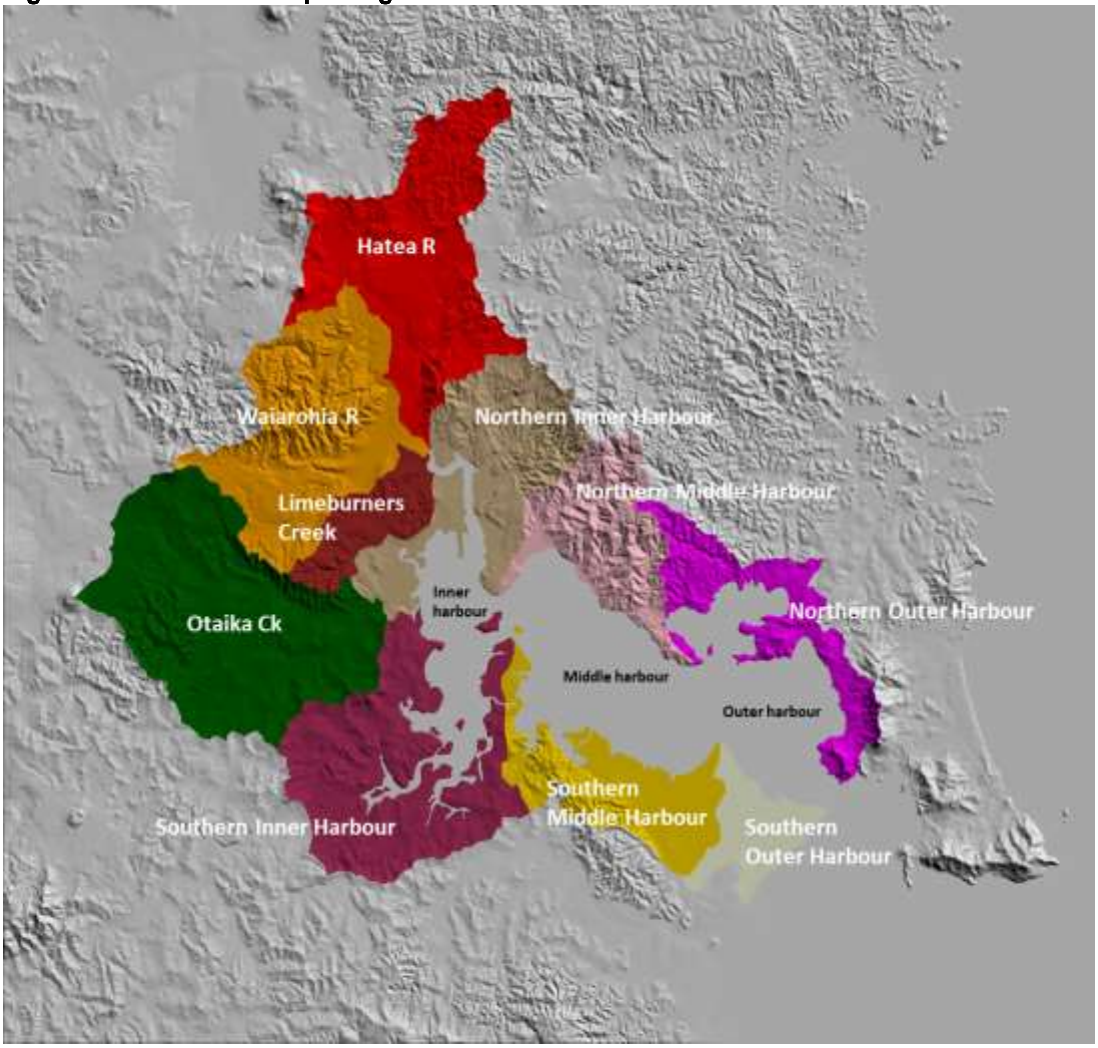
ρ (deposited-sediment density)

- Swales et al (2013) reported the deposited-sediment (dry-bulk) density averaged over **UI** as 1.18 tonnes per cubic metre.
- ρ = 1.25 tonnes per cubic metre for **PB** is based on measurements reported by Swales et al (2013) for the dry-bulk density of upper layers in cores WHG-10 and WHG-11.
- ρ = 1.00 tonnes per cubic metre for **MB** is based on the dry-bulk density of the surface layer of core WHG-7 reported by Swales et al (2013).
- ρ = 1.25 tonnes per cubic metre for **NS** is an estimate only.

6.2.2 Catchment sediment runoff

The SedNetNZ catchment sediment model has been used to predict the total mass of sediment runoff per year from each of 10 "catchment reporting zones" under the present-day catchment land use (John Dymond, Landcare Research, personal communication). The reporting zones are shown in Figure 41.

Figure 41: Catchment reporting zones used in the SedNetNZ model



Eleven sub-catchments have been defined for the purposes of developing the harbour sediment budget (C = 11). The correspondence between the SedNetNZ reporting zones and the sub-catchments is given in Table 25 (see also Figure 38).

Table 25: Correspondence between SedNetNZ catchment reporting zones and sub-catchments, with mass of sediment discharged per year (L_c) into the harbour from each sub-catchment (sediment runoff is predicted by SedNetNZ for the present-day catchment land use)

SedNetNZ catchment reporting zone	Sub-catchment	c	Sub-catchment sediment load, L_c (t/y)
Hātea 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: t/y = tonnes per year. The Northern Outer Harbour reporting zone is divided into two sub-catchments: the **NON** sub-catchment and the **NOS** sub-catchment. **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 25 also shows the annual sediment runoff predicted by SedNetNZ for the present-day land use distributed by sub-catchment. Note:

- the **NON** sub-catchment carries 61 percent of the sediment runoff from the Northern Outer Harbour reporting zone (John Dymond, Landcare Research, personal communication);
- the **NOS** sub-catchment carries 39 percent of the sediment runoff from the Northern Outer Harbour reporting zone (John Dymond, Landcare Research, personal communication).

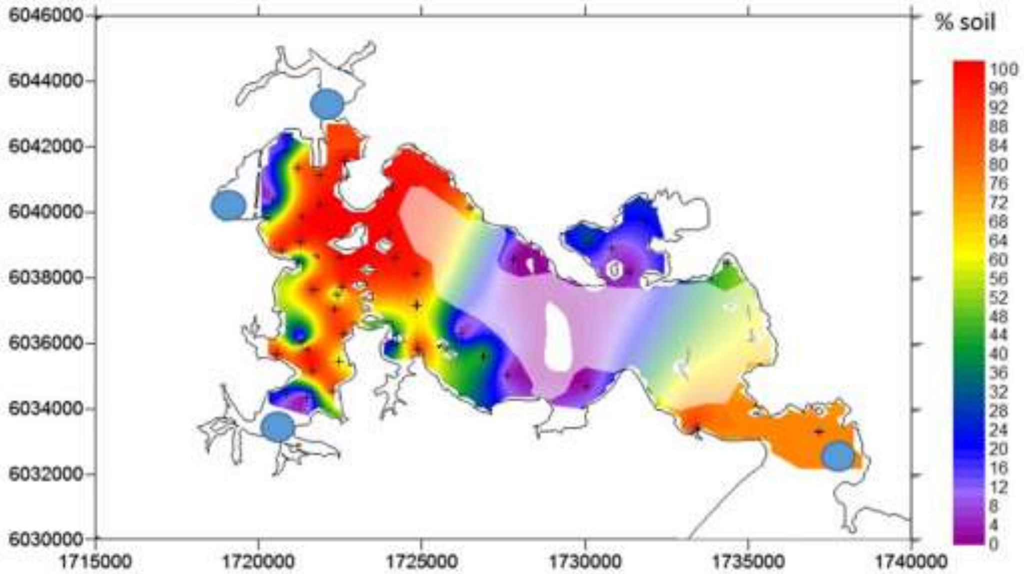
The sediment discharged to the harbour from each reporting zone is composed entirely of fine silt (John Dymond, Landcare Research, personal communication).

6.2.3 Information available on harbour sediment-transport patterns

There are 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 Swales et al (2013) that show the percentage of each of four “end members”, or sources, of sediment in the surface layer (top 2 centimetres) of harbour sediments. The maps have been produced from CSSI analyses of sediment samples. The method is fully described in Swales et al (2013). Some of the maps are reproduced in Figure 42 to Figure 45.

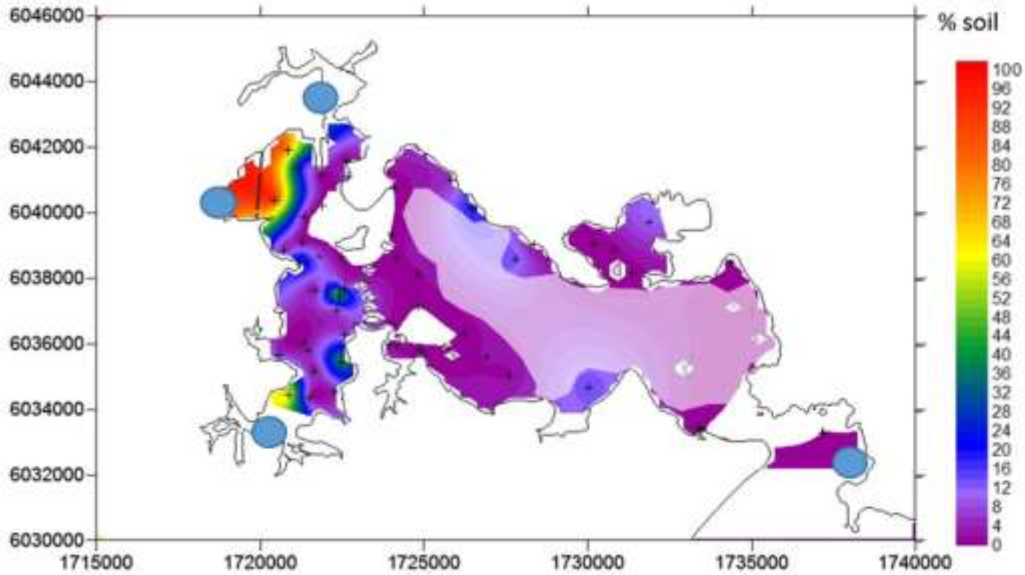
Figure 42: Percentage of Hātea River catchment sediments in surface layer (top 2 centimetres) of harbour sediments



Source: Reproduced from Swales et al (2013).

Note: For Figures 41 to 45, the x-axis and the y-axis provide a scale in metres. The map coordinate system is NZTM2000(NZ Transverse Mercator). The y-axis shows northings and the x-axis eastings, in metres, that is, the distance in metres from the origin of the NZTM2000 coordinate system.
The fogged area covers indicative extrapolated areas with no data support. Map co-ordinate system: NZTM2000. 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 Hātea River catchment, Otaika River catchment and Mangapai River catchment. The source on the right side of the figure is from Calliope Bay, which represents "coastal sediment".

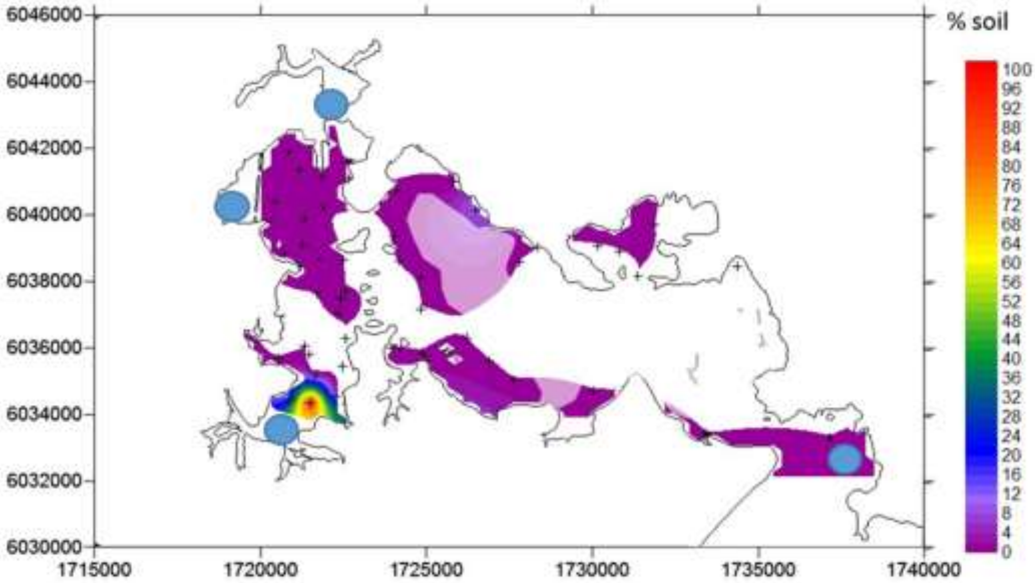
Figure 43: Percentage of Otaika River catchment sediments in surface layer (top 2 centimetres) of harbour sediments



Source: Reproduced from Swales et al (2013).

Note: The fogged area covers indicative extrapolated areas with no data support. Map co-ordinate system: NZTM2000. 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 Hātea River catchment, Otaika River catchment and Mangapai River catchment. The source on the right side of the figure is from Calliope Bay, which represents "coastal sediment".

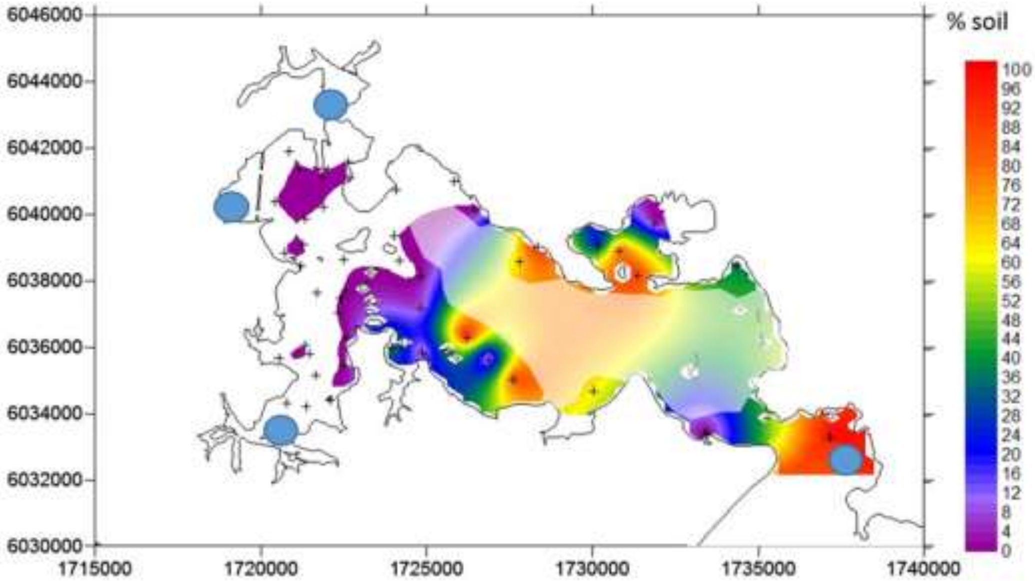
Figure 44: Percentage of Mangapai River catchment sediments in surface layer (top 2 centimetres) of harbour sediments



Source: Reproduced from Swales et al (2013).

Note: The fogged area covers indicative extrapolated areas with no data support. Map co-ordinate system: NZTM2000. 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 Hātea River catchment, Otaika River catchment and Mangapai River catchment. The source on the right side of the figure is from Calliope Bay, which represents "coastal sediment".

Figure 45: Percentage of Calliope Bay sediments in surface layer (top 2 centimetres) of harbour sediments



Source: Reproduced from Swales et al (2013).

Note: The fogged area covers indicative extrapolated areas with no data support. Map co-ordinate system: NZTM2000. 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 Hātea River catchment, Otaika River catchment and Mangapai River catchment. The source on the right side of the figure is from Calliope Bay, which represents "coastal sediment".

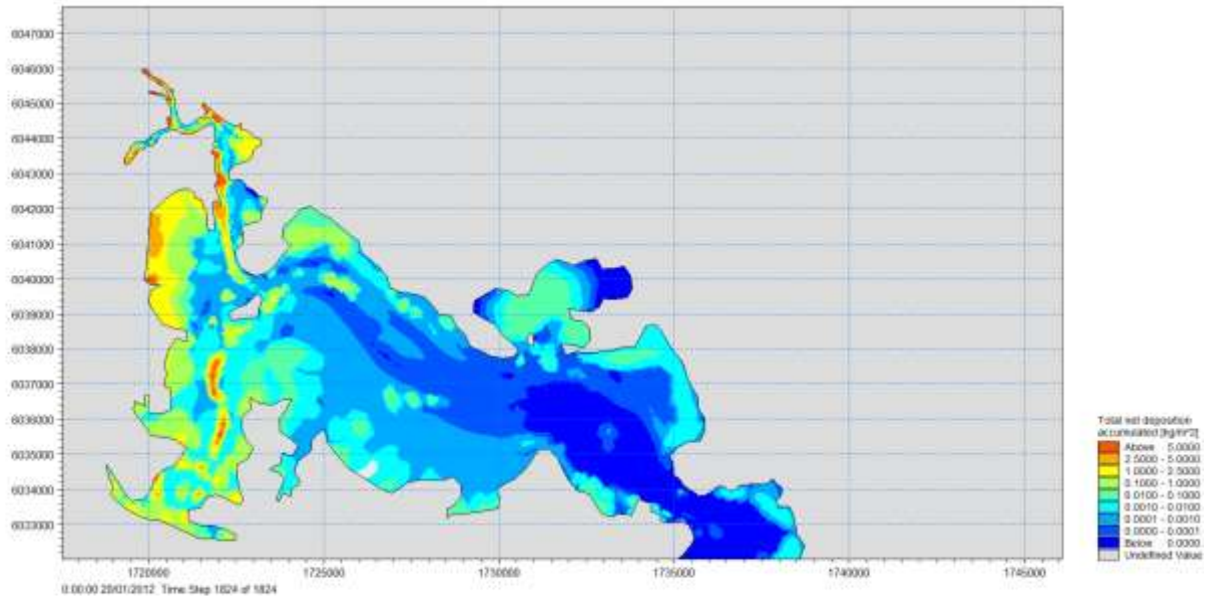
The second type of information is simulations by a numerical model of the fate in the harbour of fine silt (20 micron particle size) discharged from the Hātea, Otaika and Mangapai rivers under yearly average freshwater runoff, freshwater runoff associated with a one-year average recurrence interval (ARI) storm and freshwater runoff associated with a 10-year ARI storm. These simulations were reported by Swales et al (2013).

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 main 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 46.

Figure 46: Deposition of fine silt discharged from the Hātea, Otaika and Mangapai rivers (combined) under freshwater runoff associated with a one-year ARI storm



Source: Reproduced from Swales et al (2013).

Note: ARI = average recurrence interval. The units are kilograms of fine silt deposited per square metre of seabed.

For the Whangarei Harbour study, model outputs of Swales et al (2013) were re-analysed 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. This is the yearly average freshwater and sediment runoff, freshwater and sediment runoff associated with a one-year ARI storm, and freshwater and sediment runoff associated with a 10-year ARI storm. This re-analysis 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 45) in each basin. The results are given in Table 26 as the average over the three events.

Table 26: Fraction of fine silt discharged from Hātea River, Otaika River, Mangapai River, Waikaraka Stream, Kohinui Stream and Waitangata Stream

	Source in harbour model simulations					
Depositional basin	**Hātea 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

Note: Sources of freshwater and sediment used in harbour model simulations that deposit in each of the UI, PB, MB and NS depositional basins averaged over the yearly average runoff, runoff associated with a one-year average recurrence interval (ARI) storm and runoff associated with a 10-year ARI storm.

New model simulations were run with the harbour numerical model, which were specifically designed for the Whangarei Harbour 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** sub-catchment;
- the head of the **PB** depositional basin approximately where the Kohinui Stream discharges, representing sediment discharged from the **NON** sub-catchment; and
- the head of the **MB** depositional basin approximately where the Waitangata Stream discharges, representing sediment discharged from the **NOS** reporting zone.

These sources are called "Waikaraka Stream", "Kohinui Stream" and "Waitangata Stream", respectively. See Figure 38 for where these sources are located relative to the 11 sub-catchments.

As in Swales et al (2013), the simulations covered the yearly average freshwater and sediment runoff, freshwater and sediment runoff associated with a one-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 26 as the average over the three events.

6.3 ESTIMATION OF THE SEDIMENT FATE MATRIX

6.3.1 Depositional basin UI (e = 1)

Rearranging equation (21) and inserting the data in Table 24 (A_1 = 2 660 000 square metres, ρ_1 = 1.18 tonnes per cubic metre, S_1 = 4 millimetres per year) yields $D_1 + M_1$ = 12 555 tonnes of sediment of catchment and marine origin depositing per year in the **UI** basin.

Figure 45 shows that less than about 5 percent of the sediment depositing in the upper harbour is attributable to the Calliope Bay source, which is representative of "coastal sediment". The Calliope Bay "coastal sediment" is equated with sediment of marine origin in our model and, accordingly, it is assumed that 5 percent of the 12 555 tonnes of sediment depositing in **UI** is of marine origin. Therefore, M_1 = 628 tonnes and D_1 = 11 927 tonnes.

It is assumed that:

- the Hātea 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) sub-catchments;
- the Otaika River source used in the harbour sediment-transport modelling discharges fine silt from the **OC** (c = 4) sub-catchment;
- the Mangapai River source used in the harbour sediment-transport modelling discharges fine silt from the **SI** (c = 6) sub-catchment;

- the Waikaraka Stream source used in the harbour sediment-transport modelling discharges fine silt from the **NM** (c = 7) sub-catchment;
- the Kohinui Stream source used in the harbour sediment-transport modelling discharges fine silt from the **NON** (c = 9) sub-catchment; and
- the Waitangata Stream source used in the harbour sediment-transport modelling discharges fine silt from the **NOS** (c = 10) sub-catchment.

Since the sediment discharged from the catchment is fine silt (Section 6.2.2) and the model simulations are of fine silt, values are chosen for the sediment fate matrix out of Table 26, which gives:

- $F_{1,1}$ = 0.011, which is the fraction of the sediment (fine silt) discharged from the **HR** sub-catchment (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** sub-catchment (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** sub-catchment (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** sub-catchment (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** sub-catchment (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** sub-catchment (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** sub-catchment (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** sub-catchment (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** sub-catchment (c = 10) that is deposited in **UI** (e = 1).

Furthermore, it is assumed that no sediment from either the **SM** or **SO** sub-catchments is deposited in **UI** (that is, $F_{8,1} = F_{11,1}$ = 0). This makes little difference to the results since, in the case of the former, the sediment load is very small compared with the rest of the reporting zones, and in the case of the latter, the sediment load is zero (Table 25).

Applying these values for the sediment fate matrix to the catchment sediment runoffs given in Table 26 accounts for about one-quarter (23 percent) of the catchment sediment that is estimated to deposit in **UI** each year. That is, $D_1 = \sum_{c=1}^{11} L_c F_{c,1}$ = 2724 tonnes of catchment sediment, which is about 23 percent of the required 11 927 tonnes.

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** $F_{c,1}$, c = 1, 2, 3 and 5 (sediment from the **HR**, **WR**, **LC** and **NI** sub-catchments, delivered by the Hātea River in the harbour model simulations) is increased. This is done 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** sub-catchment, delivered by the Otaika River in the harbour model simulations) and $F_{6,1}$ (sediment from the **SI** sub-catchment, 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 Hātea

River is a dominant source of sediment deposited in **UI** (see Figure 42). $F_{4,1}$ and $F_{6,1}$ is adjusted 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 27. A greater fraction of the sediment from the **SI** sub-catchment is retained in **UI**, which seems reasonable since the Hātea River (which drains the **HR**, **WR**, **LC** and **NI** sub-catchments) and the Otaika River (which drains the **OC** sub-catchment) discharge closest to the outlet from the upper harbour to middle harbour. Note, also, that a considerable fraction of the sediment from sub-catchment **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 27: Values for the sediment fate matrix, depositional basin UI (e = 1)

	Sub-catchment										
	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

6.3.2 Depositional basin PB (e = 2)

Rearranging equation (21) and inserting the data in Table 24 (A_2 = 3 500 000 square metres, ρ_2 = 1.25 tonnes per cubic metre, S_2 = 2.5 millimetres per year) yields $D_2 + M_2$ = 10 938 tonnes of sediment of catchment and marine origin depositing per year in the **PB** basin.

Figure 45 suggests that about 50 percent of the sediment depositing in Parua Bay is attributable to the Calliope Bay source, which is representative of "coastal sediment". Accordingly, it is assumed that 50 percent of the 10 938 tonnes of sediment depositing in **PB** is of marine origin. Therefore, M_2 = 5 469 tonnes and D_2 = 5 459 tonnes.

Again, since the sediment discharged from the catchment is fine silt (Section 6.2.2) and the model simulations are of fine silt, values are chosen for the sediment fate matrix out of Table 26, and it is assumed that no sediment from either the **SM** or **SO** sub-catchments is deposited in **PB** (that is, $F_{8,2} = F_{11,2} = 0$). As noted previously, this makes little difference to the results since, in the case of the former, the sediment load is very small compared with the rest of the reporting zones, and in the case of the latter, the sediment load is in fact zero (Table 25).

Applying these values for the sediment fate matrix to the catchment sediment runoffs given in Table 25 accounts for about 57 percent (3 137 tonnes) of the catchment sediment that is estimated to deposit 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.

The following adjustments are made to deliver the required amount of fine silt to **PB**.

- A of 1 is applied for $F_{9,2}$ (the fraction of sediment from the **NON** sub-catchment that discharges into the **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 $F_{9,2}$, every other value of $F_{c,2}$ is adjusted 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 28.

Table 28: Values for the sediment fate matrix, depositional basin PB (e = 2)

	Sub-catchment										
	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

Note that sub-catchment **NON**, which drains directly into the **PB** depositional basin, deposits the largest fraction of its sediment load.

6.3.3 Depositional basin MB (e = 3)

Rearranging equation (21) and inserting the data in Table 24 (A_3 = 518 900 square metres, ρ_3 = 1.00 tonnes per cubic metres, S_3 = 3.1 millimetres per year) yields $D_3 + M_3$ = 1 609 tonnes of sediment of catchment and marine origin depositing per year in the **MB** basin.

Figure 45 suggests that about 40 percent of the sediment depositing in Munro Bay is attributable to the Calliope Bay source, which is representative of "coastal sediment". Accordingly, it is assumed that 40 percent of the 1 609 tonnes of sediment depositing in **MB** is of marine origin. Therefore, M_3 = 644 tonnes and D_3 = 965 tonnes.

As before, since the sediment discharged from the catchment is fine silt (Section 6.2.2) and the model simulations are of fine silt, values are chosen for the sediment fate matrix out of Table 26, and it is assumed that no sediment from either the **SM** or **SO** sub-catchments is deposited in **MB** (that is, $F_{8,3} = F_{11,3} = 0$).

Applying these values for the sediment fate matrix to the catchment sediment runoffs given in Table 25 accounts for about 54 percent of the catchment sediment that is estimated to deposit in **MB** each year (522 tonnes, compared with the 965 tonnes required).

To deliver the required amount of fine silt to **MB** all values of $F_{c,3}$ are reduced by about a factor of two. The final values for $F_{c,3}$ are given in Table 29.

Table 29: Values for the sediment fate matrix, depositional basin MB (e = 3)

	Sub-catchment										
	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

6.3.4 Depositional basin NS (e = 4)

Rearranging equation (21) and inserting the data in Table 24 (A_4 = 1 459 000 square metres, ρ_4 = 1.25 tonnes per cubic metre, S_4 = 1 millimetre per year) yields $D_4 + M_4$ = 1 824 tonnes of sediment of catchment and marine origin depositing per year in the **NS** basin.

Figure 44 suggests that about 10 percent of the sediment depositing in the **NS** basin is attributable to the Calliope Bay source, which is representative of "coastal sediment". Accordingly, it is assumed that 10 percent of the 1 824 tonnes of sediment depositing in **NS** is of marine origin. Therefore, M_4 = 183 tonnes and D_4 = 1 641 tonnes.

As before, since the sediment discharged from the catchment is fine silt (Section 6.2.2) and the model simulations are of fine silt, values are chosen for the sediment fate matrix out of Table 26, and we it is assumed that no sediment from either the **SM** or **SO** sub-catchments is deposited in **NS** (that is, $F_{8,4} = F_{11,4} = 0$).

Applying these values for the sediment fate matrix to the catchment sediment runoffs given in Table 25 accounts for about 32 percent of the catchment sediment that is estimated to deposit in **NS** each year.

To deliver the required amount of fine silt to **NS**, $F_{7,4}$ is increased 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 sub-catchment (**NM**) that discharges into the head of depositional basin **NS**. (**NM** discharges into the head of **NS** through Waikaraka Stream in the harbour modelling.). This action is taken 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 30. Note that sub-catchment **NM**, which drains directly into the **NS** depositional basin, deposits the largest fraction of its sediment load.

Table 30: Values for the sediment fate matrix, depositional basin NS (e = 4)

	Sub-catchment										
	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

6.4 SUMMARY OF THE HARBOUR SEDIMENT BUDGET

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

$$S_1 = \frac{(\sum_{c=1}^{11} L_c F_{c,1}) + M_1}{\rho_1 A_1 \Gamma} \quad (23)$$

where $F_{c,1}$ is given in Table 27, L_c is given in Table 25, ρ_1 and A_1 are given in Table 24 and M_1 = 628 tonnes.

Section 6.3.1 set out the relative amounts of sediment from the **HR**, **WR**, **LC**, **OC**, **NI** and **SI** sub-catchments, all of which drain into the upper harbour, and the **NM** sub-catchment, which drains into the middle harbour.

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

$$S_2 = \frac{(\sum_{c=1}^{11} L_c F_{c,2}) + M_2}{\rho_2 A_2 \Gamma} \quad (24)$$

where $F_{c,2}$ is given in Table 28, L_c is given in Table 25, ρ_2 and A_2 are given in Table 24 and M_2 = 5 469 tonnes.

It was noted in Section 6.3.2 that, for depositional basin **PB**, which is in the lower harbour, sub-catchment **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:

$$S_3 = \frac{(\sum_{c=1}^{11} L_c F_{c,3}) + M_3}{\rho_3 A_3 \Gamma} \quad (25)$$

where $F_{c,3}$ is given in Table 29, L_c is given in Table 25, ρ_3 and A_3 are given in Table 24 and M_3 = 644 tonnes.

It was noted in Section 6.3.3 that, for depositional basin **MB**, which is in the lower harbour, sub-catchment **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:

$$S_4 = \frac{(\sum_{c=1}^{11} L_c F_{c,4}) + M_4}{\rho_4 A_4 \Gamma} \quad (26)$$

where $F_{c,4}$ is given in Table 30, L_c is given in Table 25, ρ_4 and A_4 are given in Table 24 and M_4 = 183 tonnes.

It was noted in Section 6.3.4 that, for depositional basin **NS**, which is in the middle harbour, sub-catchment **NM**, which drains directly into the **NM** depositional basin, deposits the largest fraction of its sediment load.

6.5 DISCUSSION OF THE HARBOUR SEDIMENT BUDGET

Inserting the sub-catchment sediment loads L_c given in Table 25 into equations (23) to (26) will yield the sedimentation rates given in Table 24. Equations (23) to (26) may be used to predict the change in sedimentation rate resulting from either a decrease (for example, because of mitigation) or an increase in sub-catchment sediment loads. Table 25 shows how SedNetNZ sediment loads distributed by reporting zone equate to sub-catchment loads. Table 31 shows the origin by sub-catchment of the mass of sediment deposited in each depositional basin.

Table 31: Mass (tonnes) of sediment deposited per year in each depositional basin originating from each sub-catchment source

Depositional basin	Sub-catchment										
	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 sub-catchments drained by the Hātea 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) sub-catchments deposit the next largest masses of sediment. This is consistent with the CSSI results of Swales et al (2013), which show sedimentation in the upper harbour to be dominated by sediments from the Hātea River catchment.
- For depositional basin **PB**, which is in the lower harbour, sub-catchments 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. Swales et al (2013) 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 sub-catchment **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 sub-catchment (**NOS**) deposits the largest mass of sediment.
- For depositional basin **NS**, which is in the middle harbour, sub-catchments 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. Swales et al (2013) 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 sub-catchment **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.

These results are 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.

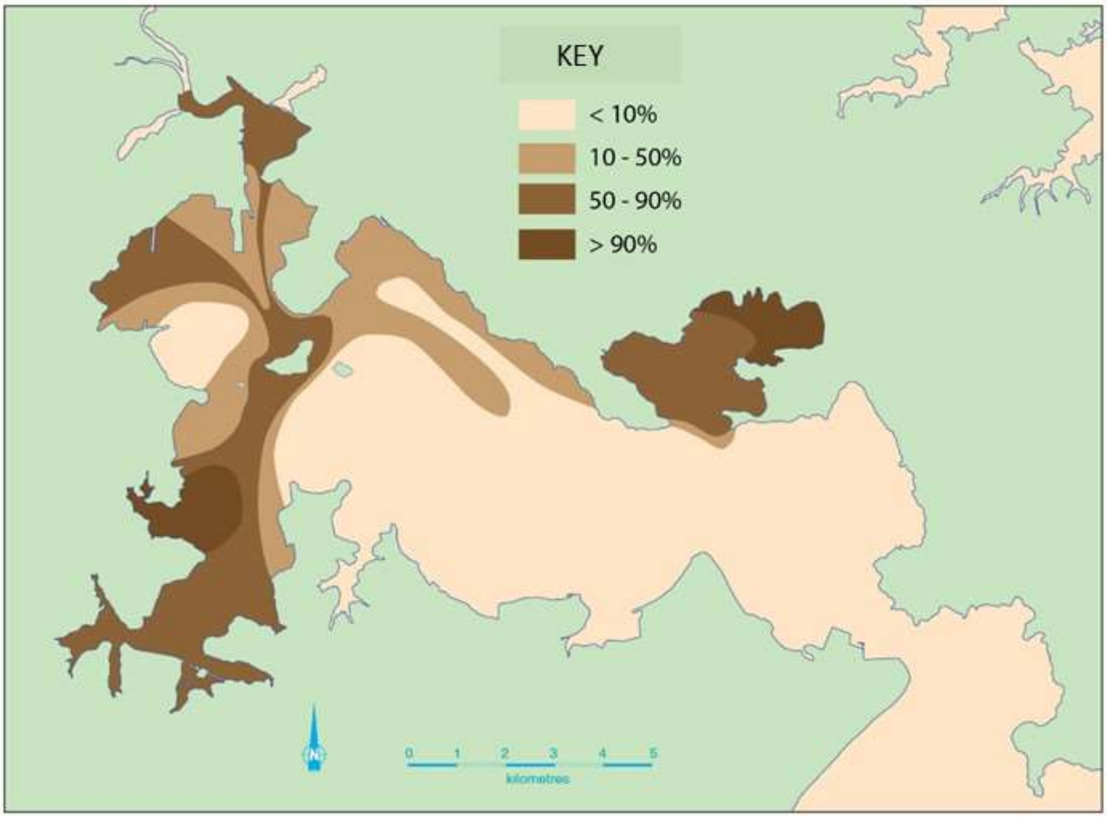
After the adjustments, 56 percent of the total catchment sediment runoff is deposited in the four depositional basins. The remainder is not accounted for in the model: it may be lost to the coastal ocean or it may be deposited elsewhere in the harbour. The final adjustments to the sediment fate matrix 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 (for example, arbitrarily force more sediment from the adjacent sub-catchment out of Parua Bay), or data indicated a change was justified (for example, retain more sediment from the Hātea River in the upper harbour based on CSSI source-tracking data). Hence, the budget has ultimately been fitted to the data, but it still rests on a "process" foundation.

Finally, referring to Figure 47, which is the isopleth map of percentage mud (by weight) in the surficial sediments of Whangarei Harbour produced by Millar (1980), 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 are subsequently 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 a 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 has been developed for the Whangarei Harbour study 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 study.

Figure 47: Isopleth map of the percentage of mud (by weight) in the surficial sediments of Whangarei Harbour (1978)



Source: 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.

7 Whangarei Harbour catchment economic modelling

The model frameworks and outputs outlined in Sections 3 to 6 were put into a catchment economic model to identify cost-effective ways to manage sediment and *E. coli* loads in the Whangarei Harbour catchment. MPI contracted Landcare Research to develop this model.

This section focuses on the development and results from the spatially distributed catchment economic model. The integrated catchment model consists of three main components:

3. baseline sediment and *E. coli* losses for each hectare of land in the study regions;
4. how these are modified with the use of mitigations (both on- and off-farm); and
5. pollutant attenuation throughout the freshwater network.

The model allows for any combination of mitigation measures to be applied at farm, sub-catchment and catchment levels to achieve spatially distributed environmental objectives that are expressed as attribute states.

The catchment economic model is based on Landcare Research's economic land use model, NZ-FARM. This is designed for detailed modelling of land uses at a catchment scale. It enables the consistent assessment of multiple policy scenarios by estimating and comparing the relative changes in economic and environmental outputs.

The Whangarei Harbour catchment version of NZ-FARM includes several farm- or parcel-level management options for managing sediment and *E. coli* loads. These include implementing farm plans, fencing streams and constructing wetlands. While the list of feasible farm management options is extensive, the study does not include all possible options to mitigate losses from diffuse sources into waterways. The results from NZ-FARM are reliant on input data (for example, farm budgets, mitigation costs and contaminant loss rates) from external sources and may vary if alternative data are used. NZ-FARM also does not account for the broader impacts of changes in land use and land management beyond the farm gate.

This section presents estimates from several model scenarios to investigate the range of costs for reducing sediment and *E. coli* loads in the catchment. These include both practice-based approaches such as fencing streams for stock exclusion, and environmental outcome-based approaches such as reducing erosion to reach harbour-sedimentation rate targets.

The focus of this part of the study is to develop and test an economic catchment model that looks at sediment and *E. coli* management in an integrated framework. It is not intended to define or analyse any specific policy or reduction target. Thus, the scenarios presented in this report should be taken as illustrative examples of how the model works and can be used in future analyses, as opposed to a rigorous analysis of a proposed policy or rule change.

7.1 METHODOLOGY

7.1.1 New Zealand Forest and Agriculture Regional Model

NZ-FARM is a comparative-static, non-linear, partial equilibrium mathematical programming model of New Zealand land use operating at the catchment scale. It was developed by Landcare Research (Daigneault et al, 2012; 2013; 2015). Its primary use is to provide decision-makers with information on the economic impacts of environmental policy as well as how a policy aimed at one environmental issue could affect other environmental factors.

The version of the model used for this study can track changes in land use, land management, agricultural production, and sediment and *E. coli* loads by imposing policy options that range from having landowners implement specific mitigation practices to identifying the optimal mix of land management to meet a particular target. The model is parameterised such that responses to policy are not instantaneous but instead assume a response that landowners are likely to take over a 10-year period.

Sediment estimates were incorporated into the NZ-FARM REC2 sub-catchments, of which there are more than 700 in the Whangarei Harbour catchment. NZ-FARM incorporated CLUES *E. coli* estimates for pasture, forest and other land use, as well as the point sources in each of the REC2 sub-catchments. In addition, the model included the attenuation rates for each sub-catchment to account for the downstream accumulation of *E. coli* in the catchment. Equations that relate catchment sediment run-off and mass marine sediments transported by waves and currents to sedimentation rates in four estuary depositional basins were also incorporated into NZ-FARM (see Figure 37).

The catchment economic model estimates the impact of land management on the water quality attributes discussed in Section 3. The study does not specify explicit targets for the attributes as part of this analysis, due to a lack of knowledge about what the "appropriate" targets should be. As a result, the study estimates the impacts to these attributes from specific management practices or loading targets, rather than trying to achieve a particular freshwater or estuary attribute state. All the scenarios are designed, however, such that the attributes will always be "maintained or improved".

7.1.2 Model data and parameterisation

NZ-FARM accounts for a variety of land-use, enterprise and land management options in a given area. The data required to parameterise each land-use, enterprise and land management combination include financial and budget data (for example, inputs, costs and prices), production data and environmental outputs (for example, sediment loads and *E. coli* loads). Table 32 lists the main variables and data requirements used to parameterise NZ-FARM, while Table 33 provides more information on the specific elements of the model. Further details on the model data and parameter assumptions used to populate the Whangarei Harbour version of the model are provided below. All of the figures in the NZ-FARM are converted to per hectare values and 2012 New Zealand dollars so that they are consistent across sources and scenarios.

Table 32: Data sources for NZ-FARM's modelling of Whangarei Harbour catchment

Variable	Data requirement	Source	Comments
Geographic area	Geographic Information System (GIS) data identifying the catchment area	Catchment and sub-catchments based on River Environment Classification	Provided by National Institute of Water and Atmospheric Research (NIWA)
Land cover and enterprise mix	GIS data file(s) of current land use with the catchment key enterprises (e.g., dairy)	Estimated using national land-use map based on AgriBase and Land Cover Database version 2	Land-use map verified by project partners
Management practices	Distribution of feasible management practices (e.g., stream fencing, farm management plan and so on)	List developed during workshop in April 2015	Data and assumptions verified by project partners
Climate	Temperature and precipitation	Historical data Future climate projections being developed in alternative project	Analysis assumes constant climate and production
Soil type	Soil maps used to divide area into dominant soil types	S-map (partial coverage only), Fundamental Soil Layer and the New Zealand Land Resource Inventory (NZLRI)	Not necessary for this project, so assumed a single, generic soil type
Stocking rates	Based on animal productivity model estimates or carrying capacity map	Average land carrying capacity from NZLRI and detailed "stocking budgets" for various pastoral enterprise systems	Used to estimate production and net farm revenue for dairy, sheep and beef, and deer enterprises
Input costs	Stock purchases, electricity and fuel use, fertiliser, labour, supplementary feed, grazing fees and so on	Obtained using a mix of: personal communication with farm consultants and regional experts, Ministry for Primary Industries (MPI) *Farm Monitoring Report* (MPI, 2013b), Lincoln University *Financial Budget Manual 2012/13* (Lincoln University, 2013)	Verified with local land managers and industry consultants
Product outputs	Milk solids, dairy calves, lambs, mutton, beef, venison, grains, fruits, vegetables, timber and so on	Used yields for Northland region, but nothing specific to Whangarei Harbour catchment	Verified with local land managers and industry consultants
Commodity prices	Same as outputs, but in dollars per kilogram or dollars per cubic metre	Obtained from MPI and other sources	Assume five-year average
Environmental indicators	Soil erosion and sediment Stream *E. coli* Harbour *E. coli*	Sediment based on SedNetNZ model *E. coli* sourced from NIWA	Data supplied by project partners

Table 33: List of the main components of NZ-FARM Whangarei Harbour catchment

Enterprise (E)	Mitigation practice (M)	Enterprise (E)	Mitigation practice (M)	Enterprise (E)
Dairy Sheep and beef Deer Forestry Grapes Horticultural crops Arable crops Scrub Native Urban Other	None Farm plan Fencing Retention Bund–wetland combination Sedimentation pond–wetland combination Mid-catchment constructed wetland Farm plan + fencing Farm plan + fencing + wetland Afforestation	Dairy Sheep and beef Deer Forestry Grapes Horticultural crops Arable crops Scrub Native Urban Other	None Farm plan Fencing Retention Bund–wetland combination Sedimentation pond–wetland combination Mid-catchment constructed wetland Farm plan + fencing Farm plan + fencing + wetland Afforestation	Dairy Sheep and beef Deer Forestry Grapes Horticultural crops Arable crops Scrub Native Urban Other

7.1.3 Land use and net farm revenue

Observed baseline land-use information is required to fit the model to an empirical baseline. Baseline land-use areas for this catchment model are based on a 2011 Geographic Information System-based land-use map created by Landcare Research using the latest information from AgriBase and the New Zealand LCDB version 2.

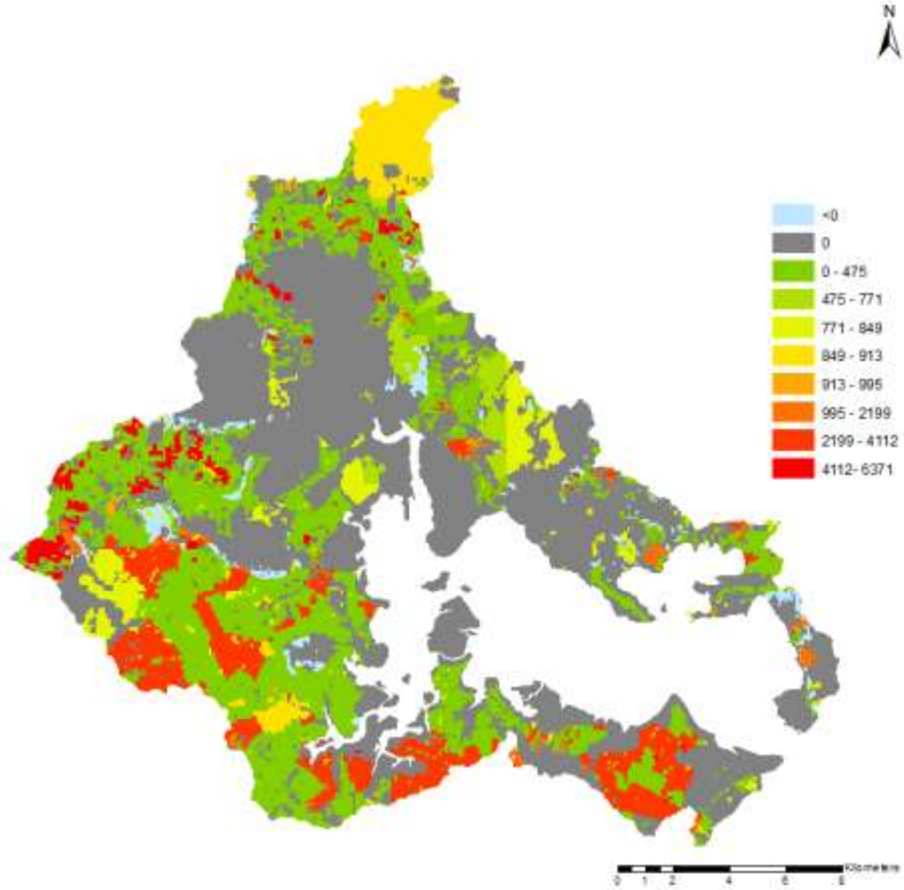
Land use for the Whangarei Harbour catchment is shown in Figure 2 in Section 2.1. The catchment is nearly 31 000 hectares in size, and main land uses include sheep and beef (35 percent), native (25 percent), dairy (11 percent), plantation forestry (10 percent) and urban (9 percent). Note that, because only 46 percent of the total catchment area is in pasture, some of the farm-based mitigation options being explored in this study may not have as large an effect as on more rural catchments that are primarily grassland. This is the case for the Whangarei Harbour catchment, where a noticeable level of both *E. coli* and sediment are found to come from non-pastoral land uses.

The baseline farm financial budgets for the catchment are based on estimates for production yields, input costs and output prices that come from a wide range of literature and national-level databases (for example, MPI *Situation and Outlook Report*, 2013a; *MPI Farm Monitoring Report*, 2013b; Lincoln University *Financial Budget Manual 2012/13*). These farm budgets form the foundation of the baseline net revenues earned by landowners, and are specified as earnings before interest and taxes (EBIT). Note that these figures assume landowners currently face no mitigation costs such as fencing streams or constructing wetlands. The national-level figures have been verified with agricultural consultants and enterprise experts. In addition, the Whangarei Harbour catchment-level figures have been shared with local land managers and consultants working in the catchment.

The distribution of net farm revenue across the catchment is shown in Figure 48. Although dairy makes up a relatively small proportion of land use, it does produce nearly 60 percent of farm net revenue in the catchment, followed by horticulture and arable (15 percent), forestry (15 percent) and sheep and beef farming (12 percent).

For this study, the net farm revenue figures are used to estimate the opportunity costs of taking land out of production in order to implement certain mitigation options, specifically wetlands. Most of the pasture-based mitigation assumes an increase in capital and maintenance expenses but no opportunity costs for production losses and hence does not take net revenues into account. In addition, the study is focused on management change within the current land use as opposed to landuse change.[9] Thus, the net farm revenue figures for this analysis are not as crucial as other catchment-level studies recently conducted to look at other impacts of the NPS-FM[10] (for example, nutrient reduction targets in Daigneault et al, 2013).

Figure 48: Baseline net revenue ($ per hectare per year)



7.1.4 Nodes of importance

The NRC classified 11 sites as nodes of importance. The sites were chosen because they are located near environmental monitoring stations and/or popular recreation sites. These are shown in Figure 29. As noted in Section 5, the total size and distribution of each REC2 in which each node of importance is located varies widely. This has an impact on the total effectiveness of implementing particular mitigation options to meet attributes for each of these nodes.

For example, nearly the entire sub-catchment that includes the site "Waiarohia at Second Ave" is classified as urban and may not benefit from implementing erosion control practices near that site. However, all sites could potentially benefit from *E. coli* mitigation in sub-catchments located upstream because the model tracks the flow and attenuation of *E. coli* through the stream network. Table 16 in Section 5 shows the land use of sites in the Whangarei Harbour catchment classified as nodes of importance. These data were inputted into the catchment economic model.

---

[9] Note: two afforestation scenarios are used to assess the possible lower bound of sediment and *E. coli* loads that could occur in the catchment. All of the other scenarios assume no land use change.

[10] See http://www.mfe.govt.nz/fresh-water/national-policy-statement/supporting-impact-papers-nps

7.1.5 Sediment loads and attributes

Sediment load estimates are taken directly from the SedNetNZ model. The land use contribution to sediment is estimated for both hill–landmass and streambank erosion. The sum of these two erosion processes is then aggregated to estimate total erosion for each REC2 sub-catchment so that aggregated loads are consistent with the resolution of the *E. coli* load modelling (Dymond, 2015). See Section 4.1 for more information on the SedNetNZ baseline sediment load estimates that were incorporated into the catchment economic model.

As outlined in Section 4, Landcare Research estimated relationships between the reduction in sediment loads and resulting freshwater attribute states for three sites in the Whangarei Harbour catchment where monitoring and flow data were available (Table 34). Modelled attributes include water clarity, euphotic depth, suspended sediment and embeddedness. NZ-FARM has been programmed with all of the equations provided by Landcare Research to relate the impact of changes in sediment to these four attributes. The default output for these attributes assumes median flow percentiles, but the model has the ability to measure impacts at other percentiles as well.

Table 34: Baseline freshwater sediment attribute estimates for three sites in the Whangarei Harbour catchment

Percentile	Flow (m^3/s)	Turbidity (NTU)	Suspended sediment (gm/m^3)	Water clarity (m)	Euphotic depth (m)
			Hātea		
10	0.15	1.47	1.40	4.58	3.80
50	0.53	4.31	3.60	1.65	2.22
80	1.11	7.71	6.00	0.95	1.66
95	2.71	15.87	11.30	0.48	1.15
			Waiairohia		
10	0.06	1.6	1.6	3.3	3.6
50	0.15	3.6	3.6	1.8	2.4
80	0.33	7.4	7.4	1.0	1.7
95	0.92	18.5	18.5	0.5	1.1
			Otaika		
10	0.14	2.2	1.4	3.1	3.1
50	0.43	6.8	4.3	1.1	1.8
80	1.13	17.9	11.3	0.4	1.1
95	2.64	41.8	26.3	0.2	0.7

Note: gm/m^3 = grams per cubic metre; m = metres; m^3/s = cubic metres per second; NTU = Nephelometric Turbidity Units.

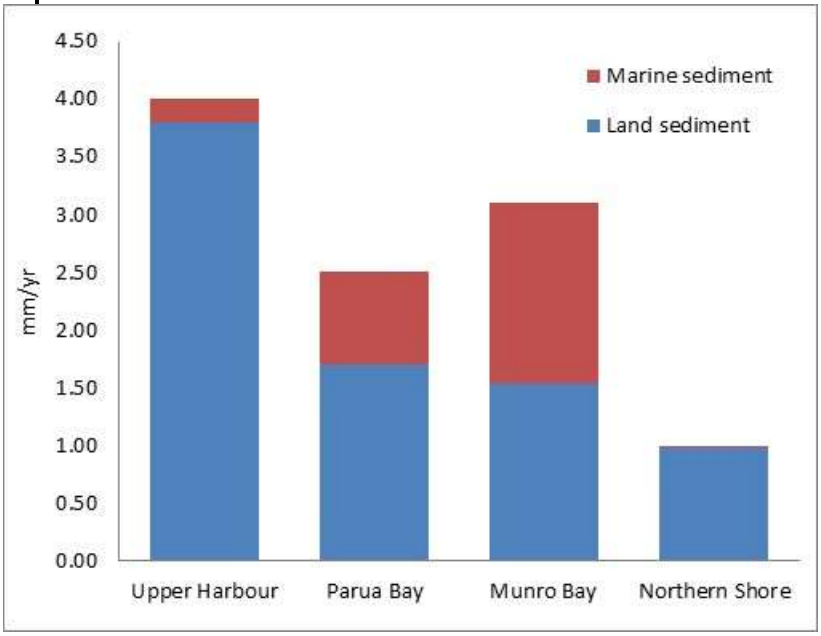
7.1.6 Harbour and estuary sediment attributes

The AASR harbour sediment attribute is estimated using methods outlined in Section 6, where equations are shown that relate catchment sediment runoff and mass marine sediment transported by waves and currents to sedimentation rate in an estuary depositional basin. This approach can be used to estimate the change in AASR (or sedimentation rate) in a depositional basin resulting from either a decrease (for example, because of mitigation) or an increase in sediment loads from anywhere in the catchment.

The baseline values for the AASR in the four harbour depositional basins are shown in Figure 49. The total AASR is broken out by land and marine sources.

Although the equations include several variables, the only one that has an impact on AASR within the catchment economic model (NZ-FARM) is the total amount of sediment discharged into the basin from landmass and streambank erosion in the catchment. Thus, we only model the impact of land management in the Whangarei Harbour catchment on the blue portion of the bars in Figure 49. This suggests that land management will have a larger influence on the AASR rate in the Upper Harbour and Northern Shore basins than the Parua Bay and Munro Bay basins.

Figure 49: Baseline annual-average sedimentation rate for the four Whangarei Harbour depositional basins



Note: mm/yr = millimetres per year.

7.1.7 *E. coli* loads and attributes

The methodology for estimating baseline freshwater and harbour *E. coli* loads is explained in Section 5

The estimated median and 95th percentile *E. coli* concentrations at the 11 nodes of importance, as specified in Section 3.2.1, are listed in Table 35. Recall that, for the NOF, the primary contact attribute state is based on concentrations at the 95th percentile, while secondary contact is measured at the median.

As stated in Table 1, an "A state" for both primary and secondary contact recreation is defined by concentrations less than or equal to 260 *E. coli* per100 millilitres, while the "B state" is defined by concentrations between 260 and 540 *E. coli* per 100 millilitres.The "C state" for secondary contact is defined by concentrations between 540 and 1000 *E. coli* per 100 millilitres. Any concentration greater than the "National Bottom Line" of 1 000 *E. coli* per 100 millilitres is considered a "D state".

Based on these values, it is important to note the high levels of both median and 95th percentile loadings for *E. coli* observed across the catchment, and that all nodes are significantly above the "D state" for primary contact. This highlights the need for significant mitigation to attain improved microbial concentrations at these sites.

Table 35: Environmental outputs at Whangarei Harbour catchment sites classified as nodes of importance

Site	Land–hill sediment (t)	Streambank sediment (t)	Total sediment (t)	Cumulative *E. coli* load (peta *E. coli*)	Median *E. coli* concentration (cfu/100 mL)	95th percentile *E. coli* concentration (cfu/100 mL)
Whangarei Falls	n/a	n/a	n/a	1.3149	439.0	2 003
Waiarohia at confluence with Waiarohia and Waikahitea	n/a	n/a	n/a	0.0644	525.0	3 485
Hātea at Mair Park Footbridge	98.2	164.3	262.5	2.5247	259.0	6 306
Waiarohia at Second Ave	7.4	59.4	66.8	0.8766	399.0	5 421
Raumanga just before it joins the Waiarohia	n/a	n/a	n/a	0.5044	941.7	12 844
Kirikiri just before it joins the Raumanga	n/a	n/a	n/a	0.0400	722.3	9 852
Raumanga at Bernard Street	n/a	n/a	n/a	0.6039	903.0	13 164
Raumanga Stream at swimming pool below falls	n/a	n/a	n/a	0.4211	211.0	3 076
Otaika at Otaika Valley Road	16.9	64.4	81.3	1.3323	484.0	4 378
Otaika weir (Golden Bay surface water take)	n/a	n/a	n/a	2.3456	871.5	7 883
Puwera just before it joins Otaika	n/a	n/a	n/a	0.7747	1 354.2	18 470

Note: cfu = colony forming unit; mL = millilitres; n/a = not applicable because segment not used to estimate changes in sediment attributes; t = tonnes.

7.1.8 Mitigation practices

Assumptions about mitigation cost and effectiveness in reducing sediment and *E. coli* loads were established by the project team during workshops in April 2015 and June 2015 (see Appendix 2) and refined accordingly as new information and assumptions arose. Additional details on the wetland mitigation were provided by NIWA (see Appendix 3). The costs are broken out by initial capital, ongoing and periodic maintenance, and opportunity costs from taking land out of production. A summary of these costs is outlined in Table 36.

The costs are converted to an annual figure so that they can be directly compared with the costs already included in the baseline net farm revenue calculation. Initial capital and periodic maintenance costs are annualised over 25 years using a discount rate of 8 percent. Annual maintenance and opportunity costs are assumed to accrue on a yearly basis and thus are directly subtracted from the base net farm revenue figure.

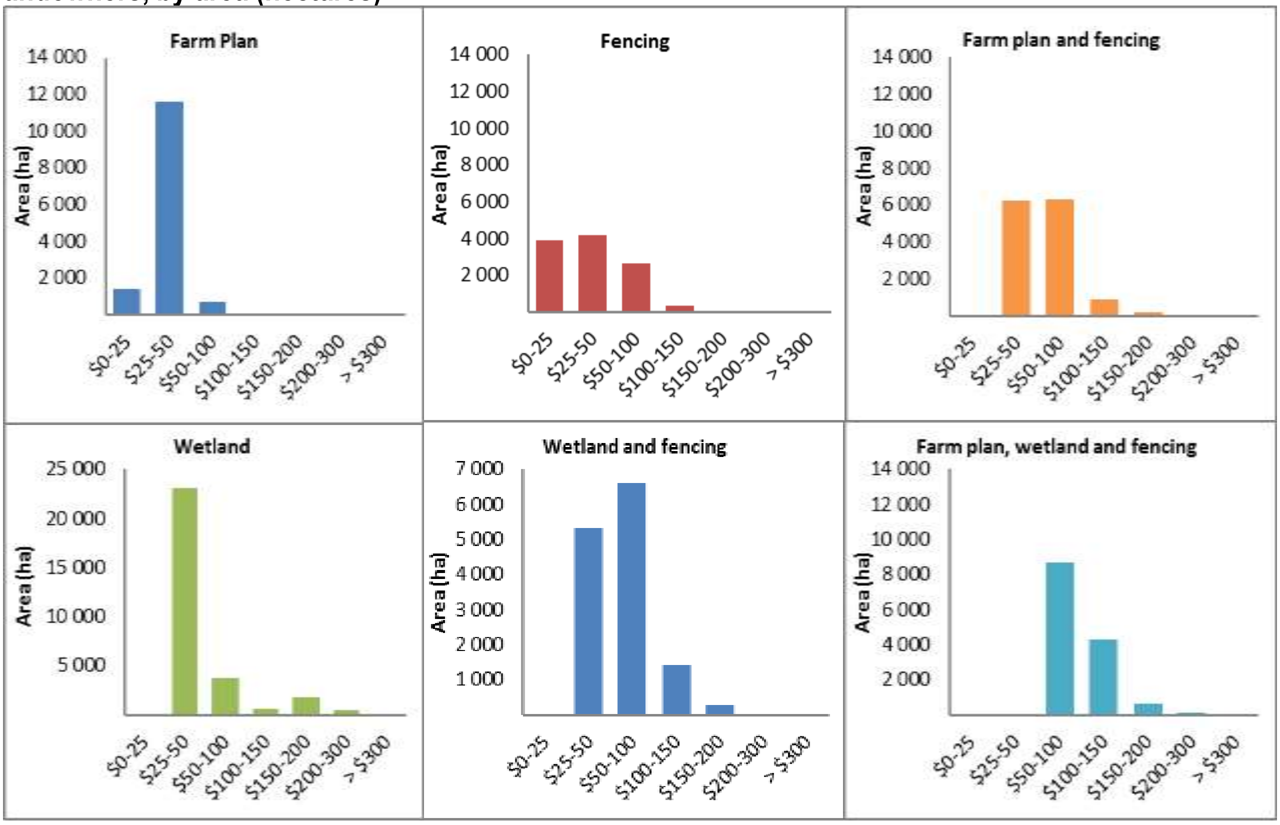
Table 36: Mitigation cost and effectiveness assumptions

Mitigation option	Eligible land uses	Maximum coverage	Cost component			Mitigation effectiveness (% from baseline)		
			Initial capital	Maintenance	Opportunity	Landmass erosion	Bank erosion	*E. coli**
1 Farm plan	Pasture	All farms	Plan: $5 000 per farm up to 100 ha + $10 per ha for each additional ha Implementation: $250 per ha	None	None, as plan assumed to identify options where benefits offset production losses	70%	0%	0%
2 Fencing	Pasture	All permanent streams	Sheep and beef: $35 per m, including materials, construction and reticulation; Dairy: $7.50 per m	None	None	0%	80%	60%
3 Retention bund–wetland combination	All, including native and urban	1 per 20 ha	$6 100 per system, including planting and fencing	$6 per system per year, $2 000 per system for sediment clearing in year 25	40% of farm income in occupied area	70%	0%	50%
4 Sedimentation pond–wetland combination	All, including native and urban	1 per 20 ha	$6 000 per system, including planting and fencing	$15 per system per year	80% of farm income in occupied area	70%	0%	50%
5 Mid-catchment constructed wetland	All, including native and urban	1 per 400 ha	$100 000 per system, including planting and fencing	$300 per system year	40% of farm income in occupied area	70%	0%	50%
6 Farm plan + fencing	Pasture	See 1 & 2	Sum of #1 and 2	None	None	70%	80%	60%
7 Farm plan + fencing + wetland	Pasture	See 1 to 5	Sum of #1, 2 and 3, 4 or 5	Sum of #1, 2 and 3, 4 or 5	40% of farm income in area occupied by wetland	70%	80%	60%

Note: ha = hectare; m = metre. *Assumed to have same effect on median and 95th percentile concentrations.

The impact of each mitigation option could differ based on the size, location and net revenue of the farm (Figure 50). For example, a large sheep and beef farm next to a large stream will likely face higher absolute costs for the fencing option than the farm plan because the farm plan consists of a large fixed cost that does not vary by farm size. On the contrary, a dairy farm that needs to fence only a short length of stream would likely face higher costs for constructing a wetland because it could take some land out of production.

Figure 50: Annual mitigation costs ($ per hectare) for Whangarei Harbour catchment landowners, by area (hectares)



7.2 POLICY SCENARIOS MODELLED

The NRC, with input from MPI, has specified that a range of mitigation scenarios be analysed. These include (1) practice-based approaches, such as fencing streams for stock exclusion, and (2) target-based approaches that include reducing erosion to reach harbour-wide sedimentation targets or decreasing *E. coli* in key sites to achieve secondary contact recreation targets.

The practice-based approaches investigate the maximum amount of reductions that could be achieved when implementing certain mitigation options. The target-based approaches investigate the impact of setting a specific reduction target but then allowing landowners to collectively select the set of mitigation options that will meet the target. Table 37 provides a summary of the policy scenarios modelled.

It is not intended that the catchment economic model define or analyse any specific policy or reduction target. Thus, the scenarios presented in this report should be taken as illustrative examples of how the model works and can be used in future analyses, as opposed to a rigorous analysis of a proposed policy or rule change.

Table 37: Whangarei Harbour catchment economic model scenarios

Scenario name	Description	Sediment target	*E. coli* target
	Minimum loads		
Afforestation – all	Afforestation of all non-native land in the catchment with native bush to estimate the minimum loads possible	n/a	n/a
Afforestation – pasture	Afforestation of all pasture (dairy, dry stock and lifestyle) in the catchment with native bush	n/a	n/a
	Practice-based scenarios		
Current fencing	Proportion of dairy (75%) and some dry stock and lifestyle (20%) match current stream fencing data from NRC to establish status quo impact of mitigation	n/a	n/a
Fence all	Fence all permanent streams adjacent to pasture for stock exclusion	n/a	n/a
Farm plan	All pastoral farms implement farm plan for hillside and landmass erosion control	n/a	n/a
Wetlands	Construct wetlands and sediment ponds on maximum amount of land possible, including urban and forested areas	n/a	n/a
Max mitigation	Raise fences for stock exclusion, implement farm plans and construct wetlands on all possible land	n/a	n/a
	Target-based scenarios: Harbour sediment load reduction below the baseline		
Harbour sediment 20%	20% reduction in total annual sediment to each depositional basin	20%	n/a
Harbour sediment 40%	40% reduction in total annual sediment to each depositional basin	40%	n/a
Harbour sediment 60%	60% reduction in total annual sediment to each depositional basin	60%	n/a
	Target-based scenarios: E. coli load reduction below the baseline		
E. coli 20%	20% reduction in total stream and harbour *E. coli* load in each REC2 sub-catchment	n/a	20%
E. coli 40%	40% reduction in total stream and harbour *E. coli* load in each REC2 sub-catchment	n/a	40%
E. coli 60%	60% reduction in total stream and harbour *E. coli* load in each REC2 sub-catchment	n/a	60%
	Target-based scenarios: E. coli secondary contact recreation attribute target		
Secondary contact "B"	Stream *E. coli* concentrations at all "nodes of importance" meet NPS-FM "B" attribute state of 540 cfu/100mL	n/a	540 cfu/100mL
Secondary contact "A"	Stream *E. coli* concentrations at all "nodes of importance" meet NPS-FM "A" attribute state of 260 cfu/100mL	n/a	260 cfu/100mL

Note: cfu = colony forming unit; mL – millilitres; n/a = not applicable; NPS-FM = National Policy Statement for Freshwater Management; NRC = Northland Regional Council; REC = River Environment Classification.

7.2.1 Baseline data

NZ-FARM must establish a baseline for the Whangarei Harbour catchment before conducting any scenario analysis. Here we specify that the distribution of enterprise area in each of the model's 700-plus sub-catchments matches the land-use map. The baseline also assumes no sediment or *E. coli* mitigation practices or policies have been implemented (including existing farm plans or stream fencing).[11] The "no mitigation" baseline is the same assumption that was used for sediment modelling in SedNetNZ but not the *E. coli* modelling in CLUES.

In the case of *E. coli*, NIWA calibrated the model to empirical data in Northland, which implicitly account for management such as stream fencing within the catchment. However, as there was no spatially explicit information on which farms in the catchment are currently fenced nor how effective that fencing is, we opted not to incorporate this mitigation into the

[11] In reality, mitigation practices, such as fencing streams, have been imposed by some landowners in the catchment. Thus, the baseline used for this study is likely to overestimate the impact of mitigation.

NZ-FARM baseline.12 Thus, the NZ-FARM *E. coli* mitigation figures may be an overestimate of the actual reduction that could occur under the different model scenarios.

A summary of the main economic and environmental outputs is listed Table 38. Total net farm income from land-based operations with the current land-use mix is estimated at $16.6 million per year or $548 per hectare for all land and $964 per hectare for land that is currently earning revenue from farming and forestry. Total sediment load is over 31 000 tonnes, of which more than 85 percent comes from landmass erosion. Nearly 20,000 tonnes of sediment is deposited into the four depositional basins in the harbour. The total stream and harbour *E. coli* loads are estimated to be 84 peta per year and 293 peta per year, respectively.[13]

Table 38: Baseline area, farm earnings and environmental outputs by land use

Scenario	Area (ha)	Total net farm revenue ($)	Net farm revenue ($/ha)	Landmass erosion (t)	Streambank erosion (t)	Total erosion (t)	Harbour deposit (t)	Stream *E. coli* (peta)	Harbour *E. coli* (peta)
Dairy	3 236	9 961 530	3 078	2 059	345	2 404	1 517	13.3	84.3
Sheep and beef	10 435	2 082 365	200	9 524	1 689	11 213	6 998	42.0	53.5
Forestry	3 094	1 929 094	623	3 824	279	4 103	2 565	1.2	15.6
Horticulture and arable	490	2 661 541	5 431	158	38	196	121	0.4	0.0
Native	9 674	0	0	10 129	1 138	11 267	7 386	8.1	17.0
Urban	2 851	0	0	731	886	1 618	1 034	16.3	115.7
Other	576	0	0	458	97	554	348	2.7	6.6
Total	30 356	16 634 530	548	26 883	4 472	31 355	19 968	84.0	292.7

Note: ha = hectares; t = tonnes.

7.3 RESULTS OF THE SCENARIO ANALYSIS

This section reports the economic and environmental impacts of the sediment and *E. coli* mitigations modelled. The main results reported include net farm revenue, total annual cost, landmass and streambank sediment loads, AASR, and stream and harbour *E. coli* loads. The mitigation impacts on the four freshwater sediment attributes and the two *E. coli*-based recreation attributes at the nodes of importance are also reported, where applicable.

The estimates in this section compare the “no policy” baseline with the policy scenario after it has been fully implemented.[14] Key outputs on the dynamic transition of the policy from the baseline to fully implemented policy are highlighted in Appendix 4. All values are listed as mean annual figures.

Given the considerable uncertainties with the *E. coli* and sediment baseline load estimates, the findings from the catchment economic model should only be used to assess the relative impact of the different mitigations. The results should not be interpreted as specific predictions of the likely cost of a policy.

[12] We model current fencing in one of the scenarios, which presents a possible sensitivity of our no mitigation assumption.
[13] Recall that the issue with stream *E. coli* is focused on concentrations at specific sites, not the sum of total load in the streams.
[14] For this analysis, it is assumed that the policy is fully implemented over a relatively long period of 10 years or more to allow landowners adequate time to adopt new mitigation practices.

A series of maps showing the spatial distribution of the main findings for each policy scenario is presented in Appendix 5. A sensitivity analysis is conducted for some of the practice-based scenarios in which the farm plan, fencing and wetland mitigation options are assumed to be less effective than our standard assumption, which is summarised in Appendix 6.

7.3.1 Catchment-wide results

The extent of possible reductions in contaminant loads is limited in this analysis because only 46 percent of the Whangarei Harbour catchment is in pasture, with a significant proportion classified as native or urban. This means management options that only target pastoral enterprises will not be enough to achieve large reductions in environmental contaminants.

The total estimated impacts for the entire Whangarei Harbour catchment are listed in Table 39. The table indicates that the impacts vary widely across scenarios.

To achieve specific targets for the attributes modelled at lowest cost, the mitigations need to be targeted to the particular land uses in the areas of key importance in a catchment. For the Whangarei Harbour catchment, the most cost-effective approach focuses effort where particular hot spots of sediment and *E. coli* occur. These areas are upstream of sites with important water-quality objectives and use a combination of fencing, farm plans and wetlands, with landowners deciding on the optimal combination of mitigations for their farm.

The two afforestation schemes carry an unrealistic set of estimated impacts because of the assumption that most or all land is taken out of production. Doing so could reduce total sediment by up to 49 percent, while reducing stream and harbour *E. coli* loads by almost 75 percent. These figures serve as the potential upper bound of reductions that could be achieved under any policy scenario, and they provide a logical check for expectations of what can be done under more realistic scenarios that focus on specific management practices or reduction targets.

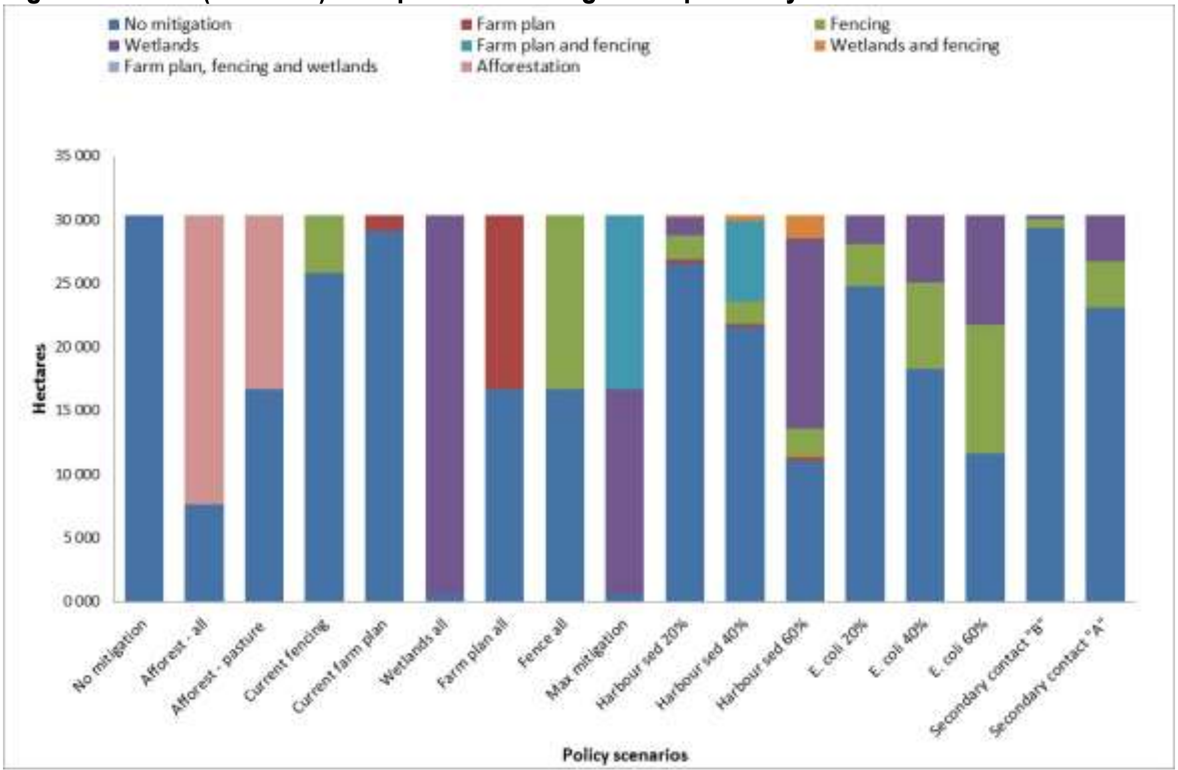
Table 39: Key model scenario estimates for the entire Whangarei Harbour catchment

Scenario	Net revenue (mil $)	Total annual cost (mil $/yr)	Land & hill erosion (t/yr)	Stream-bank erosion (t/yr)	Total erosion (t/yr)	Total harbour depositio n (t/yr)	*E. coli* load – stream (peta)	*E. coli* load – harbour (peta)
No mitigation	16.6	0.00	26 883	4 472	31 355	19 968	84.0	292.7
Afforest – all	0.0	16.63	13 437	2 463	15 901	10 175	22.5	75.8
Afforest – pasture	4.6	12.04	16 436	2 643	19 079	11 454	36.7	177.6
Current fencing	16.5	0.11	26 883	3 995	30 878	19 689	69.3	233.6
Current farm plan	16.6	0.03	26 495	4 472	30 967	19 715	84.0	292.7
All wetlands	15.2	1.47	7 866	4 472	12 338	7 928	43.3	149.7
All farm plan	16.3	0.35	18 429	4 472	22 901	14 731	84.0	292.7
Fence all streams	16.2	0.44	26 883	2 845	29 728	18 988	39.8	182.5
Maximum mitigation	14.7	1.92	7 866	2 845	10 711	6 948	32.3	122.1
Harbour sediment 20%	16.6	0.04	20 705	4 357	25 062	15 975	74.2	224.2
Harbour sediment 40%	16.4	0.19	14 680	4 303	18 983	11 981	71.3	224.1
Harbour sediment 60%	16.0	0.60	9 229	3 548	12 777	7 967	47.8	189.7
E. coli 20%	16.4	0.19	25 366	4 077	29 443	18 751	67.2	234.2
E. coli 40%	16.2	0.42	23 151	3 621	26 772	17 031	50.4	175.6
E. coli 60%	15.9	0.76	20 836	2 980	23 816	15 132	33.6	117.1
Second contact “B”	16.6	0.02	26 779	4 254	31 033	19 770	71.1	292.7
Second contact “A”	16.3	0.31	24 017	3 770	27 787	17 754	59.0	292.7
Change from no mitigation baseline								
Afforest – all	–100%	16.63	–50%	–45%	–49%	–49%	–73%	–74%
Afforest – pasture	–72%	12.04	–39%	–41%	–39%	–43%	–56%	–39%
Current fencing	–1%	0.11	0%	–11%	–2%	–1%	–18%	–20%
Current farm plan	–0.2%	0.03	–1%	0%	–1%	–1%	0%	0%
All wetlands	–9%	1.47	–71%	0%	–61%	–60%	–48%	–49%
All farm plan	–2%	0.35	–31%	0%	–27%	–26%	0%	0%
Fence all streams	–3%	0.44	0%	–36%	–5%	–5%	–53%	–38%
Maximum mitigation	–12%	1.92	–71%	–36%	–66%	–65%	–62%	–58%
Harbour sediment 20%	–0.3%	0.04	–23%	–3%	–20%	–20%	–12%	–23%
Harbour sediment 40%	–1%	0.19	–45%	–4%	–39%	–40%	–15%	–23%
Harbour sediment 60%	–4%	0.60	–66%	–21%	–59%	–60%	–43%	–35%
E. coli 20%	–1%	0.19	–6%	–9%	–6%	–6%	–20%	–20%
E. coli 40%	–3%	0.42	–14%	–19%	–15%	–15%	–40%	–40%
E. coli 60%	–5%	0.76	–22%	–33%	–24%	–24%	–60%	–60%
Second contact “B”	–0.1%	0.02	0%	–5%	–1%	–1%	–15%	0%
Second contact “A”	–2%	0.31	–11%	–16%	–11%	–11%	–30%	0%

Note: ha = hectare; mil = million; t = tonnes, yr = year.

The distribution of mitigation practices is varied (Figure 51). For the practice-based scenarios, the mitigation is prescribed. For the outcome-based scenarios, mitigation is selected within NZ-FARM to achieve the specified target of at least total aggregate cost to the catchment. As a result, landowners implement a mix of farm plans, fencing and wetlands, for the harbour deposition reduction scenarios, and a combination of wetlands and fencing for the scenarios that focus on reducing *E. coli*.

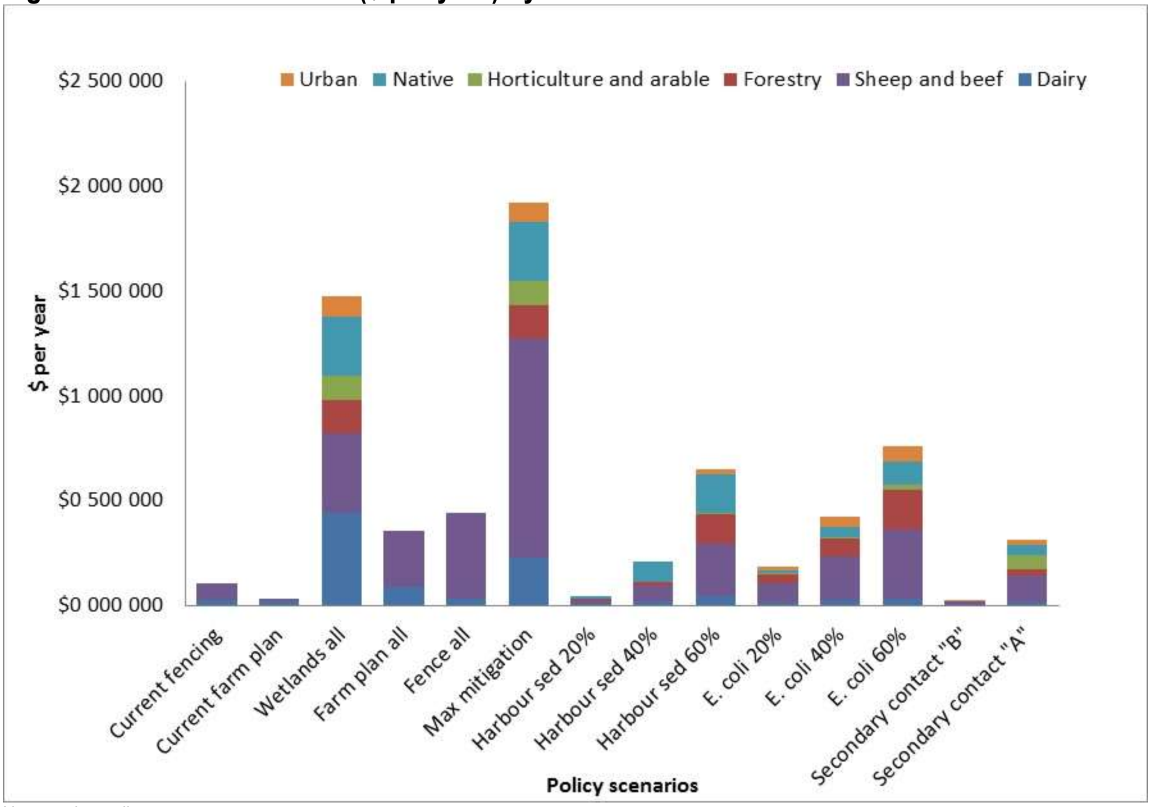
Figure 51: Area (hectares) of implemented mitigation options by scenario



Note: sed = sediment.

Costs for the non-afforestation scenarios range from $20 000 per year, for achieving the secondary contact target, to about $1.9 million per year for implementing the maximum amount of mitigation on all land in the catchment. Sheep and beef farms face the greatest total costs for nearly all scenarios (as shown in Figure 52).This is to be expected because this enterprise makes up the largest area of productive land and pasture in the catchment. All land uses face costs for any of the scenarios that include wetlands because this was the only mitigation option that could be implemented on the non-pastoral areas of the catchment.

Figure 52: Total annual cost ($ per year) by land use



Note: sed = sediment.

The mean annual mitigation costs for each scenario are broken out into per hectare values in Table 40. It is apparent from these figures that there is a wide distribution of impacts across both land use and scenario. Per hectare costs are generally higher for the wetlands scenarios because they account for opportunity costs from taking some land out of production. Many of the estimates from the outcome-based scenarios appear relatively cheaper than the practice-based scenarios, because mitigation is not necessarily implemented on every parcel of land in the catchment.

On average, sheep and beef farmers face the highest costs per hectare, followed by forestry and then horticulture and arable. This is because:

- sheep and beef farms have a lot of streams that need to be fenced, and they are often on steep land;
- most forestry is on steep land with relatively high erosion rates, and thus more wetlands would be constructed there than other places, particularly for the practice-based scenarios;
- horticulture and arable face high opportunity costs when constructing wetlands.

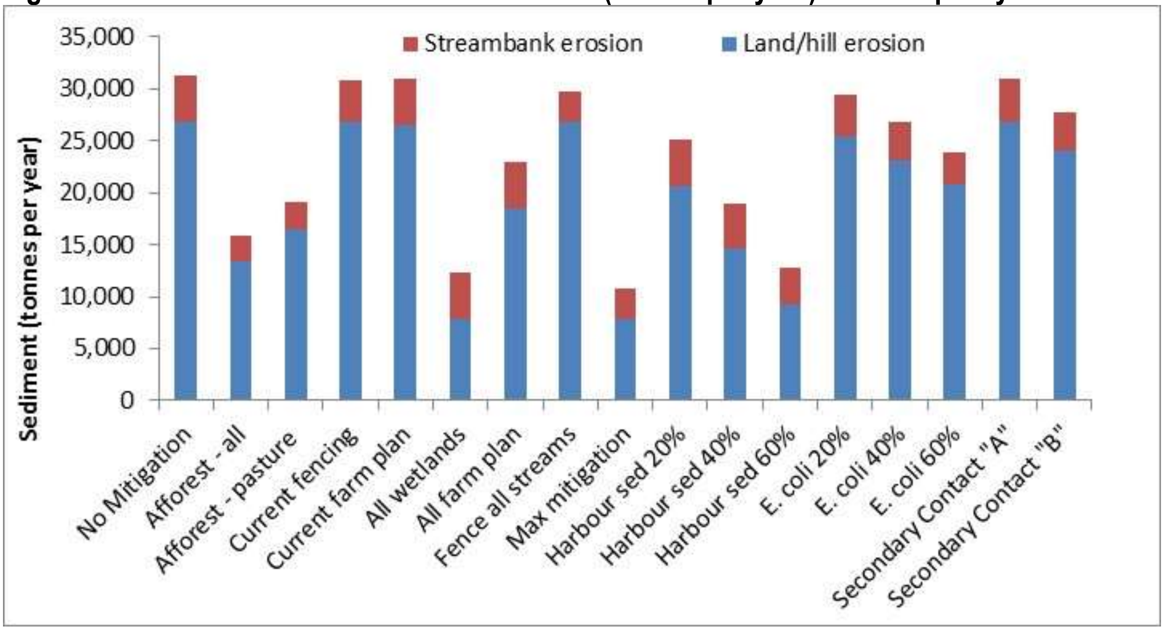
Table 40: Mean annual mitigation cost ($ per hectare per year)*

Scenario	Dairy ($)	Sheep and beef ($)	Forestry ($)	Hort and arable ($)	Native ($)	Urban ($)	All ($)	Pastoral only ($)
Afforest – all	3 078	200	623	5 432	0	0	548	881
Afforest – pasture	3 078	200	0	0	0	0	397	881
Current fencing	7	8	0	0	0	0	4	8
Current farm plan	5	1	0	0	0	0	1	2
Wetlands all	136	37	52	239	29	34	49	60
Farm plan all	26	26	0	0	0	0	12	26
Fence all	10	39	0	0	0	0	15	32
Maximum mitigation	71	100	52	239	29	34	63	93
Harbour sediment 20%	2	2	0	0	2	0	1	2
Harbour sediment 40%	6	7	6	0	8	0	6	7
Harbour sediment 60%	12	21	44	14	18	8	20	19
E. coli 20%	5	9	14	5	1	7	6	8
E. coli 40%	7	20	28	11	5	16	14	17
E. coli 60%	9	32	61	52	12	25	25	27
Secondary contact “B”	0	2	0	0	0	0	1	2
Secondary contact “A”	4	12	10	141	5	9	10	10

Note: Hort = horticulture. * Estimated as total mitigation cost divided by total area for each land use.

The modelled scenarios estimate a wide-range of impacts on not only total sediment (3 percent to 65 percent) but also the two main sources of sediment. In most cases, sediment from hill and landmass erosion is reduced more than that from streambanks (Figure 53). The two exceptions are the current and all pasture-fencing scenarios. This is because just fencing streams without any other mitigation practices does not have an impact on landmass sediment.

Figure 53: Catchment sources of total sediment (tonnes per year) for each policy scenario



7.4 SCENARIO-SPECIFIC FINDINGS

This section presents the main findings for each set of modelled scenarios. While estimates of the spatial impacts are provided for most of the modelled scenarios, additional outputs are given in Appendix 5.

7.4.1 Catchment-wide afforestation

Afforesting all land provides an estimate of the best possible outcome for reducing *E. coli* in the catchment and one of the highest outcomes for sediment. NZ-FARM estimates that total sediment could be reduced by as much as 49 percent, while the total *E. coli* loads in the streams and reaching the harbour could be reduced by 73 percent and 74 percent, respectively. Note, however, that as some of the nodes of importance are already located in heavily forested areas of the catchment, this management option does not lead to large changes in attributes measured at those nodes relative to the baseline (see Section 7.5).

Afforesting pasture land results in similar, but less pronounced, results than those identified in the full-afforestation scenario.

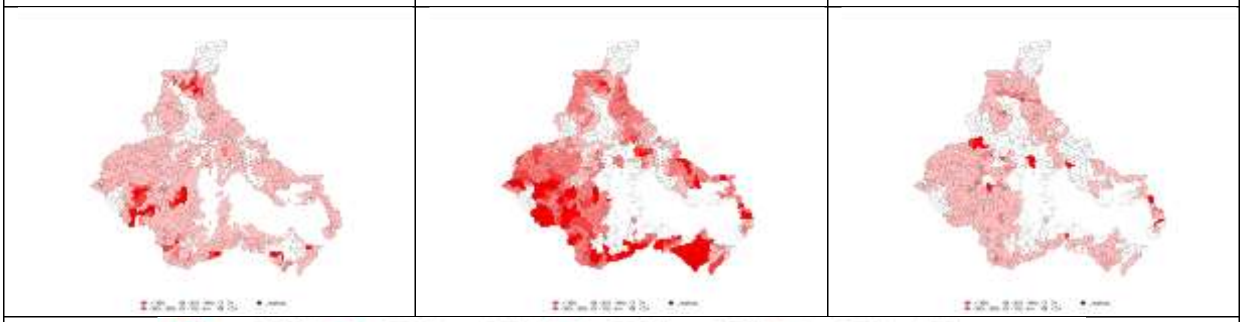
7.4.2 Current fencing

The current fencing option assumed that 75 percent of dairy and 20 percent of sheep and beef and deer farms have already fenced waterways. This option is estimated to have some effect on reducing streambank erosion (11 percent) and *E. coli* loads (about 20 percent) relative to a no-mitigation baseline. Because streambank erosion is only about 15 percent of total erosion in the catchment, and fencing is assumed to have no impact on landmass erosion, total erosion is estimated to be reduced by only 2 percent. The total cost of the current fencing along pastoral streams is estimated to be $107 000 per annum or about $8 per hectare per year. Figure 54 shows the spatial impacts for total sediment, stream *E. coli* and net farm revenue as a percent reduction relative to the no-mitigation baseline.

Many dairy farms are located on the south side of the catchment and therefore their contaminant loadings do not feed directly into the nodes of importance. Thus, while fencing these streams does have an impact on the total loads for both *E. coli* and sediment, it does not have as much of an effect on some of the main areas of concern for this study. Note also that, because these assumptions were applied equally to all pastoral enterprises next to streams, actual impacts could vary, depending on where the actual fencing has been implemented in the catchment (for example, some farms have 100 percent of their streams fenced) on specific farms.

Figure 54: Spatial impacts of the current fencing scenario (percentage change from baseline)

Total sediment	Stream *E. coli*	Net farm revenue

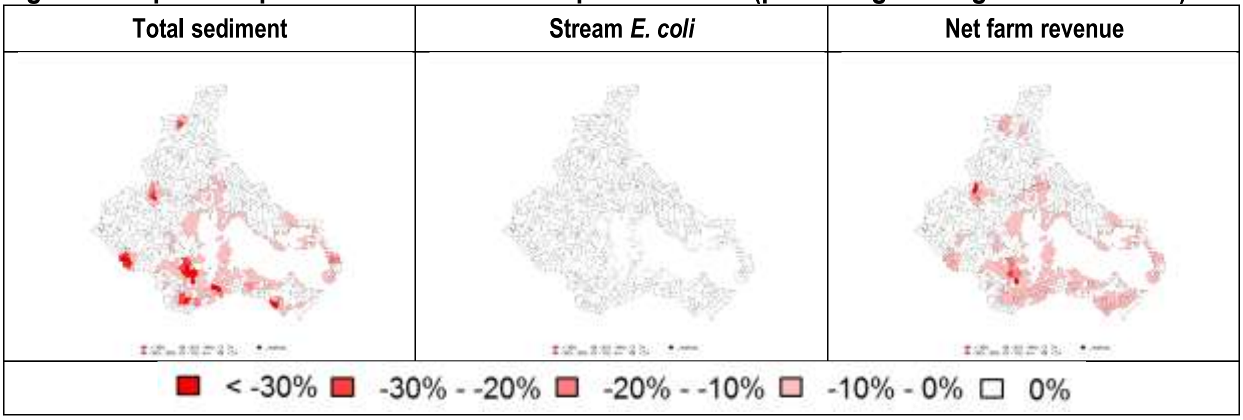


< -30% | -30% - -20% | -20% - -10% | -10% - 0% | 0%

7.4.3 Current farm plan

The current farm plan option assumed that just 1240 hectares of farm plans that have been implemented by the NRC on pastoral farms are mature and fully effective (Figure 55). Farm plans are only assumed to affect landmass erosion, which is estimated to be reduced by 1 percent relative to the baseline. Although the plans are found to have limited impact on sediment and *E. coli* in the catchment (and the related attributes), these plans may be focusing on alternative issues and thus have more of an impact on other metrics not measured in this study. The total cost of the current farm plans, which consists of the cost to prepare and implement the plan, is estimated to be $32 000 per annum or about $26 per hectare per year on the area where they have been implemented.

Figure 55: Spatial impacts of the current farm plan scenario (percentage change from baseline)



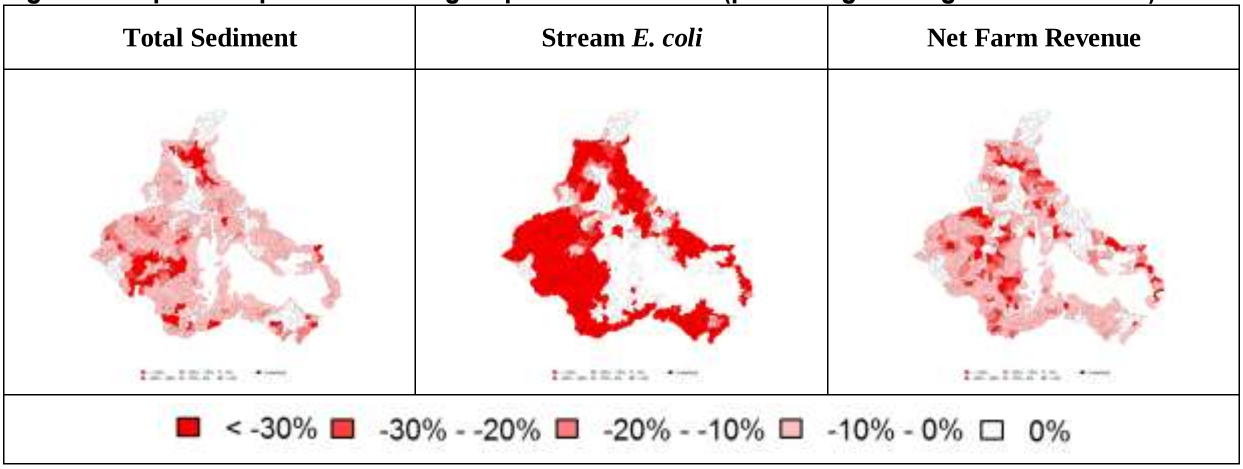
7.4.4 Fencing all pasture

Fencing all pasture land has an effect on streambank erosion and *E. coli* from pasture, but no impact on landmass erosion. As a result, the greatest impact of this management option is on stream *E. coli* loads, which are estimated to be reduced by more than 50 percent relative to the baseline (Figure 56). Fencing streams is also expected to make 10 of the 11 nodes of importance reach at least the "B" state for secondary contact recreation (for the median concentration). Figure 56 indicates where fencing is likely to be most effective, which provides useful information for the NRC to target fencing at particular "hot spots".

Streambank erosion from pasture is a relatively small proportion of total sediment in the catchment (15 percent), so although fencing all streams adjacent to pasture results in a 36 percent reduction in streambank erosion, that equates to just a 5 percent reduction in total erosion. Thus, more mitigation may have to be carried out in the Whangarei Harbour catchment to achieve significant improvements in sediment-related attributes.

The total cost of fencing all streams in the catchment is estimated to be $443 000 per year (or $33 000 per year if current fencing is excluded). This equates to an average of $32 per hectare per year for all pastoral farms.

Figure 56: Spatial impacts of fencing all pastoral streams (percentage change from baseline)



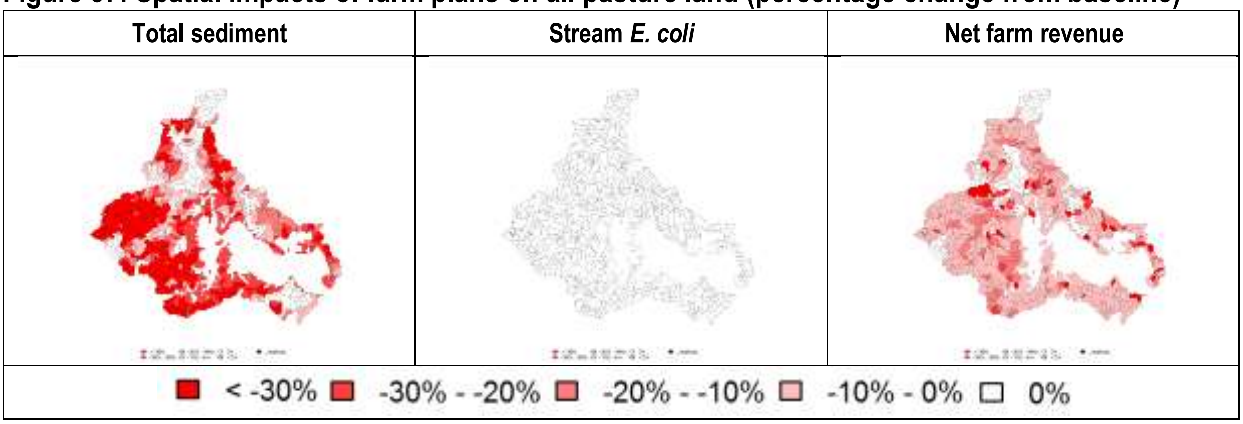
7.4.5 Farm plans on all pasture

Farm plans are assumed to mitigate only landmass sediment from pastoral enterprises but not other land uses. They are also assumed to have no effect on streambank sediment or *E. coli*. Because pasture is just 46 percent of total land cover, and not necessarily located at the top of the catchment where there can be high levels of erosion, farm plans may not achieve the desired outcome for all sediment and *E. coli*-related impacts in the catchment. NZ-FARM estimates that implementing farm plans on all pasture results in a 31 percent reduction in landmass erosion and a 27 percent reduction in total sediment in the catchment (Figure 57).

Implementing farm plans across all pastoral farms in the catchment can reduce harbour sediment by 26 percent relative to the baseline, and thus has some measurable impact on the harbour sediment attribute (AASR) in each of the four deposition basins. Farm plans, however, do not have an effect on two of the three nodes of importance that were assessed for freshwater sediment attributes because the land surrounding these nodes is primarily native forest, scrub and/or or urban. This suggests that farm plans need to be implemented with wetlands to produce an improvement in some freshwater sediment attributes at the Whangarei Harbour catchment's nodes of importance.

The total cost of implementing farm plans on all pastoral land in the catchment is estimated to be $354 000 per year (or $322 000 per year if current farm plans are excluded). This equates to an average of $26 per hectare per year for all pastoral farms.

Figure 57: Spatial impacts of farm plans on all pasture land (percentage change from baseline)



7.4.6 Wetlands on all land uses

Constructing wetlands and sediment ponds has an effect on landmass erosion and *E. coli* from all land uses. It is estimated to be the most effective option from a single management perspective because it is the only mitigation that can be applied to all land uses (Figure 58). As a result, total sediment is estimated to be reduced by 61 percent while stream and harbour *E. coli* are estimated to be reduced by nearly 50 percent. Wetlands, however, are assumed to have no effect on streambank erosion, so land managers may have to consider coupling them with fencing to get even further reductions (for example, the maximum mitigation scenario).

Wetland-based mitigation is estimated to have a noticeable effect on the entire range of modelled attributes. The *E. coli* concentrations target for the A-state secondary contact recreation attribute is estimated to be met in five nodes of importance, while at least the B-state is achieved in all but one node. In terms of harbour sediment, an AASR of 1.9 millimetres per year or less is achieved in all four of the harbour basins. Freshwater sediment attributes are also estimated to improve relative to the baseline, with the largest improvements occurring at the Otaika River site. These findings suggest that, if wetlands are constructed throughout the catchment, large changes in sediment and *E. coli*-related attributes can be achieved.

It is estimated that implementing the maximum amount of wetland mitigation in the Whangarei Harbour catchment results in costs of $1.47 million per year or an average of $49 per hectare per year. The costs of implementing wetlands on a particular parcel of land are sometimes higher than other mitigation options, particularly if accounting for high opportunity costs from taking highly profitable land out of production. Co-ordination and cost constraints could also limit the level of uptake in reality. Note that, in Figure 58, many of the sub-catchments are estimated to have high losses in net farm revenues (that is 30 percent or more). This is attributed mostly to constructing wetlands on urban, native and scrub land, which is assumed to create no net revenue in the baseline rather than due to high opportunity costs.[15]

Figure 58: Spatial impacts of wetlands on all land (percentage change from baseline)

Total sediment	Stream *E. coli*	Net farm revenue

< -30% -30% - -20% -20% - -10% -10% - 0% 0%

7.4.7 Maximum mitigation (farm plans, fencing and wetlands)

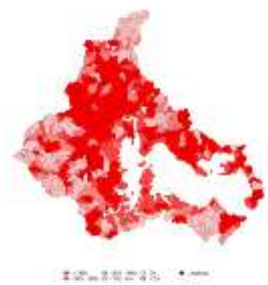
The maximum mitigation scenario assumes that all pastoral farms implement farm plans and fencing while all other land constructs wetlands. This mitigation approach results in significant reductions in sediment load (66 percent) and *E. coli* loads (58 percent to 62 percent) although at a relatively high cost. The change in the landmass erosion is the same as the farm plan scenario, but adding fencing reduces streambank erosion as well, thus reducing total erosion by more than either "standalone" mitigation option (Figure 59).

[15] Note, this applies to all of the scenarios where there is a high amount of wetland mitigation on non-productive land.

It is estimated that the *E. coli* concentrations target for the A-state secondary contact recreation attribute is met in six nodes of importance, while the B-state is met in the other five nodes. In addition, an AASR rate of 1.9 millimetres per year or less is achieved in all four of the harbour basins. These findings suggest that, if a full mitigation plan is implemented in the catchment, large improvements in sediment and *E. coli*-related attributes can be achieved. As with the other mitigation scenarios, there are larger improvements in freshwater sediment attributes at the Otaika River site because it has the greatest diversity of land use and, hence, benefits more from mitigation.

The total cost of this mitigation option is estimated to be about $1.9 million per year. This equates to an average of $63 per hectare per year.

Figure 59: Spatial impacts of the maximum mitigation on all land scenario (percentage change from baseline)

Total sediment	Stream *E. coli*	Net farm revenue
		
< -30% ; -30% - -20% ; -20% - -10% ; -10% - 0% ; 0%		

7.4.8 Harbour sediment deposition reduction policies

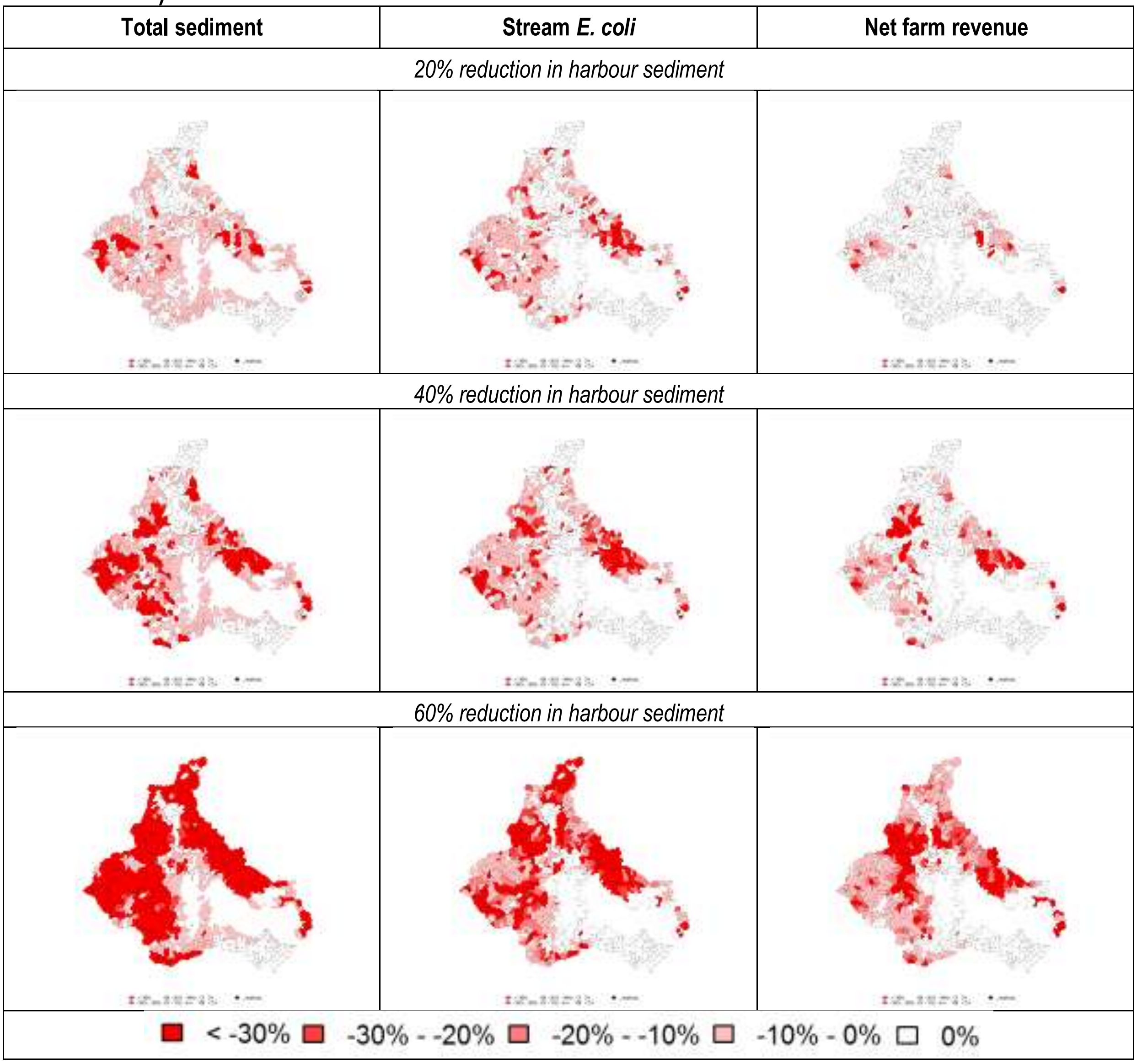
These scenarios estimate the impacts of achieving a 20 percent, 40 percent and 60 percent reduction in harbour sediment in the four deposition basins. The scenarios do not mandate a particular management option but, rather, allow the model to estimate how landowners in the catchment could collectively implement cost-effective mitigation to achieve the targets. In the low reduction target scenarios, we find there is minimal change in certain areas of the catchment (Figure 60). This suggests it is optimal to target specific “hotspots” with farm plans and wetlands. We also estimate that there are larger relative reductions in landmass sediment (23 percent to 66 percent) than streambank sediment (3 percent to 21 percent), regardless of the reduction target. This highlights that fencing streams with the sole intent of reducing erosion may be a less cost-effective option.

It is estimated that a 20 percent reduction target reduces basin-level AASR rates between 10 percent and 19 percent relative to the baseline, while a 60 percent reduction target is estimated to reduce the AASR by 30 percent to 57 percent. The 20 percent reduction target does not have much of an effect on freshwater sediment attributes because of where the mitigation is implemented in the catchment, but the 60 percent reduction target results in estimates similar to the maximum mitigation practice-based scenario.

A policy that targets sediment reduction results in the implementation of some practices, such as wetlands and fencing, that also affect *E. coli* loads. This is an unintended co-benefit. As a result, stream *E. coli* loads could be reduced by 12 percent to 43 percent and harbour *E. coli* loads by 23 percent to 35 percent. The 60 percent reduction target also leads to 8 of the 11 sites of importance achieving at least the “B” state for secondary contact recreation, two more sites than the baseline.

The total cost of these scenarios is estimated to range from $43 000 per year for the 20 percent target to about $600 000 per year for the 60 percent reduction scenario. These figures equate to $1 per hectare per year and $20 per hectare per year, respectively.

Figure 60: Spatial impacts of the harbour sediment reduction scenarios (percentage change from baseline)



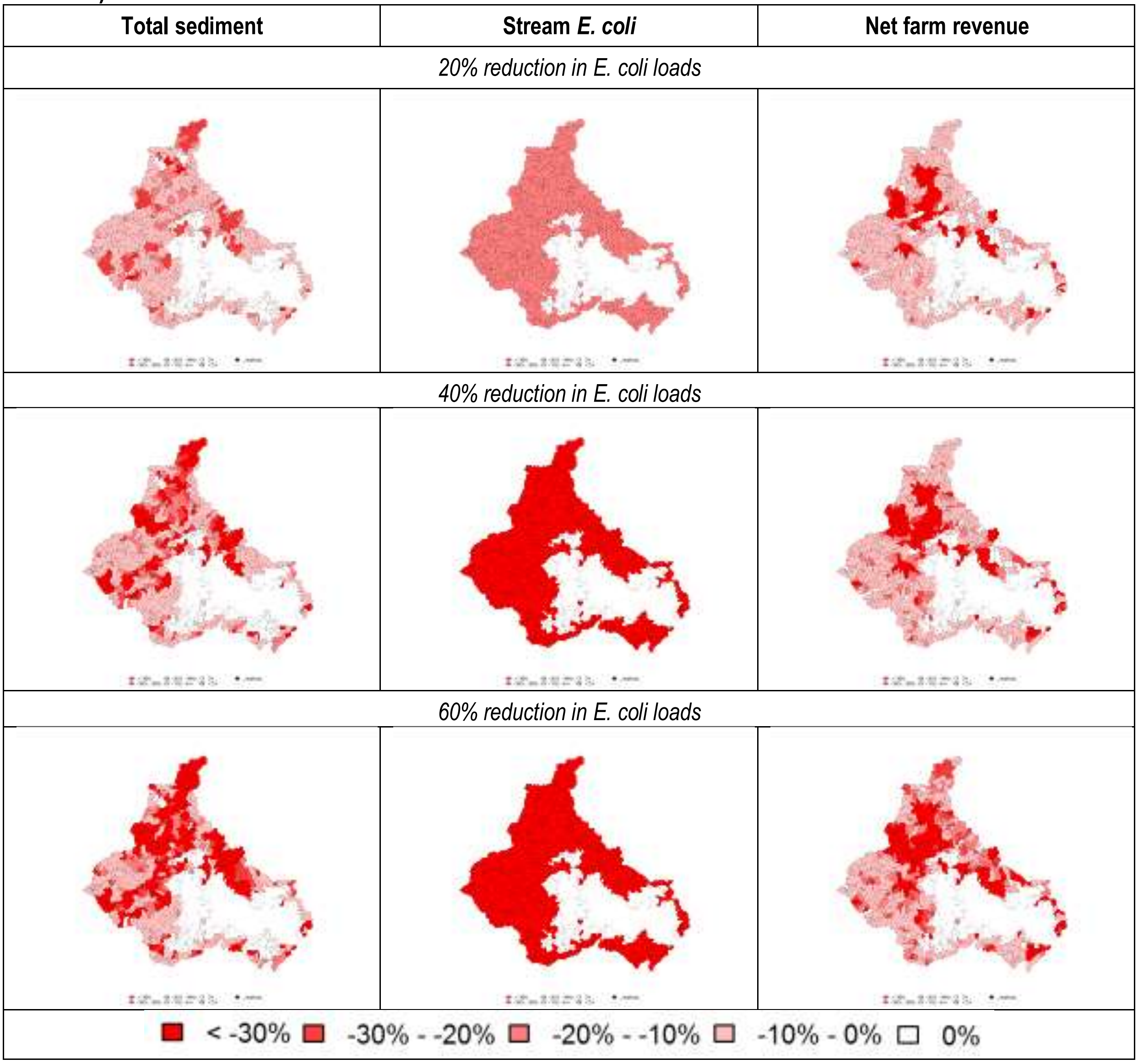
7.4.9 *E. coli* load reduction policies

The scenarios that reduce *E. coli* loads by between 20 percent and 60 percent in all REC2 sub-catchments are estimated to lead to reductions in not just *E. coli* loads (20 percent to 60 percent) but total sediment as well (6 percent to 24 percent). Thus, as with the scenarios that only focus on reducing sediment, *E. coli*-specific scenarios can create co-benefits (Figure 61). This is because the mitigation practices implemented include fencing, followed by constructing wetlands, which both have the ability to reduce *E. coli* and sediment.

The *E. coli* attribute state for secondary contact recreation at the nodes of importance does not change much from its current state for the 20 percent reduction scenario. However, the 60 percent reduction scenario results in six nodes achieving the A-state of 260 cfu per 100 millilitres and four of the five remaining nodes reaching the B-state. This suggests that large reduction targets may have to be specified in the catchment to achieve the best attribute state at all sites.

The total cost of these scenarios is estimated to range from $19 000 per year for the 20 percent target to about $760 000 per year for the 60 percent reduction scenario. These figures equate to about $6 per hectare per year and $25 per hectare per year, respectively.

Figure 61: Spatial impacts of the *E. coli* load reduction scenarios (percentage change from baseline)



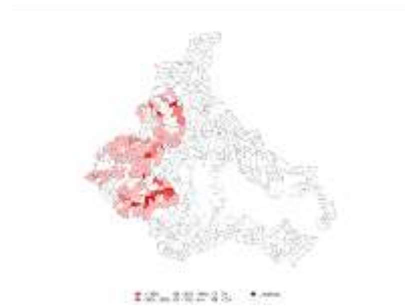
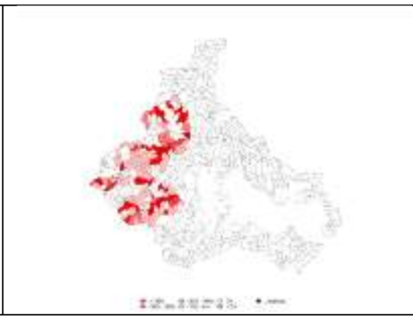
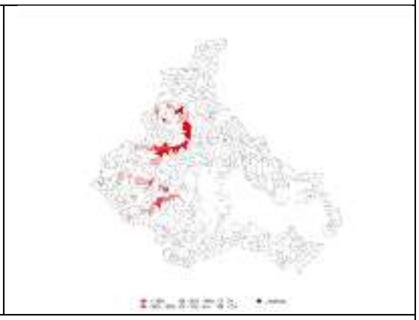
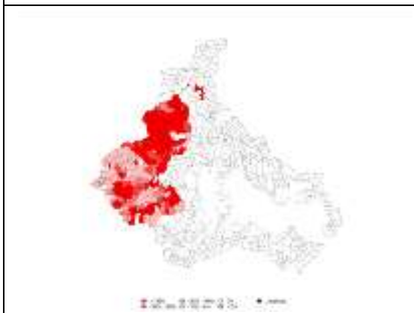
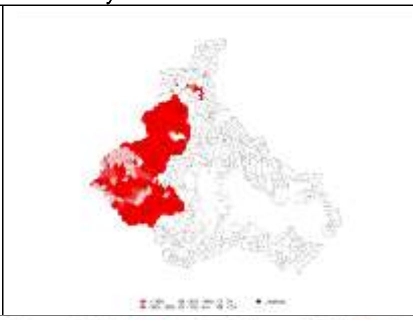
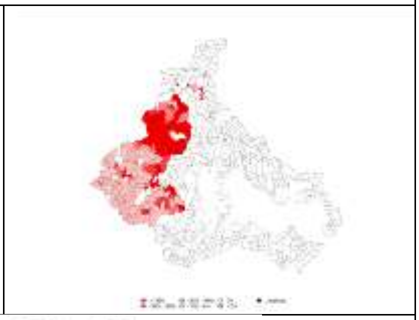
7.4.10 *E. coli* secondary contact recreation

For these scenarios, the model selected the optimal distribution of mitigation practices required to achieve the "B" and "A" secondary contact recreation attribute states at the Whangarei Harbour catchment's 11 nodes of importance (based on a median estimate at each site). Taking this approach results in the implementation of fencing and wetland practices that reduce stream *E. coli* loads by 15 percent to 30 percent and total sediment loads by 1 percent to 11 percent. There is no change in harbour *E. coli* loads because all of the nodes are located towards the middle of the catchment (Figure 62).

The model estimated that implementing practices above each of the nodes can lead to reductions in *E. coli* concentration that allow all of the sites in the catchment to reach at least the "B" state of 540 cfu per 100 millilitres. However, we also found that the "A" state concentration of 260 cfu per 100 millilitres could not be achieved at 4 of the 11 sites, although all of these nodes had median concentrations of less than 330 cfu per 100 millilitres. This suggests that additional research may have to go into finding even more effective mitigation options than those included in this study (that is, practices that reduce *E. coli* by more than 60 percent) to achieve the desired outcome.

The total cost of achieving the respective “B” and “A” attribute state targets is estimated to be $22 000 and $312 000 per year, respectively. These figures equate to about $1 per hectare per year and $10 per hectare per year, respectively, if the costs are spread across all 30 000 hectares in the catchment. However, if only the area where mitigation is actually implemented is accounted for, the respective costs are $22 per hectare per year and $43 per hectare per year.

Figure 62: Spatial impacts of the secondary contact recreation attribute state scenarios (percentage change from baseline)

Total sediment	Stream *E. coli*	Net farm revenue
“B” secondary contact recreation attribute state		
		
“A” secondary contact recreation attribute state		
		
< -30% -30% - -20% -20% - -10% -10% - 0% 0%		

7.5 ATTRIBUTE ESTIMATES

7.5.1 Freshwater sediment attributes

A wide range of impacts occurs on water clarity, euphotic depth, suspended sediment concentration and embeddedness – the four freshwater sediment attributes of interest for this study. Estimates for water clarity and euphotic depth are presented in Table 41, while suspended sediment concentration and embeddedness are presented in Table 42.

Impacts in the Hātea sub-catchment are minimal unless a large amount of wetland-based mitigation is put in place. This is because the site is largely composed of native and urban land. However, as landmass erosion only constitutes about 37 percent of the total erosion flowing to the site, even implementing the maximum area of wetlands only reduces total sediment loads in the catchment by 26 percent. Thus, to see significant impacts on sediment in this sub-catchment, additional research is required to estimate feasible ways to mitigate streambank erosion in catchments predominantly made up of native and urban land.

The Waiarohia stream shows barely any changes in freshwater sediment attributes relative to the baseline. This is because it is situated in a sub-catchment that is almost 100 percent urban use with minimal landmass erosion in the baseline and limited mitigation potential (that is, only wetlands). As with the Hātea sub-catchment, streambank mitigation for urban areas will be required to see large reductions in sediment at this site.

Attributes in the Otaika sub-catchment are estimated to have the largest improvement because it is situated in a sub-catchment with a significant amount of sheep and beef farming. As a result, water clarity and euphotic depth could increase by as much as 77 percent and 35 percent, respectively, if maximum mitigation were put in place. NZ-FARM estimates a wide range of impacts to the attribute levels at this site for the outcome-based scenarios, based on both the target reduction and focus of the policy. For example, the harbour sediment reduction scenarios with targets of 20 percent and 40 percent estimate no change in load because there is lower cost mitigation that is more effective for achieving the target elsewhere in the Whangarei Harbour catchment. Thus, additional policies may have to be put in place to ensure site-specific attribute objectives are achieved.

Table 41: Water clarity and euphotic depth at three Whangarei Harbour catchment sites

Scenario	Hātea River		Waiarohia Stream		Otaika River	
	Value	% Change	Value	% Change	Value	% Change
Water clarity (metres)						
No mitigation	1.65	0	1.77	0	1.07	0
Afforest – all	1.79	9	1.79	1	1.82	71
Afforest – pasture	1.65	0	1.77	0	1.73	62
Current fencing	1.65	0	1.77	0	1.13	6
Current farm plan	1.65	0	1.77	0	1.10	3
Wetlands	2.29	39	1.88	6	1.24	16
Farm plan	1.65	0	1.77	0	1.11	4
Fence all	1.65	0	1.77	0	1.51	41
Maximum mitigation	2.29	39	1.88	6	1.89	77
Harbour sediment 20%	1.65	0	1.77	0	1.07	0
Harbour sediment 40%	1.65	0	1.77	0	1.07	0
Harbour sediment 60%	2.29	39	1.77	0	1.75	64
E. coli 20%	1.86	13	1.81	2	1.16	9
E. coli 40%	2.13	29	1.86	5	1.27	19
E. coli 60%	2.29	39	1.88	6	1.41	32
Second contact “B”	1.65	0	1.77	0	1.07	0
Second contact “A”	1.65	0	1.88	6	1.76	65
Euphotic depth (metres)						
No mitigation	2.22	0	2.42	0	1.76	0
Afforest – all	2.31	4	2.44	1	2.34	33
Afforest – pasture	2.22	0	2.42	0	2.27	29
Current fencing	2.22	0	2.42	0	1.82	3
Current farm plan	2.22	0	2.42	0	1.76	0
Wetlands	2.64	19	2.52	4	1.91	8
Farm plan	2.22	0	2.42	0	1.80	2
Fence all	2.22	0	2.42	0	2.12	20
Maximum mitigation	2.64	19	2.52	4	2.38	35
Harbour sediment 20%	2.22	0	2.42	0	1.76	0
Harbour sediment 40%	2.22	0	2.42	0	1.76	0
Harbour sediment 60%	2.64	19	2.43	0	2.29	30
E. coli 20%	2.36	7	2.46	2	1.84	4
E. coli 40%	2.54	14	2.50	3	1.93	10
E. coli 60%	2.64	19	2.52	4	2.04	16
Second contact “B”	2.22	0	2.42	0	1.76	0
Second contact “A”	2.22	0	2.52	4	2.29	30

Table 42: Suspended sediment concentration and embeddedness at three Whangarei Harbour catchment sites

Scenario	Hātea River		Waiarohia Stream		Otaika River	
	Value	% Change	Value	% Change	Value	% Change
Suspended sediment (grams per cubic metre)						
No mitigation	3.60	0	3.60	0	4.30	0
Afforest – all	3.34	–7	3.54	–2	2.45	–43
Afforest – pasture	3.60	0	3.60	0	2.59	–40
Current fencing	3.60	0	3.60	0	4.04	–6
Current farm plan	3.60	0	3.60	0	4.30	0
Wetlands	2.66	–26	3.32	–8	3.67	–15
Farm plan	3.60	0	3.60	0	4.17	–3
Fence all	3.60	0	3.60	0	2.99	–31
Maximum mitigation	2.66	–26	3.32	–8	2.36	–45
Harbour sediment 20%	3.60	0	3.60	0	4.30	0
Harbour sediment 40%	3.60	0	3.60	0	4.30	0
Harbour sediment 60%	2.66	–26	3.60	0	2.55	–41
E. coli 20%	3.22	–11	3.49	–3	3.94	–8
E. coli 40%	2.84	–21	3.38	–6	3.58	–17
E. coli 60%	2.66	–26	3.32	–8	3.22	–25
Second contact "B"	3.60	0	3.32	–8	4.30	0
Second contact "A"	3.60	0	3.32	–8	2.55	–41
Embeddedness (grams of trapped sediment per cubic metre of water)						
No mitigation	n/a	n/a	122.6	0%	n/a	n/a
Afforest – all	n/a	n/a	120.6	–2%	n/a	n/a
Afforest – pasture	n/a	n/a	122.6	0%	n/a	n/a
Current fencing	n/a	n/a	122.6	0%	n/a	n/a
Current farm plan	n/a	n/a	122.6	0%	n/a	n/a
Wetlands	n/a	n/a	113.1	–8%	n/a	n/a
Farm plan	n/a	n/a	122.6	0%	n/a	n/a
Fence all	n/a	n/a	122.6	0%	n/a	n/a
Maximum mitigation	n/a	n/a	113.1	–8%	n/a	n/a
Harbour sediment 20%	n/a	n/a	122.6	0%	n/a	n/a
Harbour sediment 40%	n/a	n/a	122.6	0%	n/a	n/a
Harbour sediment 60%	n/a	n/a	122.5	0%	n/a	n/a
E. coli 20%	n/a	n/a	118.8	–3%	n/a	n/a
E. coli 40%	n/a	n/a	115.0	–6%	n/a	n/a
E. coli 60%	n/a	n/a	113.1	–8%	n/a	n/a
Second contact "B"	n/a	n/a	113.1	–8%	n/a	n/a
Second contact "A"	n/a	n/a	113.1	–8%	n/a	n/a

Note: n/a = not applicable.

7.5.2 Estuary sediment attribute

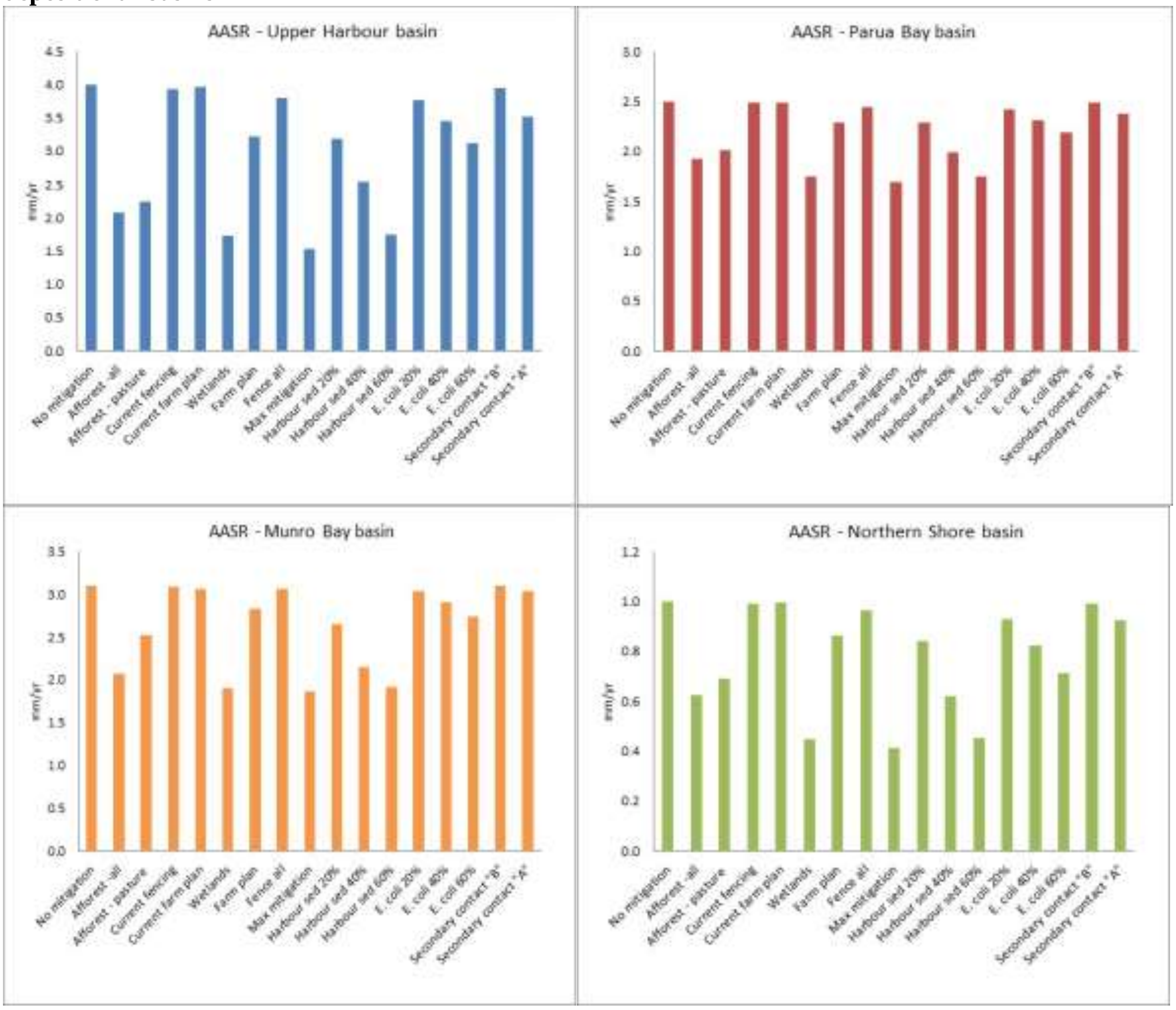
Nearly all scenarios result in a noticeable reduction in the AASR in the four depositional basins (Figure 63), but impacts vary widely across the scenarios and basins. Green et al (2015) suggested potential targets of 1, 2 and 3 millimetres per year for each basin.

It is estimated that the 3 millimetres per year target can be met in each basin for nearly all of the scenarios in the Parua Bay, Munro Bay and Northern Shore basins. The target is not met in the Upper Harbour basin, though, unless a large amount of farm plan and wetland-based mitigation is put in place. This is because the baseline AASR is already well above the

3 millimetre rate, as there is relatively little sediment deposition in that basin from marine sources with most coming from land-based sources.

The optimistic 1 millimetre per year AASR target is only reached in the Northern Shore basin, but note that this basin also achieved that target in the baseline. This finding is not only a result of not enough sediment being mitigated from landmass and streambank erosion, but also because the marine sediment that contributes to the AASR is assumed to remain constant for all scenarios. This finding is further supported by the fact that the scenarios that focused on a 20 percent to 60 percent reduction in sediment from land-based mitigation did not result in the same percent reduction in AASR for any of the basins.

Figure 63: Annual average sedimentation rate (millimetres per year) for four Whangarei Harbour depositional basins



7.5.3 *E. coli* attributes

E. coli concentration estimates for the median and 95th percentile are listed in Table 43. It is found that implementing mitigation practices in the Whangarei Harbour catchment leads to reductions in concentrations that allow many, and sometimes all, of the nodes of importance to reach at least the "B" state of 540 cfu per 100 millilitres, for secondary contact recreation. None of the modelled scenarios, even the case of full afforestation, result in all of the nodes achieving the "A" state of 260 cfu per 100 millilitres for secondary contact recreation.

NZ-FARM estimated that, even under the best possible scenario of full afforestation, *E. coli* concentrations for primary contact recreation are all above the "B" target of 540 cfu per 100 millilitres. It signals that this target, which is based on the 95th percentile measurements for

E. coli concentrations at all nodes of importance, could not be met under any land-use or land management conditions.

This does not mean that a particular site is always unsuitable for swimming. For example, at the popular swimming site Hātea at Whangarei Falls, the recreational swimming programme results for 2014/15, where sampling is carried out weekly over summer months (end of November to end of February), were lower than 540 *E. coli* per 100 millilitres on 18 out of 24 sampling occasions, or 75 percent of the time. Those lower results compared to modelled year round concentration are to be expected as summer months tend to be drier with less rainfall related land run-offs.

Additional work may have to be undertaken to assess if there are other methods to estimate 95th percentile *E. coli* concentrations in the catchment, perhaps under different flow assumptions or time constraints. Also, it is valuable to reflect on the way that microbial concentrations at the 95th percentile are related to microbial loads, given that this result has been identified in a framework in which one is assumed to be a linear function of the other.

Table 43: Estimated *E. coli* concentrations (colony forming units per 100 millilitres) for the Whangarei Harbour catchment's nodes of importance

Scenario	Whangarei Falls	Waiarohia at confluence with Waiarohia and Waikahitea	Hātea at Mair Park Footbridge	Raumanga just before it joins the Waiarohia	Waiarohia at Second Ave	Kirikiri just before it joins the Raumanga	Raumanga at Bernard Street	Raumanga Stream at swimming pool below falls	Otaika at Otaika Valley Road	Otaika weir (Golden Bay surface water take)	Puwera just before it joins Otaika
Median concentration (secondary contact recreation)											
No mitigation	439	525	259	942	399	722	903	211	484	871	1 354
Afforest – all	143	383	80	226	161	320	204	48	133	234	228
Afforest – pasture	201	415	118	642	287	358	517	88	147	249	231
Current fencing	388	504	230	858	380	676	805	184	382	682	981
Current farm plan	439	525	259	942	399	722	903	211	484	871	1 354
Wetlands	221	263	130	472	200	365	452	106	244	437	678
Farm plan	439	525	259	942	399	722	903	211	484	871	1 354
Fence all	216	419	127	540	304	491	436	83	135	234	280
Maximum mitigation	165	236	97	371	176	307	335	74	156	278	409
Harbour sediment 20%	436	467	248	903	386	558	877	204	474	819	1 325
Harbour sediment 40%	409	385	240	896	376	525	872	203	461	806	1 188
Harbour sediment 60%	260	277	155	799	237	391	777	176	247	432	643
E. coli 20%	349	420	207	752	313	567	722	170	388	698	1 083
E. coli 40%	259	315	155	563	237	430	540	127	291	524	813
E. coli 60%	173	221	104	387	168	298	371	85	195	350	542
Secondary contact "B"	439	410	259	540	229	540	540	115	371	540	540
Secondary contact "A"	260	223	202	328	164	278	277	58	172	260	275
95th Percentile concentration (primary contact recreation)											
No mitigation	2 003	3 485	6 306	12 844	5 421	9 852	13 164	3 076	4 378	7 883	18 470
Afforest – all	652	2 541	1 937	3 089	2 185	4 360	2 978	698	1 207	2 119	3 111
Afforest – pasture	919	2 753	2 863	8 759	3 896	4 878	7 541	1 289	1 331	2 249	3 154
Current fencing	1 771	3 344	5 596	11 701	5 163	9 220	11 739	2 686	3 459	6 166	13 379
Current farm plan	2 003	3 485	6 306	12 844	5 421	9 852	13 164	3 076	4 378	7 883	18 470
Wetlands	1 009	1743	3 166	6 431	2 713	4 977	6 586	1 539	2 203	3 955	9 246
Farm plan	2 003	3 485	6 306	12 844	5 421	9 852	13 164	3 076	4 378	7 883	18 470
Fence all	986	2 782	3 086	7 369	4 130	6 694	6 357	1 210	1 218	2 120	3 814
Maximum mitigation	754	1 568	2 361	5 063	2 391	4 187	4 885	1 073	1 413	2 515	5 582
Harbour sediment 20%	1 990	3 100	6 049	12 320	5 242	7 609	12 780	2 971	4 290	7 412	18 075
Harbour sediment 40%	1 865	2 556	5 837	12 217	5 103	7 166	12 712	2 952	4 166	7 287	16 197
Harbour sediment 60%	1 187	1 841	3 771	10 897	3 222	5 339	11 328	2 573	2 237	3 909	8 765
E. coli 20%	1 593	2 788	5 046	10 253	4 253	7 731	10 523	2 474	3 507	6 310	14 776
E. coli 40%	1 184	2 091	3 770	7 685	3 224	5 861	7 877	1 845	2 635	4 737	11 082
E. coli 60%	792	1 466	2 526	5 280	2 279	4 070	5 412	1 235	1 767	3 169	7 388
Secondary contact "B"	2 003	2 724	6 306	8 584	3 108	7 365	7 872	1 672	3 356	4 884	7 365
Secondary contact "A"	1 187	1 480	4 919	4 467	2 229	3 793	4 034	839	1 552	2 352	3 750

NPS-FM attribute state	A (< 260)	B (260–540)	C (540–1 000)	D (> 1 000)

Note: NPS-FM = National Policy Statement for Freshwater Management

8 Limitations

NZ-FARM has been developed to assess economic and environmental impacts over a wide range of land uses, but it does not account for all sectors of the economy. The economic land-use model should be used to provide insight on the relative impacts and trade-offs across a range of policy scenarios (for example, practice versus outcome-based targets), rather than for explicitly modelling the absolute impacts of a single policy scenario. Thus, it should be used to compare impacts across a range of scenarios or policy options.

The parameterisation of the model relies on biophysical and economic input data from several different sources. Therefore, the estimated impacts produced by NZ-FARM should be used in conjunction with other decision support tools and information not necessarily included in the model to evaluate the “best” approach to manage sediment and *E. coli* in the Whangarei Harbour catchment. Some of the modelling limitations from the study are detailed below.

1. **Input data:** The quality and depth of the economic analysis depends on the datasets and estimates provided by biophysical models like SedNetNZ and CLUES, farm budgeting data based on information published by MPI and industry groups, and spatial datasets such as maps depicting current land use and sub-catchments. Estimates derived from other data sources or models not included in this analysis may provide different results for the same catchment. Thus, analysis presented here should be used in conjunction with other information (for example, input from key stakeholders affected by policy, study of health and recreational benefits from water quality improvements) during any decision-making process.

2. **Representative farms:** The model only includes data and mitigation practices for representative farms for the Whangarei Harbour catchment that were parameterised based on their physical characteristics (for example, land-use capability, slope and so on). It does not explicitly model the economic impacts on a specific farm in the catchment. As a result, some landowners in the catchment may actually face higher or lower costs than what are modelled using this representative farm approach.

3. **Contribution of dairy and forestry:** At this stage, we are unable to reliably differentiate between the contribution from dairy and other pastoral activities to *E. coli* loads (apart from the influence of dairy effluent).
   - The overall loading from pasture is approximately six-times larger than that from forested areas.
   - Runoff from some of the forested catchments has unexpectedly high *E. coli* concentrations. This applies especially to sites in the Whangarei Harbour catchment.
   - This information implies that reducing *E. coli* loads by controlling pasture sources alone may not be as effective, making it difficult to achieve concentration targets.
   - Investigating some of the forested catchments would be beneficial for identifying the sources of *E. coli* and the measures most likely to minimise *E. coli* concentrations in runoff.

4. **Uncertainty in *E. coli* modelling:** Overall, there is high uncertainty in model predictions, due to currently unknown factors. This uncertainty should be acknowledged when:
   - determining risks (Which catchments should be prioritised for implementation of mitigation strategies?); and
   - prioritising investment (Which mitigation tools should be implemented, and where should they be implemented in the catchment?).

5. **Not all sites are measured:** Stream flows and *E. coli* concentrations are not currently measured at all of the sites of interest in the catchment (nodes of importance). The estimated concentrations and loads at some of these sites are high and relatively uncertain. It would be advantageous to monitor *E. coli* at these nodes to improve load estimates.

6. **Baseline conditions:** The NZ-FARM baseline assumed that (1) land use in the catchment was the same as a 2011 land-use map; (2) that net farm revenue was based on a five-year average of input costs and output prices; and (3) that no landowners were implementing management practices intended to reduce sediment and *E. coli* in the catchment. Assumption number three is likely to have the greatest impact on model estimates, as the NRC has indicated that some farms in the catchment have implemented farm plans and/or fenced their streams. However, the number of farms that have implemented these management options to their maximum effectiveness is uncertain and likely to be relatively small.

7. **Management practices:** The study only includes management practices deemed feasible and likely to be implemented in a catchment as a result of *E. coli* and sediment reduction policies, given the current state of knowledge and technology available. It does not account for new and innovative mitigation options that might be developed in the future as a result of incentives created under the policy. Although not all possible mitigation options may be included in the model, the suite of management practices will be large enough to account for a wide-range of mitigation costs (for example, change in farm profit) and effectiveness (for example, change in sediment or *E. coli* loads). Therefore, the average cost of the modelled scenarios should be within the range of what the actual average costs are likely to be as a result of the policy scenario analysed.

8. **Mitigation effectiveness:** Each management practice included in the model is assumed to have a fixed relative rate of effectiveness for reducing sediment and *E. coli* loads (for example, 50 percent of baseline loads). In reality, the actual impact of a given practice is likely to vary, depending on where, when and how well the practice is implemented.

9. **Optimisation routine:** For this analysis, NZ-FARM has been programmed such that all landowners are assumed to collectively select the "optimal" combination of management practices required to achieve specific outcomes related to managing sediment and *E. coli* in the Whangarei Harbour catchment. This is assumed to occur over at least 10 years, as landowners typically need adequate time to make significant changes to their operation. In reality, not all landowners will necessarily select the option that is considered most optimal.

9 Summary and conclusions

The NRC has identified that sediment and *E. coli* are significant water quality challenges in the Northland region. As a result, the council engaged in a joint venture with MPI and MfE to undertake a sediment and *E. coli* study in the Whangarei Harbour catchment.

The study's objective was to identify cost-effective ways to manage sediment and *E. coli* loads in streams and rivers in the Whangarei Harbour catchment, as well as in the harbour itself. The study had a particular focus on the impact of mitigation on various sediment and *E. coli* attributes.

The Whangarei Harbour catchment has a lot of area classified as urban or native, which is managed differently from rural productive land uses such as dairy, sheep and beef, and forestry. Only 46 percent of the catchment is in pasture, so management options that only target pastoral enterprises may not be enough to achieve large reductions in environmental contaminants.

The most effective mitigations are those that focus on a combination of fencing, farm plans and wetlands, with landowners deciding on the optimal combination of mitigations for their farm. This mitigation enables a focus on the particular hotspots of sediment and *E. coli*. This mitigation cost of $0.65 million per year reduced net revenue in the catchment by around 4 percent, but total sediment loads are estimated to fall by around 60 percent, with total sediment deposition in the harbour also estimated to be reduced by 60 percent. *E. coli* loads in streams are estimated to reduce by around 44 percent.

In considering each mitigation practice on its own, constructing wetlands and sediment ponds is estimated to be the most effective option, as it is the only mitigation to can be applied to all land uses. Sediment loads are estimated to reduce by 61 percent and *E. coli* loads in streams by 48 percent. It is also the only mitigation option that has a positive impact on the sediment attributes of water clarity and euphotic depth in all three measured sites in the catchment. For example, constructing wetlands near the Otaika River improves water clarity at median flows by up to 77 percent and euphotic depth by 35 percent.

However, co-ordination and cost constraints could limit uptake of this management option. For example, wetlands were estimated to cost $1.5 million per year across the catchment, which represents an annual cost of $49 per hectare. This compares with that cost of fencing pastoral streams at $443 000 per year or $15 per hectare per year.

Fencing all pasture land has an effect on streambank erosion and *E. coli* from pasture, but no impact on landmass erosion (85 percent of sediment in the catchment results from landmass erosion). As a result, the greatest impact of this management option is on *E. coli* loads in streams, which are estimated to be reduced by more than 50 percent relative to the baseline.

Implementing farm plans on pastoral farms is only assumed to mitigate sediment from hill–landmass erosion. Most of the pasture in the catchment is not located at the top of the catchment, where there can be high levels of landmass erosion, so farm plans may not be the most cost-effective option for reducing sediment and *E. coli* loads in the catchment.

Nearly all scenarios estimated a noticeable reduction in the harbour sediment attribute included in the Whangarei Harbour study, the AASR. Estimates varied widely across the four deposition basins, though, as they are all affected differently in terms of the amount of sediment they receive annually from both land and marine sources. Thus, the suggested "high" attribute state of 1 millimetre per year may not be achievable for all of the harbour basins.

Implementing mitigation practices in the Whangarei Harbour catchment can lead to reductions in *E. coli* concentration that allow many, and sometimes all, of the important sites in the catchment to reach at least the "B" state of 540 cfu per 100 millilitres for secondary contact recreation (this is based on an annual median estimate). Some sites of importance reach the "A" state of 260 cfu per 100 millilitres when particular mitigations are applied.

Achieving *E. coli* targets for primary contact recreation is not possible in the Whangarei Harbour catchment. Even if the catchment was completely covered in forest, it would not be possible to meet the NPS-FM target for primary contact recreation (a maximum of 540 cfu per 100 millilitres) in any of the 11 key sites. This target is based on the 95th percentile measurements. Additional work is required to assess if there are other methods to estimate 95th percentile concentrations in the catchment, perhaps under different flow assumptions or time constraints.

Catchment-wide policies that only target reductions in either *E. coli* or sediment can have a noticeable effect on reducing the non-targeted contaminant as well, but not necessarily to the same degree. For example, a policy that targets a 40 percent reduction in sediment can also reduce *E. coli* loads in the catchment by 15 percent to 23 percent, while a policy that targets a 40 percent reduction in *E. coli* can reduce sediment by 15 percent. It also highlights that the specific location of these mitigations within the catchment can have an effect on other attributes that are not necessarily targeted by the policy.

10 Glossary

Average recurrence interval (ARI): The average or expected value of the periods between exceedances of a given rainfall total accumulated over a given duration. It is implicit in this definition that the periods between exceedances are generally random.

Attribute: A measurable characteristic of freshwater, including physical, chemical and biological properties, which supports particular values.

Attribute state: The level to which an attribute is to be managed for a specific attribute specified.

Average annual sedimentation rate (AASR): The per annum rate at which sediments are deposited into a harbour basin. Includes sediment deposited from land, streambanks and marine sources.

Baseline: The economic and environmental state of the catchment before the implementation of any practice or policy intended to reduce sediment or *E. coli* in the catchment.

Catchment Land Use for Environmental Sustainability (CLUES): A GIS based modelling system that assesses the effects of land use change on water quality and socio-economic indicators.

Compound-Specific Stable Isotope (CSSI): A forensic method developed by NIWA to track sources of eroded soil deposited in estuaries. It is able to link eroded soil to specific land uses.

Concentration: The amount of a particular substance per unit of another substance (for example, grams of sediment per cubic metre of water).

Contaminant: Biological (for example, bacterial and viral pathogens) or chemical (for example, toxicants) introductions capable of producing an adverse effect in a waterbody.

Discharge: The release of contaminants into the environment either directly into water or onto (or into) land.

Diffuse source discharge: Pollutants sourced from widespread or dispersed sources (for example, from pasture runoff of animal wastes, fertiliser and sediments, as well as runoff of pollutants from paved surfaces in urban areas). Also called non-point source discharges.

Earnings Before Interest and Tax (EBIT): Farm profits that exclude interest and tax. It is used interchangeably with net farm revenue.

***E. coli*:** Bacteria that live in the intestines of people and animals. A primary indicator of pathogenic microorganisms that can impact human health.

Erosion: The group of processes, including weathering, dissolution, abrasion, corrosion, and transportation, by which material is worn away from the Earth's surface.

Euphotic depth: The distance of water through which light travels and becomes attenuated to 1 percent of the surface light intensity. The distance defines the euphotic zone in which there is sufficient light for photosynthesis and periphyton and macrophytes may be sustained.

Generalised Additive Modelling (GAM): A generalised linear model in which the linear predictor depends linearly on unknown smooth functions of some predictor variables, and interest focuses on inference about these smooth functions. The purpose of generalized additive models is to maximize the quality of prediction of a dependent variable Y from various distributions, by estimating unspecific (non-parametric) functions of the predictor variables which are "connected" to the dependent variable via a link function.

Geographic Information System (GIS): A system designed to capture, store, manipulate, analyse, manage, and present all types of spatial or geographical data.

Land Cover Database (LCDB): A digital map of New Zealand's land surface. It is created by grouping together similar classes that can be identified in satellite images.

Land Use Capability (LUC): The LUC system has two key components. Firstly, Land Resource Inventory (LRI) is compiled as an assessment of physical factors that are critical for long-term land use and management. Secondly, the inventory is used for LUC Classification, where land is categorised into eight classes according to its long-term capability to sustain one or more productive uses.

Load: The flux of a contaminant passing a point of interest. Generally measured as mass (sediment) or number of individual organisms (*E. coli*) per unit area and per unit time (for example, kilograms per hectare per year). In this study, typically presented as annual estimates at a catchment or sub-catchment scale.

Mitigation: The moderation of the intensity of one or more environmental contaminants through implementing changes in resource or land management.

Mitigation cost: The annual cost of implementing a specific mitigation practice. Includes capital and implementation costs, annual operating and maintenance costs, and opportunity costs of removing land and/or stock from production.

National Policy Statement for Freshwater Management (NPS-FM): The NPS-FM provides direction about how local authorities should carry out their responsibilities under the Resource Management Act 1991 for managing fresh water. It's particularly important for regional councils, as it directs them to consider specific matters and to meet certain requirements when they are developing regional plans for fresh water.

National Objectives Framework (NOF): The 2014 amendments to the NPS-FM added a "National Objectives Framework". The objective of the National Objectives Framework is to provide an approach to establish freshwater objectives for national values, and any other values that is nationally consistent and recognises regional and local circumstances.

Nephelometric Turbidity Units (NTU): A unit measuring the lack of clarity of water. is measured with an electronic instrument called a nephelometer. The water to be measured is placed in a standard container. A light beam passes through the water and strikes a sensor on the other side of the container. A second sensor is mounted at right angles to the beam, measuring light scattered by particles in the water. From the ratio between the light intensities at the two sensors the turbidity in NTU can be calculated.

Net farm revenue: The main measurement of economic output from land-based activities at the catchment scale incorporated in NZ-FARM. Based on farm earnings before interest and tax. Includes wages for management and capital and implementation costs for mitigation practices.

New Zealand Forest and Agriculture Regional Model (NZ-FARM): A catchment-scale economic landuse model, that optimises total net farm revenue subject to economic, environmental, and resource constraints. The model estimates the economic and environmental impacts of policy and management scenarios relative to a baseline (that is, no policy or mitigation).

New Zealand Land Resource Inventory (NZLRI): A national database of physical land resource information. It comprises two sets of data compiled using stereo aerial photography, published and unpublished reference material, and extensive field work. The first data set is an inventory of five physical factors (rock type, soil, slope, present type and severity of erosion, and vegetation). The second data set is a Land Use Capability (LUC) rating of the ability of each polygon to sustain agricultural production, based on an assessment of the inventory factors above, climate, the effects of past land use, and the potential for erosion.

Nodes of importance: 11 sites within the Whangarei Harbour catchment of particular interest to the Northland Regional Council. They are located near environmental monitoring stations and/or popular recreation sites.

Point source discharge: Discharge of contaminants into a waterbody from a single fixed point, such as a pipe or drain (for example, from sewerage, factory and dairy shed outfalls).

Primary contact recreation: Activities likely to involve full immersion in water (for example, swimming). NOF *E. coli* targets for primary contact recreation are measured using the 95th percentile.

River Environment Classification (REC): A database that maps rivers that have a similar character across New Zealand's landscape. Individual river sections are mapped according to physical factors such as climate, source of flow for the river water, topography, and geology, and catchment land cover.

Secondary contact recreation: Activities with occasional immersion in water and some ingestion of water (for example, wading and boating). NOF *E. coli* targets for secondary contact recreation are measured using the annual median estimate.

Sediment: Geological material, such as silt, sand, rocks and fossils that has been transported and deposited by water or wind.

SedNetNZ: a spatially distributed, time-averaged model that routes sediment through the river network using a sediment budgeting approach. It is based on a relatively simple physical representation of hillslope and channel processes that contribute to each stream link in a river network.

Suspended sediment concentration: The ratio of the mass of dry sediment in a water–sediment mixture to the volume of the mixture.

Target: Limit that must be met at a defined time in the future. Often expressed as a percent change from a baseline.

Turbidity: The cloudiness of water caused by scattering of light from suspended particles.

Water clarity: The distance of water through which an object can be clearly seen. A direct measure of the immediate foraging range of fish.

11 References

Basher, L R; Hicks, D M; Clapp, B; Hewitt, T (2011) Sediment yield response to large storm events and forest harvesting, Motueka river, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 45(3): 333–356.

Clausen, B; Plew, D (2004) How high are bed-moving flows in New Zealand rivers? *Journal of Hydrology (NZ)* 43(1): 19–37.

Curran-Cournane, F; Holwerda, N; Mitchell, F (2013) *Quantifying catchment sediment yields in Auckland*. Auckland Council Technical Report 2013/042. Auckland Council, Auckland.

Daigneault, A; Greenhalgh, S; Samarasinghe, O; Jhunjhnuwala, K; Walcroft, J; de Oca Munguia, O M (2012) *Sustainable land management and climate change – catchment analysis of climate change: final report*. Ministry for Primary Industries, Wellington.

Daigneault, A; Samarasinghe, O (2015) *Whangarei Harbour sediment and E. coli study: catchment economic modelling.* Prepared for the Ministry for Primary Industries by Landcare Research Ltd; Auckland (unpublished).

Daigneault, A; Samarasinghe, O; Lilburne, L (2013) *Modelling economic impacts of nutrient allocation policies in Canterbury – Hinds Catchment*. Landcare Research Contract Report LC1490 prepared for the Ministry for the Environment. Ministry for the Environment, Wellington.

Davies-Colley, R J; Ballantine, D J; Elliott, S H; Swales, A; Hughes, A O; Gall, M P (2014) Light-attenuation – a more effective basis for the management of fine suspended sediment than mass concentration? *Water Science and Technology* 69(9): 1867–1874.

Davies-Colley, R J; Nagels, J W (2008) Predicting light penetration into river waters. *Journal of Geophysical Research* 103: G03028.

Dymond, J R; Betts, H D; Schierlitz, C S (2010) An erosion model for evaluating land-use scenarios in New Zealand. *Environmental Modelling and Software* 25: 289–298.

Dymond, J (2015) *Temporal disaggregation of sediment loads in the Whangarei Harbour Catchment and response to soil conservation.* Report prepared for the Ministry for Primary Industries and AgResearch by Landcare Research Ltd; Palmerston North (unpublished).

Elliott, A H; Alexander, R B; Schwarz, G E; Shankar, U; Sukias, J P S; McBride, G B (2005) Estimation of nutrient sources and transport for New Zealand using the hybrid mechanistic-statistical model SPARROW. *Journal of Hydrology (New Zealand)* 44(1): 1–27.

Green, M (2013) Catchment sediment load limits to achieve estuary sedimentation targets. *New Zealand Journal of Marine and Freshwater Research* 47(2): 153–180.

Green, M (2015) *Northland sediment study: Whangarei Harbour sediment budget.* Prepared for the Ministry for Primary Industries by the National Institute of Water and Atmospheric Research Limited (NIWA),;Hamilton (unpublished).

Green, M; Dymond, J; Matthaei, C; and Elliott, S (2015) *Northland sediment study: sediment and E. coli attributes.* Prepared for the Ministry for Primary Industries by the National Institute of Water and Atmospheric Research Limited (NIWA); Hamilton (unpublished).

Hicks, D M; Gomez, B; Trustrum, N A (2000) Erosion thresholds and suspended yields, Waipaoa River Basin, New Zealand. *Water Resources Research* 36(4): 1129–1142.

Julian, J P; Davies-Colley, R J; Gallegos, C L; Trana, T T (2013) Optical water quality of inland waters: a landscape perspective. *Annals of the Association of American Geographers* 103(2): 309–318.

Lange, K; Townsend C R; Matthaei, C D (2014) Can biological traits of stream invertebrates help disentangle the effects of multiple stressors in an agricultural catchment? *Freshwater Biology* 59(12): 2431–2446.

Lincoln University (2013) *Financial Budget Manual 2012/13*. Lincoln University Press, Christchurch.

Matthaei, C D; Piggott, J J; Townsend, C R (2010) Multiple stressors in agricultural streams: interactions among sediment addition, nutrient enrichment and water abstraction. *Journal of Applied Ecology* 47(3): 639–649.

Millar, A S (1980) *Hydrology and surficial sediments of Whangarei Harbour*. Master of Science thesis; Department of Earth Sciences, University of Waikato, New Zealand.

Ministry for Primary Industries (2013a) *Situation and outlook for primary industries 2013*. Ministry for Primary Industries, Wellington.

Ministry for Primary Industries (2013b) *Farm monitoring report*. Wellington, New Zealand.

Palliser, C; Elliott, S; and Yalden, S (2015a) *Northland sediment study: E. coli modelling.* Prepared for the Ministry for Primary Industries by the National Institute of Water and Atmospheric Research Limited (NIWA), Hamilton (unpublished).

Palliser, C; Elliott, S; Yalden, S; Shankar, U (2015b) *Waitaki water quality catchment modelling*. Prepared for Environment Canterbury, NIWA Client Report HAM2015-002. National Institute of Water and Atmospheric Research Limited (NIWA), Hamilton.

Piggott, J J; Lange, K; Townsend, C R; Matthaei, C D (2012) Multiple stressors in agricultural streams: a mesocosm study of interactions among raised water temperature, sediment addition and nutrient enrichment. *PLoS ONE* 7(11): e49873. DOI:10.1371/journal.pone.0049873.

Piggott, J J; Salis, R K; Lear G; Townsend, C R; Matthaei, C D (2015a) Climate warming and agricultural stressors interact to determine stream periphyton community composition. *Global Change Biology* 21(1): 206–222.

Piggott, J J; Townsend, C R; Matthaei, C D (2015b) Climate warming and agricultural stressors interact to determine stream macroinvertebrate community dynamics. *Global Change Biology* 21(5): 1887–1906. DOI: 10.1111/gcb.12861.

Semadeni-Davies, A; Elliott, S; Shankar, U (2011) *The CLUES project: tutorial manual for CLUES 3.0*. Prepared for Ministry of Agriculture and Forestry, NIWA Client Report HAM2011-003. National Institute of Water and Atmospheric Research Limited; Hamilton.

Semadeni-Davies, A; Elliott, S; Yalden, S (2015) *Modelling E. coli in the Waikato and Waipa river catchments. Development of a catchment-scale microbial model*. Prepared for Waikato Regional Council, NIWA Client Report AKL2015-017. National Institute of Water and Atmospheric Research Limited; Auckland.

Suttle, K B; Power, M E; Levine, J M; McNeely C (2004) How fine sediment in riverbeds impairs growth and survival of juvenile salmonids. *Ecological Applications* 14(4): 969–974.

Swales, A; Gibbs, M; Pritchard, M; Budd, R; Olsen, G; Ovenden, R; Costley, K; Hermanspahn, N; Griffiths, R (2013) *Whangarei Harbour sedimentation: sediment accumulation rates and present-day sediment sources*. Prepared for Northland Regional Council, NIWA Client Report HAM2013–14. National Institute of Water and Atmospheric Research Limited; Hamilton.

Tanner, C C; Hughes, A; Sukias, J P S (2013) *Assessment of potential constructed wetland sites within the Waituna catchment.* NIWA Client Report No. HAM2013-071 prepared for Environment Southland and DairyNZ.

Townsend, C R; Uhlmann, S S; Matthaei, C D (2008) Individual and combined responses of stream ecosystems to multiple stressors. *Journal of Applied Ecology* 45(6): 1810–1819.

Wagenhoff, A; Lange, K; Townsend, C R; Matthaei, C D (2013) Patterns of benthic algae and cyanobacteria along twin-stressor gradients of nutrients and fine sediment: a stream mesocosm experiment. *Freshwater Biology* 58(9): 849–1863.

Wagenhoff, A; Matthaei, C D (2012) Macroinvertebrate responses along broad stressor gradients of deposited fine sediment and dissolved nutrients: a stream mesocosm experiment. *Journal of Applied Ecology,* 49: 892-902.

Wagenhoff, A; Townsend, C R; Phillips, N; Matthaei, C D (2011) Subsidy-stress and multiple stressor effects along gradients of deposited fine sediment and dissolved nutrients in a regional set of streams and rivers. *Freshwater Biology* 56(9): 1916–1936.

Appendix 1: Derivation of turbidity percentiles from flow percentiles

The probability that flow is less than a given value x is given by:

$$P(x) = \int_{-\infty}^{x} f(s)\mathrm{d}s \qquad \text{(A1-1)}$$

where s is the flow ranging from minus infinity to x. When turbidity y is a monotonic function of x, expressed as $y = g(x)$, then, equation (A1-1) may be rewritten as:

$$P(y) = \int_{-\infty}^{y} f(g)\mathrm{d}g \qquad \text{(A1-2)}$$

This shows that for a given flow percentile x with probability P of non-exceedance, the turbidity $y = g(x)$ has the same probability of non-exceedance and is therefore the equivalent turbidity percentile.

This result relies on being able to equate $f(s)\mathrm{d}s$ with $f(g)\mathrm{d}g$. This requires $g(x)$ to be a monotonic function. If there are errors in $g(x)$ then they need to be small and evenly distributed if $f(s)\mathrm{d}s$ is to be approximately equated with $f(g)\mathrm{d}g$. If this is not the case then a Monte Carlo simulation of turbidity values from flow values could be used to estimate turbidity percentiles.

Appendix 2: April 2015 workshop notes: mitigations from sediment and *E. coli* in the Whangarei Harbour catchment

The focus of the workshop is to identify the actions required to estimate the cost and efficacy of alternative mitigations for microbes and sediment along the treatment train.

Mitigations are usually more effective the closer they are to the source.

The study is focusing on a catchment-level approach consistent with a high-level study, rather than a farm-level focus.

WETLAND OPTIONS

Sediment traps are located off the mainstream, lower down the catchment.

- These are usually on a lower gradient channel for sediment to settle out.
- They need to be cleared out after large storm events.
- These may cover high-value land. However, there is an existing version in the catchment, close to the station.
- Sediment traps are used during forestry harvest to prevent discharge.

Retention ponds are duck ponds present in the stream channel.

- To be effective, they require maintenance and also investment within fencing, reticulation, and pumping.
- Generally, the number of farms possessing dams is at capacity and decreasing in fashion.
- The main focus from a management perspective is how to improve them.
- These will work mostly in summer because they can arrest the flow by absorbing capacity.

Retention bunds are possible. They are likely to provide no *E. coli* benefit; they could even increase microbial loadings.

- Northland does not have many well-drained soils.
- Wetlands can be used on poorly drained soils to enhance the retention bund.
- There is likely to be no benefit for reducing microbial loads.

Existing wetlands are a strong feature of the Northland landscape.

- The management focus is fencing them. This has received much uptake by farmers.
- Keeping stock out can reduce the sediment and microbial loads lost from the wetland.
- It is sound to assume no loss of grazing value.
- Existing wetlands have been mapped well.

Constructed wetlands are a possibility, both for intercepting surface drains and floodplains.

- Identify their impact on *E. coli* loadings. If high flows are coming then, then mitigation will occur.
- Interception of subsurface drainage not that important in Northland.
- Focus on using the natural landscape as much as possible.

Most of the sediment arrives during big storm events, and a much bigger wetland is needed to address turbidity because of the fine sediment associated with these events. Biggest sediment is easier to trap within a smaller wetland.

STREAMBANK MITIGATION

Streambank losses of sediment have been separated from the farm, and are therefore abatement strategies focused at the source and are dealt with as a separate mitigation process. Land use will be provided by stream length. This will be important to determine the value of lost grazing land.

The size of the buffer is irrelevant. The main focus is keeping stock out to stop direct deposition of manure and keep stock off the streambank.

The main focus should be keeping stock out of the channels.

There is an 80 percent reduction in annual-average streambank erosion when beef and cattle are fenced out. This assumes that woody shrubs will grow, but type of vegetation within the buffer is unimportant, it is just critical that there is no bare ground. This level of reduction will also be achieved if sheep are causing bank erosion and they are excluded.

Start at the mouth and work back in terms of priorities.

The simple option is to use two-wire fencing everywhere, especially because more expensive fences are prone to damage from soil slippage.

Trying to re-contour the stream was highlighted as expensive.

Recommended to assume there is no loss of productive value by setting the fence back. The small losses could be recovered by managing the farm better. However, it could be useful to consider this value to help gain support from farmers, by showing that it has been costed. Use a 3 metre gap generically to highlight the need to fence around the natural floodplain of the watercourse.

Buffers are of little benefit for reducing microbial loads in storm run-off.

There is a 60 percent reduction in baseline (median) flows of microbes from streambank fencing. High rainfall and flooding will impact on the statistics, so likely to be a 50 percent reduction. There is likely to be a 65 percent reduction for the 95th percentile. A 3 metre buffer might increase efficacy by 10 percent percent.

The baseline sediment modelling assumes that there is no streambank erosion.

Reticulation cost is around two to three times the cost of fencing, along with ongoing maintenance costs, pumping and installation. The water supply costs should be implemented on a per kilometre of stream length basis.

Northland Regional Council has costs of fencing. These costs are 50 percent for labour and 50 percent for materials.

Current level of adoption is 25 percent in Waipa, 25 percent in TukiTuki and 30 percent in Ruamahanga. Assume 20 percent on sheep and beef in Northland, and probably higher for dairy farms.

HILL STABILISATION OPTIONS

SedNetNZ is used to estimate hillside erosion.

Detailed information is not available on how to decompose and address the sediment arising from each farm.

Use farm plans to achieve a 70 percent reduction in sediment (once the plan is implemented and mature) at a cost of $250 per hectare (Horizons).

Cost of $5000 per farm plan for an average farm, with $1000 per additional 100 hectares.

The instrument variable is the farm plan.

The farm plan could include reversion of native forest.

Farm plans are achieving targeted mitigations on farms, especially as related to gully erosion. The cost of farm plans will increase with the number of different land forms present in a single unit.

E. COLI MANAGEMENT OPTIONS

The main mitigations for sheep and beef land are fencing streams and wetlands. De-stocking could help, but this relationship is tenuous and is difficult to relate to the approach being used for catchment modelling of microbes.

The main mitigations for dairy land are fencing streams and wetlands, plus also improving effluent management. The focus is on identifying the benefit associated with switching the farms that currently discharge to water to discharging onto land.

Do not focus on delayed effluent application, because there is little data and because most farmers will be doing this anyway if they possess multiple ponds.

Do not distinguish between low and high-rate effluent application, because there is little data and most of the benefit will be gained from delaying effluent application.

Point sources of microbial losses are being dealt with within the modelling. Abatement of point sources is not being treated because of a lack of data and a focus of the District Council on reducing loads from municipal infrastructure. A primary source will be effluent ponds, and these will be dealt with.

Assume effluent systems are being managed according to best practice, in line with Overseer.

FULL AFFORESTATION

Reduces erosion by 90 percent.

Reduces erosion by 80 percent when the harvesting cycle is considered.

POINT SOURCES

Many point sources for microbial loadings and sediment exist. For example, this includes lane ways, gates, troughs, crops and tracks. These could be included using average incidence across an area. The major source is likely to be winter crops, especially turnips, and maize crops. This would be useful to include. Laneways are point sources, but there are not many dairy farms within the catchment. Overall, it was decided that most of these point sources were specific and inconsistent with the focus on high-level mitigations.

Sediment arising from point sources (urban) is very small and dominated by agricultural additions. They are also likely to be managed more intensively through using, for example, sediment traps. Thus, this source should be excluded from the analysis.

Appendix 3: Wetland mitigation assumptions

Table 44: Assumptions about wetland applicability and effectiveness

Mitigation	Applicability 1 Hydrological flow path	Applicability 2 Catchment slope	Proportional areal applicability (% of area)	Proportion of load intercepted (% of load)	Efficacy sediment (% load reduction)	Efficacy *E.coli* (% load reduction)	Density of mitigation (nos or area per ha)	Notes and references
Retention bund–wetland combination	Ephemeral channels/1st order catchment at one per 20 hectares (ha)	>15 deg	80%	100%	70%	50%	one per 20 ha = 0.05 systems/ha	See 1 below
Sedimentation pond–wetland combination at 0.25% of catchment area	Drains and first-order streams	<15 deg	80%	100%	70%	50%	one per 20 ha = 0.05 systems/ha	See2 below
Mid-catchment constructed wetland intercepting 2nd–3rd order streamflow	In absence of 3rd order stream position in lower section of Second-order stream. Where stream 3rd order or greater position in lower section of 3rd order stream.	<15 deg	80%	100%	70%	50%	Occupy 0.25% of area = 0.0025 ha/ha or 1 ha wetland per 400 ha of contributing catchment/ha	See 2below

1. Assume one per 20-hectare sub-catchment (based on general assessment of relevant catchment sizes) and storage volume of 120 cubic metres per hectare assuming riser outlet height of 1.8 metre, area of 200 square metres per hectare to give volume at one-third of surface area (based on Eastern Bay of Plenty recommendations) so approximately 4 hectares per 20 hectare catchment = occupy approximately 2 percent of the contributing catchment when full. Assume 5 percent of temporarily impounded area is permanent fenced off wetland area (that is., 0.1 percent or 0.02 hectares (or 200 square metres) per 20 hectares catchment).

2. Expected performance based on modelling studies for Waituna (Tanner et al, 2013) and median performance for International Stormwater Best Managmeent Practices (BMP) database (Dec 2014 update). Costings for construction and maintenance based on underlying calculations for Waituna catchment (Tanner et al, 2013) assuming wetland sizes around 1 hectare for partially excavated wetlands utilising the natural contour of the land. This has been converted to a cost per hectare of farmland mitigated. In the absence of information specific to sediment settling characteristics for the Whangarei catchment, we have estimated wetland size of 0.25 percent of catchment (1 hectare wetland per 400 hectare contributing catchment) based on our experience and recent data from Swedish wetlands (Johannesson et al, 2015). There is evidence that smaller wetlands 0.1 percent or less can provide significant sediment retention (e.g., Baskerud et al, 2002–05, in Norway and Ockenden et

al, 2012, in the United Kingdom); however, most of this information is for arable catchments where much higher quantities of heavy sediment are transported. Also the trapping efficiency for finer clay particles was poorer for these systems than for coarser material.

Table 45: Cost of wetland construction (all costs assume activities are permitted and do not incur resource consent charges)

Mitigation	Construction cost	Planting cost	Fencing cost	Land area occupied cost	Maintenance cost	Ancillary benefits and/or costs	Notes and references
Retention bund–wetland combination	$5 000 each = $250 per hectare (ha) of land mitigated	0.02 ha wetland planting per system at $20 000/ha = $400/system =$20/ha of land mitigated	0.02 ha fenced per system, assume need 80 metre fencing/system at $6/metre installed and materials = $480 plus gate and hinges at $220 = $700/system = $35/ha of land mitigated	Loss of lower value grazing, in 0.02-a permanent wetland/system or 0.01 ha/ha of mitigated land with estimated 40% of average farm income/ha	General maintenance = $0.30/ha of land mitigated per year, plus pipework replacement and some sediment removal at $2 000 after 25 years	Only small area taken out of production; other areas are temporarily flooded (<3 days). Reduced stock misadventure and disease risk (vet bills, time to extract stuck stock, injury to stock) in high risk area, critical source area turned into sink.	See 1 below
Sedimentation pond–wetland combination at 0.25% of catchment area*	0.25% of 20 ha catchment = 0.05 ha = 500 m^2 at $120 000/ha of planting, a gate and fencing = $6 000/system = $300/ha of land mitigated	Included in construction costs	Gate and fences included in construction costs	0.25% of catchment but in many cases likely to be constructed on normal productive agricultural value – assume overall 80% of average farm income/ha	$0.75/ha of land mitigated per year	50% reduction in profit loss due to benefits	
Mid-catchment constructed wetland intercepting 2nd-3rd order stream flow	$100 000/ha of actual wetland inclusive of planting, a gate and fencing $250/ha of farmland mitigated	Included in construction costs	Gate and fences included in construction costs	0.25% of catchment but likely to be constructed in water-logged and flood-prone areas with reduced agricultural value -say 40% of average farm income/ha	$0.75/ha of land mitigated per year	Removal of nitrogen and phosphorous. Provision of wildlife habitat, hunting, reduced flood flows and streambank erosion, avoid need to fence large perimeter areas upstream Requires bigger tract of land lower in the catchment	

1. Assume one per 20 hectare sub-catchment (based on general assessment of relevant catchment sizes) and storage volume of 120 cubic metres per hectare assuming riser outlet height of 1.8 metres, area of 200 square metres per hectare to give volume at one-third of surface area (based on Eastern Bay of Plenty recommendations) so approximately 4 hectares per 20 hectare catchment = occupy approximately 2 percent of contributing catchment when full. Assume 5 percent of temporarily impounded area is permanent fenced off wetland area (that is, 0.1 percent or 0.02 hectare (or 200 square metres) per 20 hectare catchment).

Appendix 4: Key baseline estimates by sub-catchment

Figure 64: Total net farm revenue ($ per year)

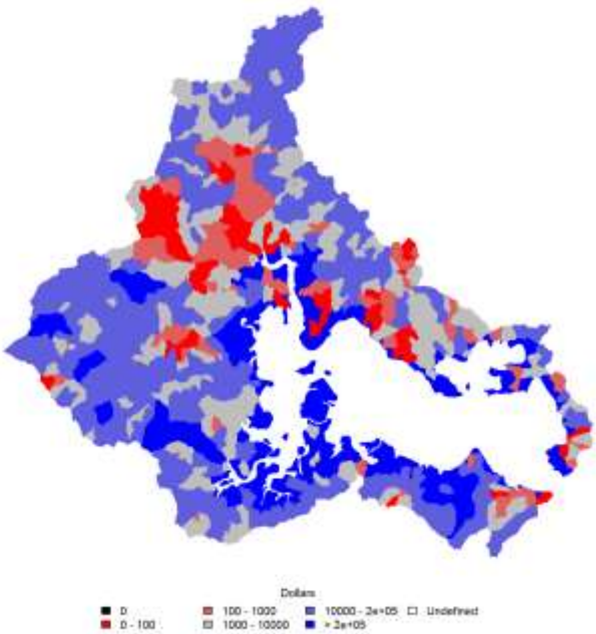


Figure 65: Total sediment (tonnes per year)

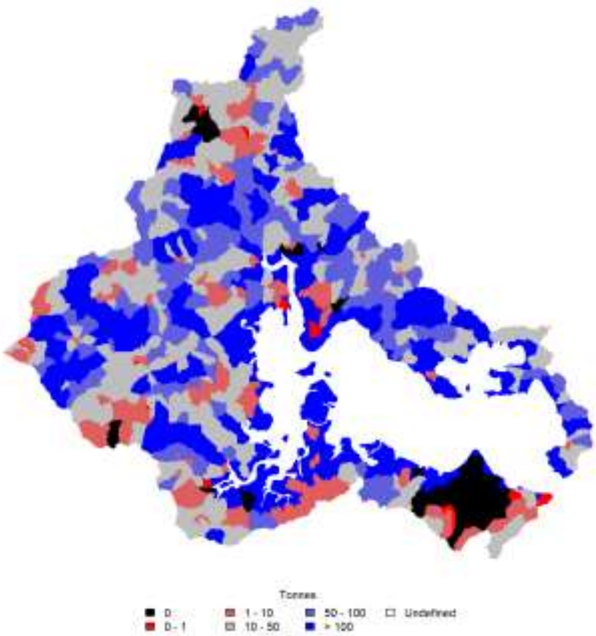


Figure 66: Hill/landmass sediment (tonnes per year)

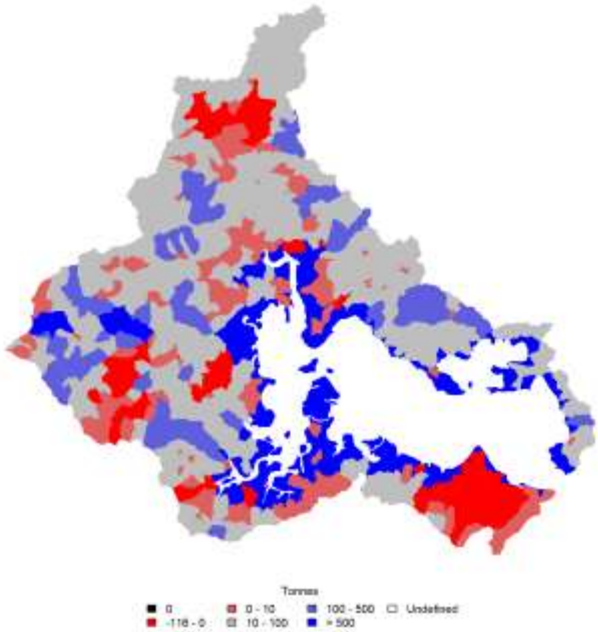


Figure 67: Streambank sediment (tonnes per year)

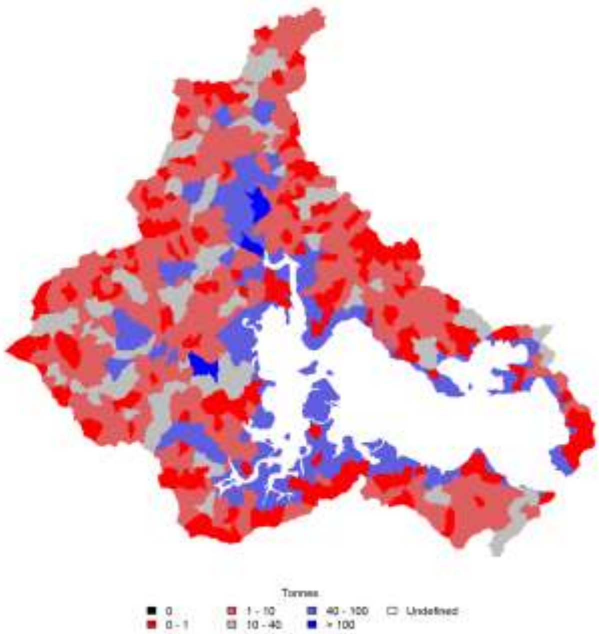


Figure 68: Stream *E. coli* loads (peta *E. coli* per year)

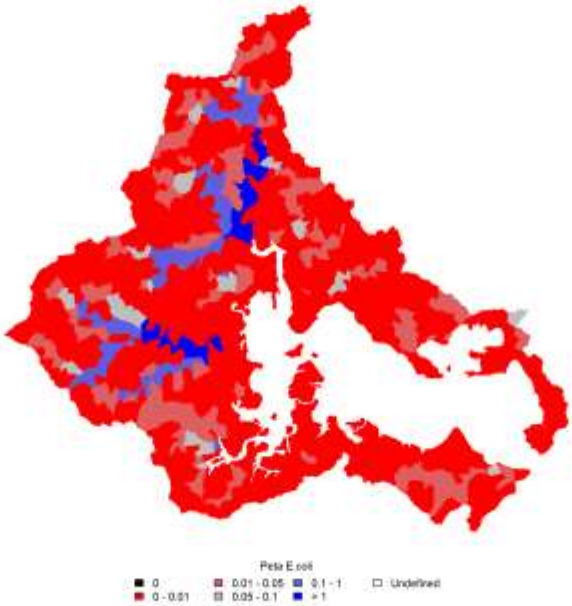
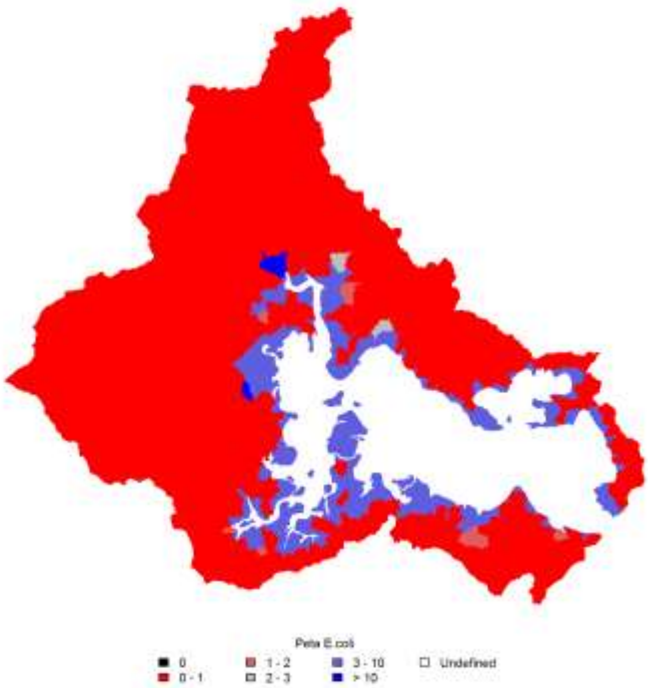


Figure 69: Harbour *E. coli* loads (peta *E. coli* per year)



Appendix 5: Key scenario estimates by sub-catchment

Spatially explicit maps were created for each of the policy scenarios for six key outputs: net revenue, landmass sediment, streambank sediment, total sediment loads, and stream and harbour *E. coli* loads. Estimates of these key outputs depict percentage changes for each policy scenario compared to the baseline. This was done by taking the mean estimates for each of the 755 REC2 sub-catchments from NZ-FARM and overlaying them onto the baseline land use map.

Figure 70: Spatial impacts for afforestation – all

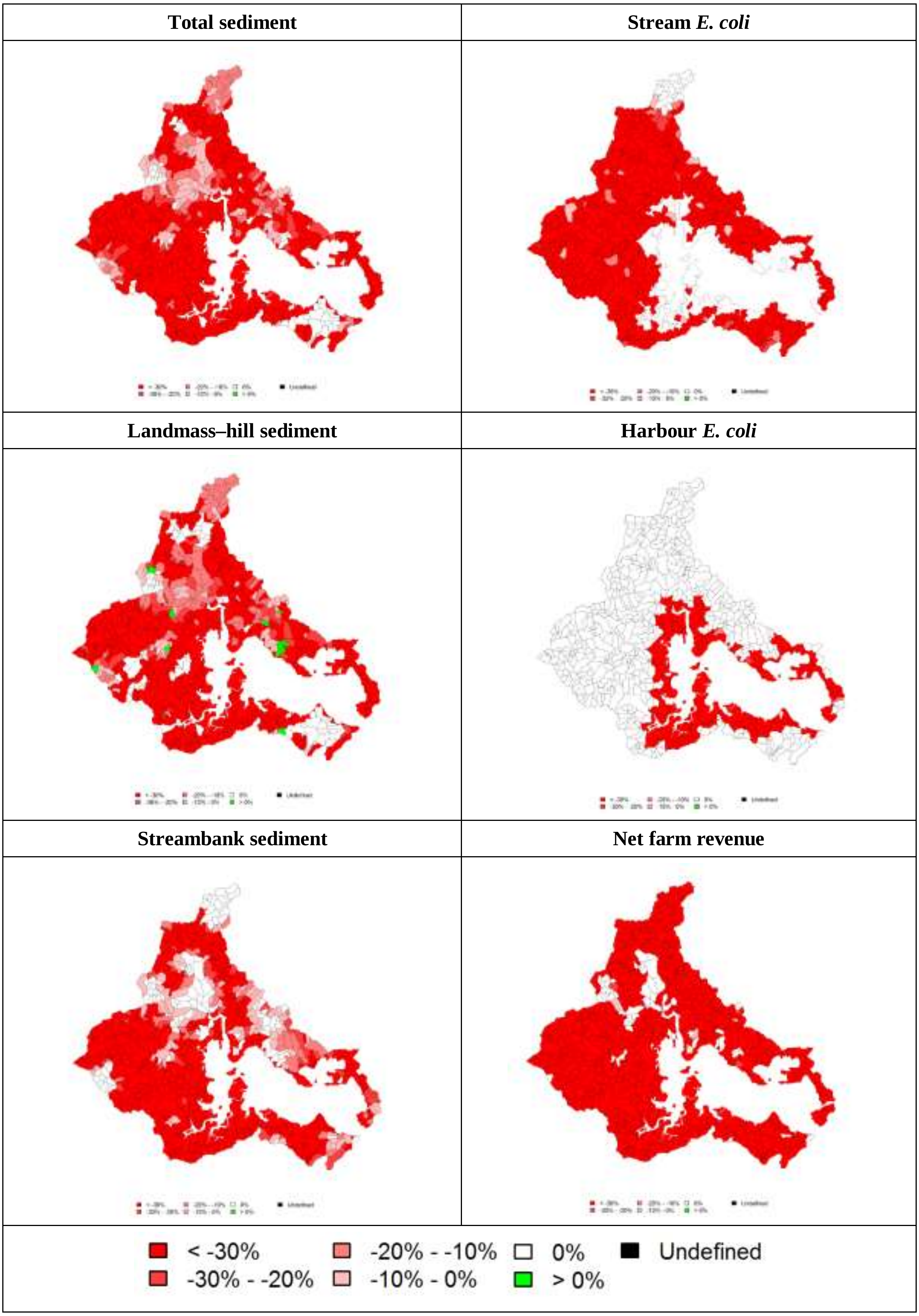


Figure 71: Spatial impacts for afforestation – pasture

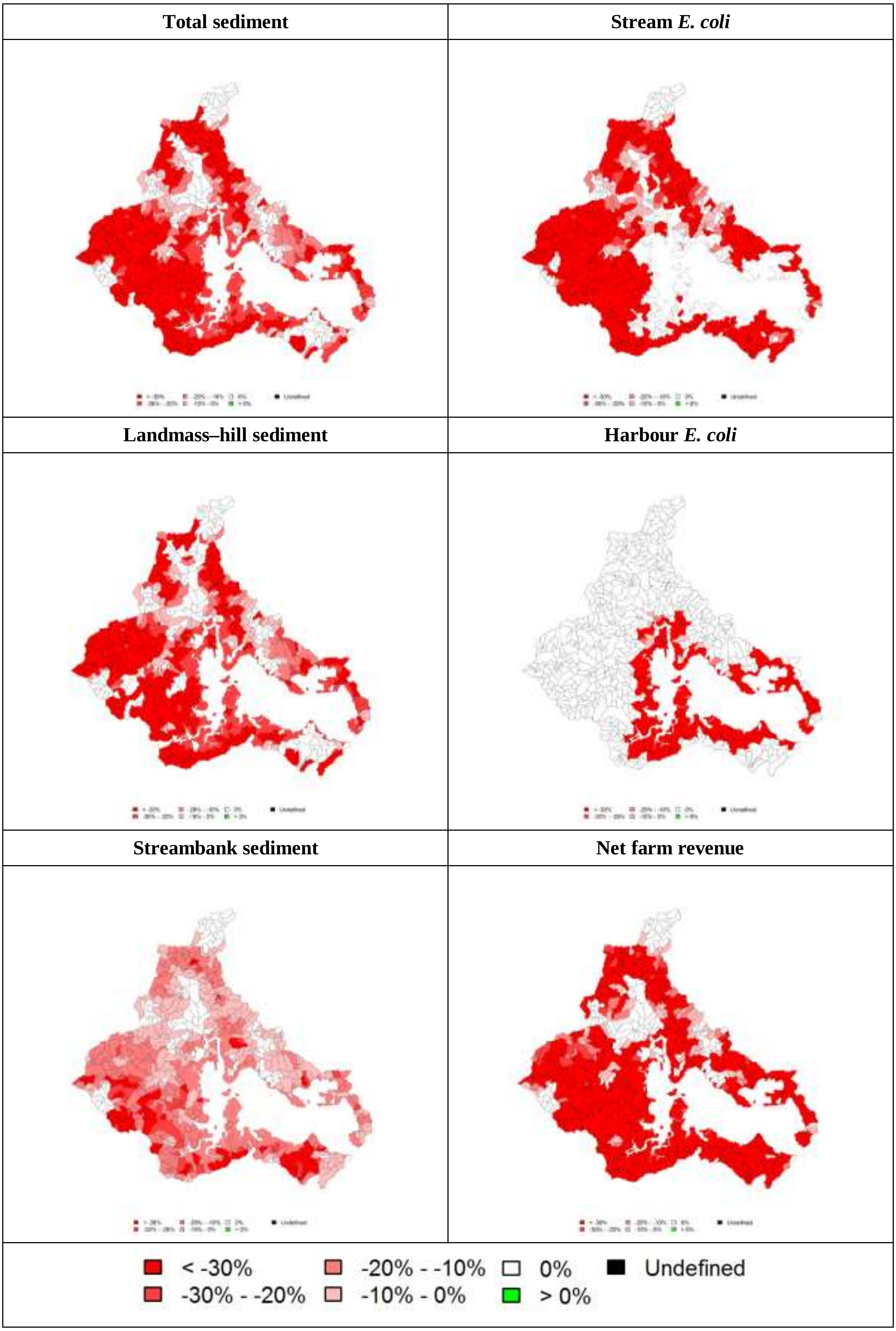


Figure 72: Spatial impacts for current fencing

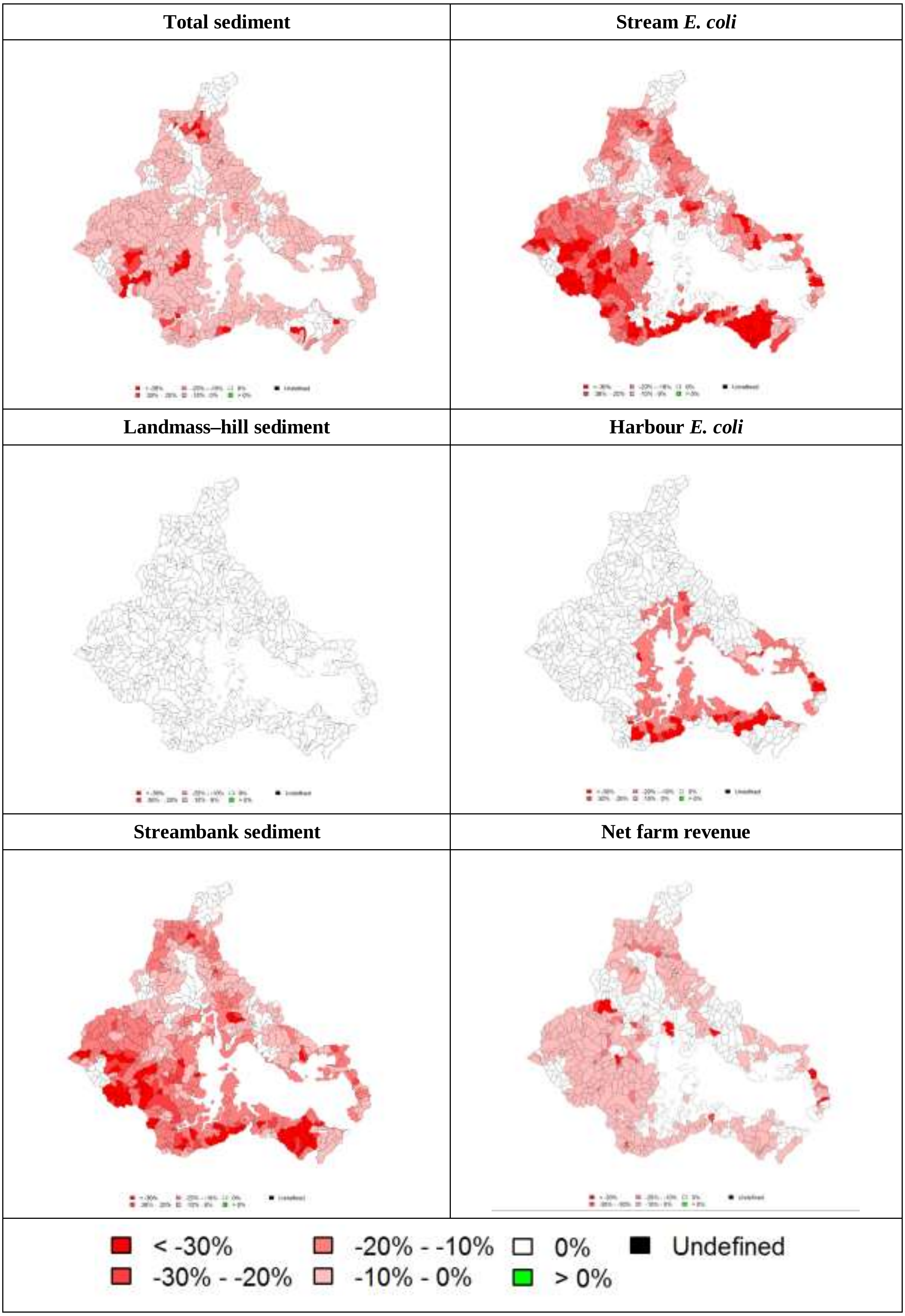


Figure 73: Spatial impacts for current farm plans

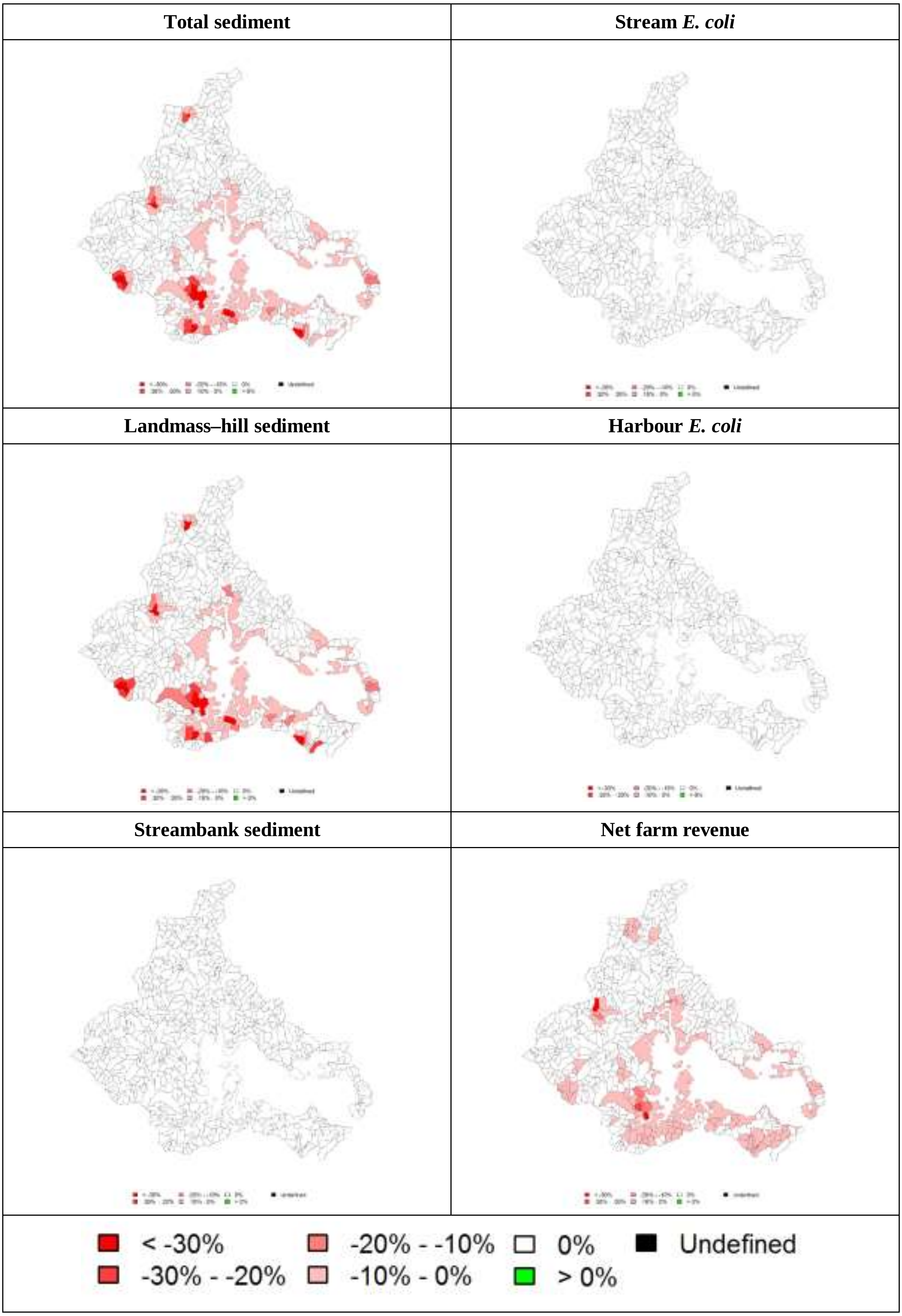


Figure 74: Spatial impacts for wetlands - all

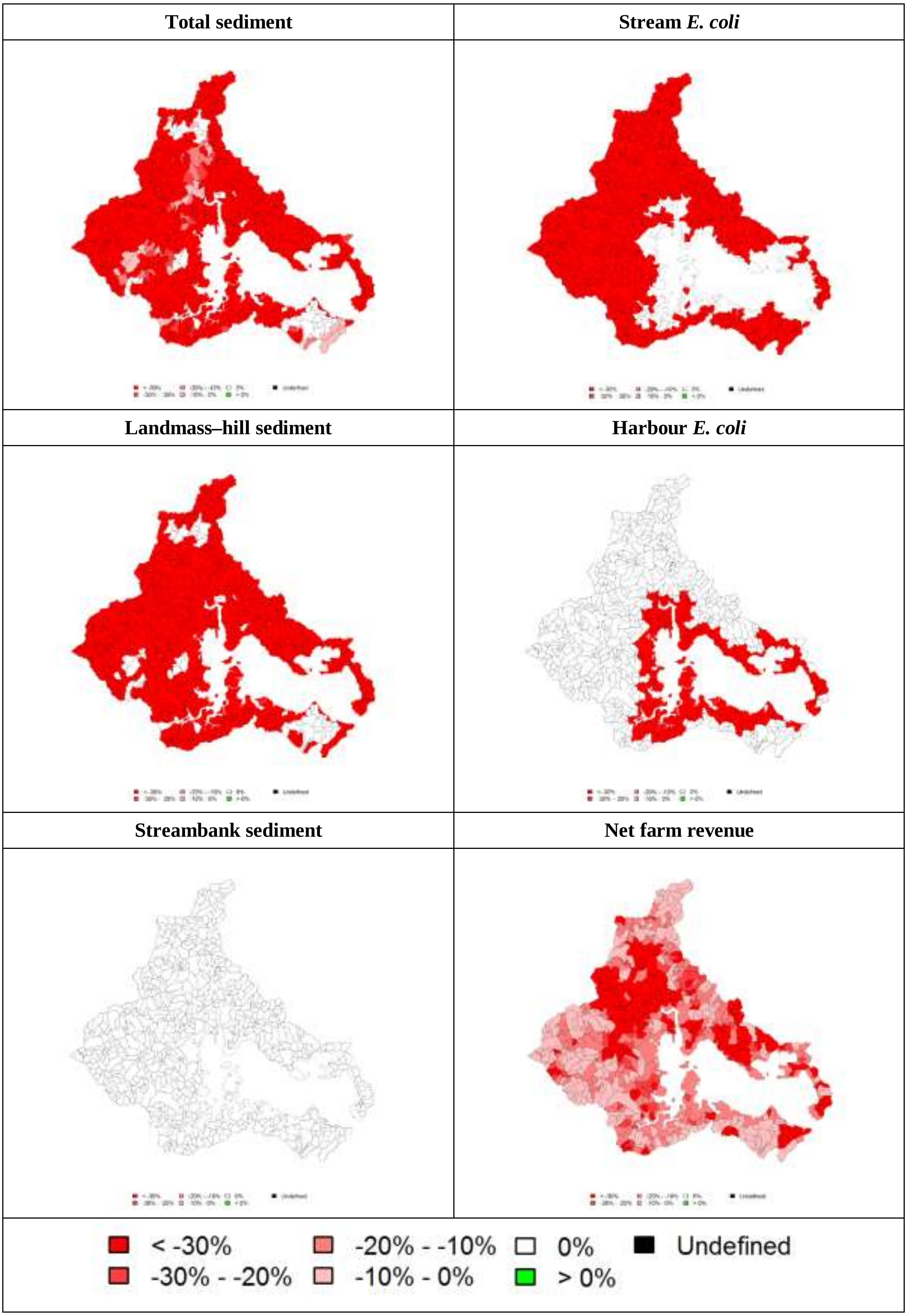
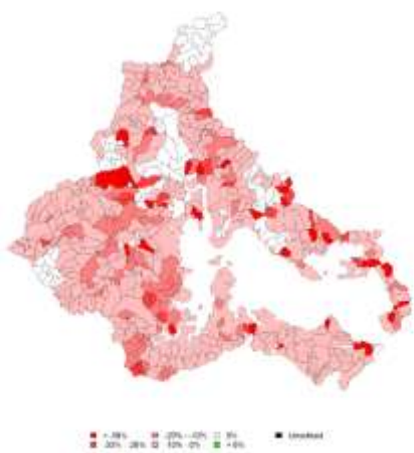
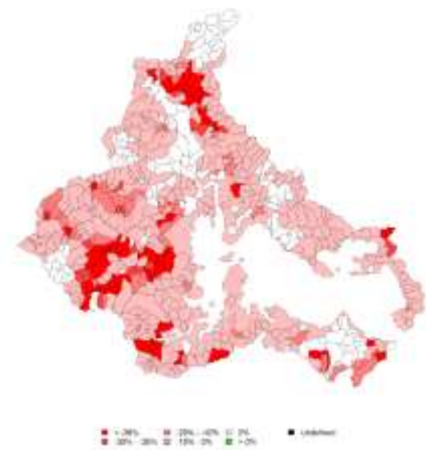


Figure 75: Spatial impacts for farm plan - all

Total sediment	Stream *E. coli*
	
Landmass–hill sediment	**Harbour *E. coli***
	
Streambank sediment	**Net farm revenue**
	

< -30% | -20% - -10% | 0% | Undefined
-30% - -20% | -10% - 0% | > 0%

Figure 76: Spatial impacts for fencing – all

Total sediment	Stream *E. coli*
	
Landmass–hill sediment	**Harbour *E. coli***
	
Streambank sediment	**Net farm revenue**
	

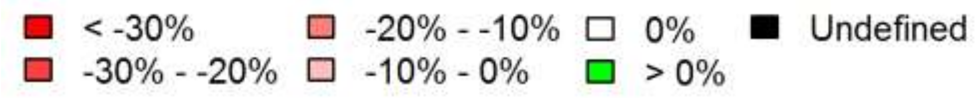
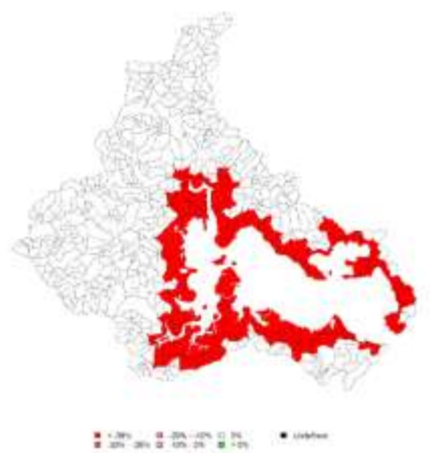


Figure 77: Spatial impacts for maximum mitigation

Total sediment	**Stream *E. coli***
	
Landmass–hill sediment	**Harbour *E. coli***
	
Streambank sediment	**Net farm revenue**

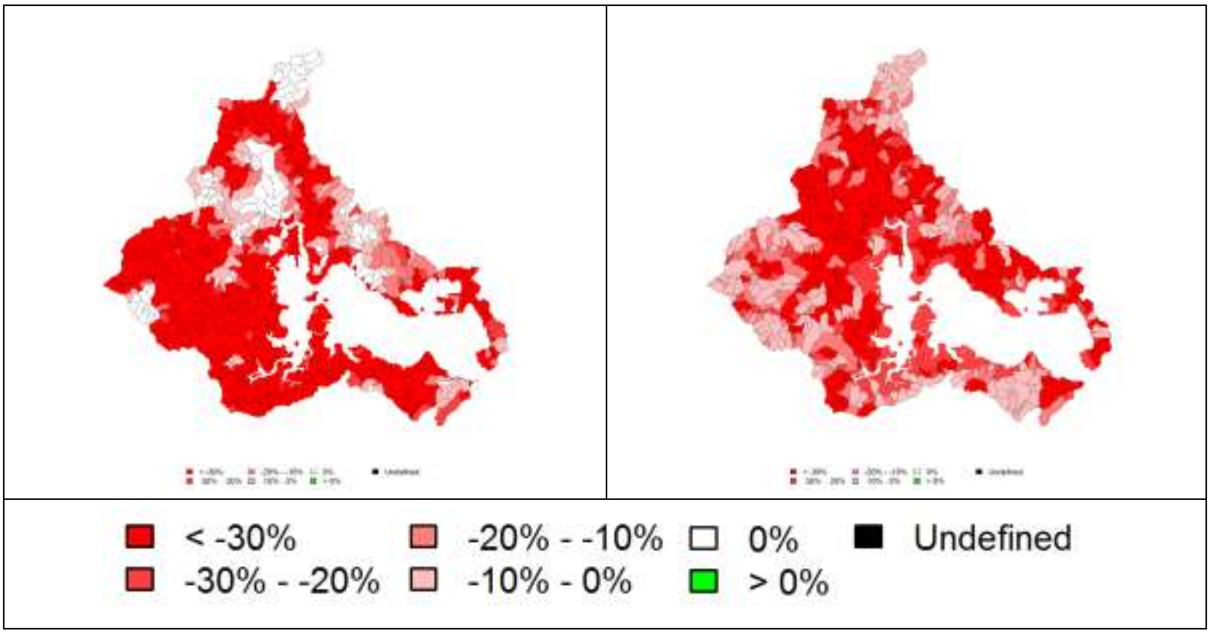
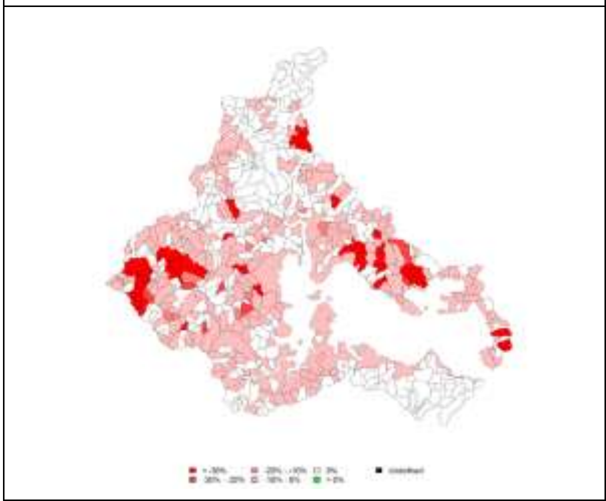
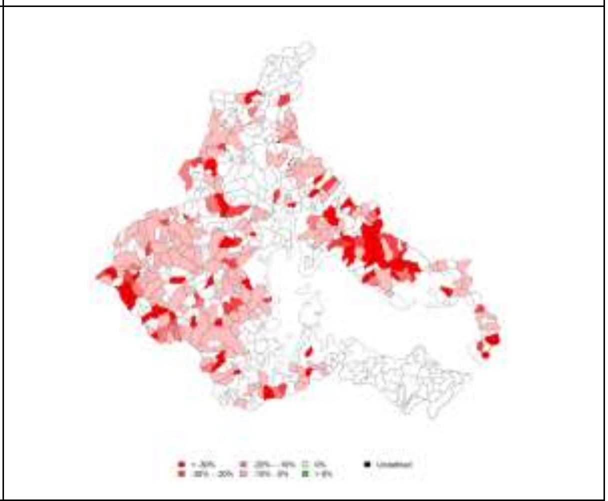
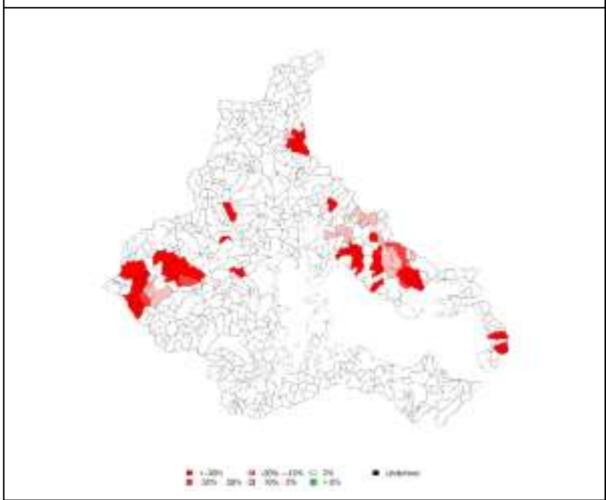
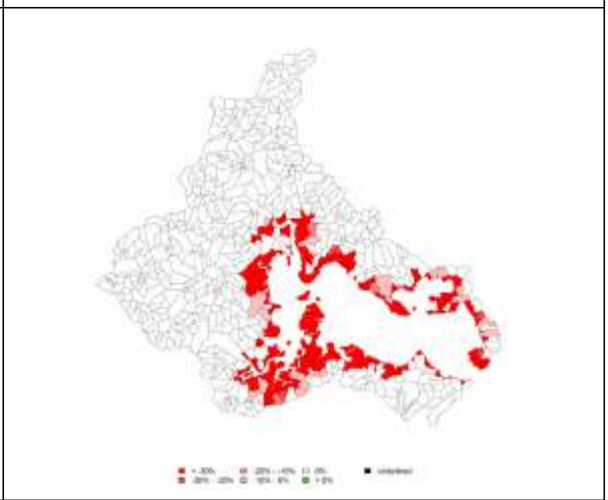
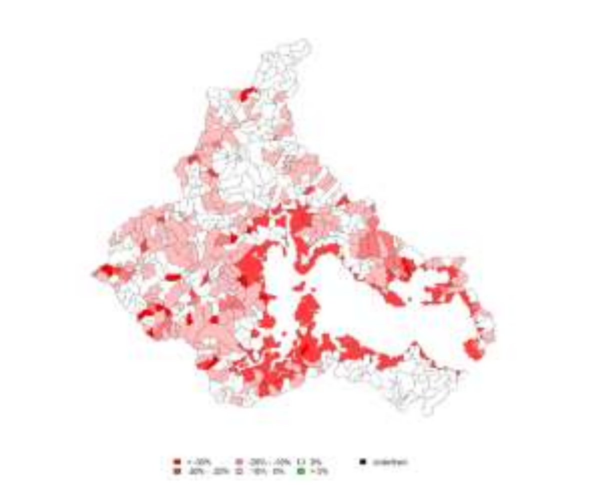
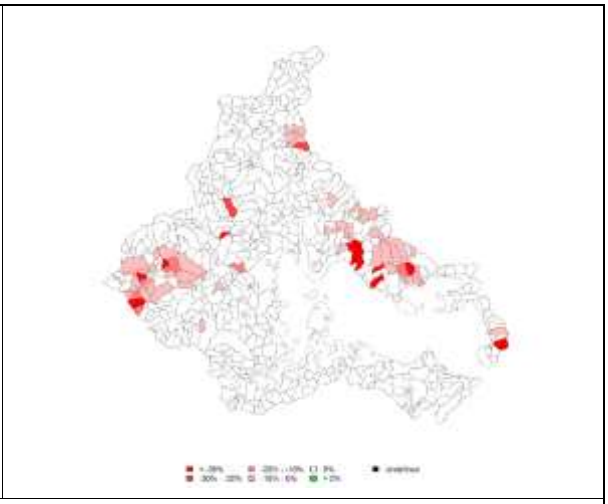


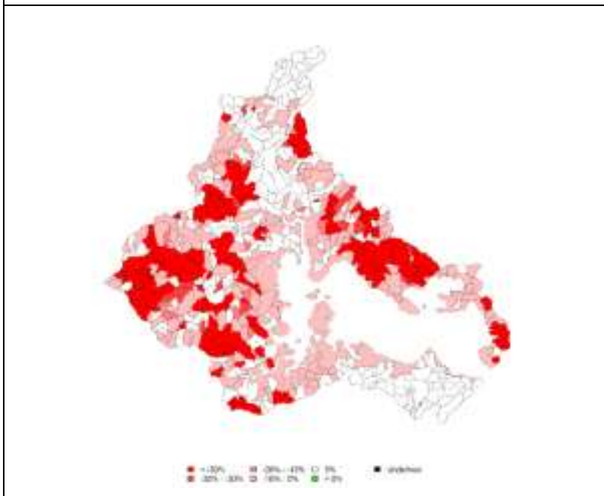
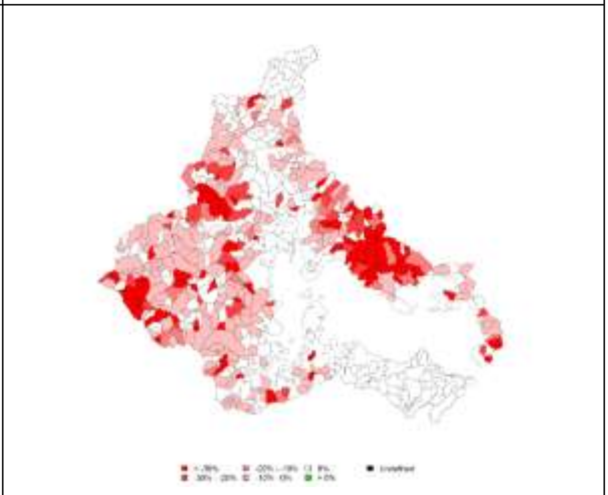
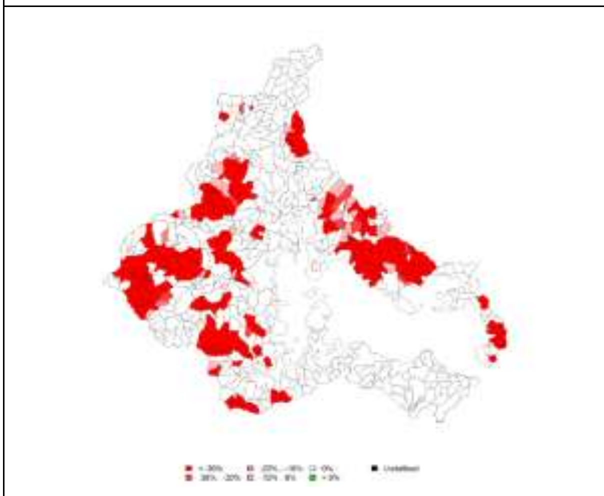
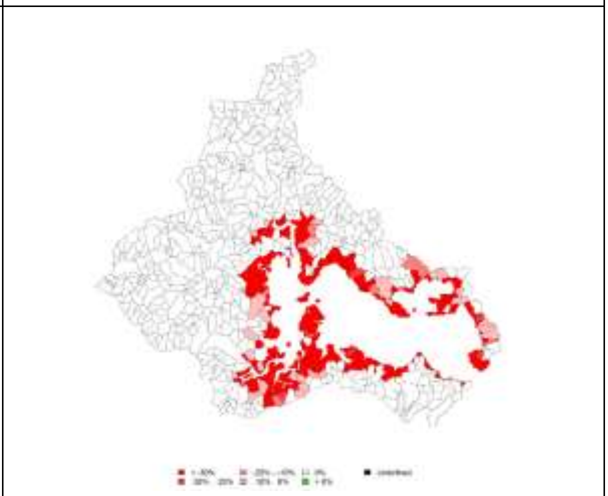
Figure 78: Spatial impacts for harbour sediment – 20 percent

Total sediment	Stream *E. coli*
	
Landmass–hill sediment	**Harbour *E. coli***
	
Streambank sediment	**Net farm revenue**

< -30% | -20% - -10% | 0% | Undefined
-30% - -20% | -10% - 0% | > 0%

Figure 79: Spatial impacts for harbour sediment – 40 percent

Total sediment	**Stream *E. coli***
	
Landmass–hill sediment	**Harbour *E. coli***
	
Streambank sediment	**Net farm revenue**

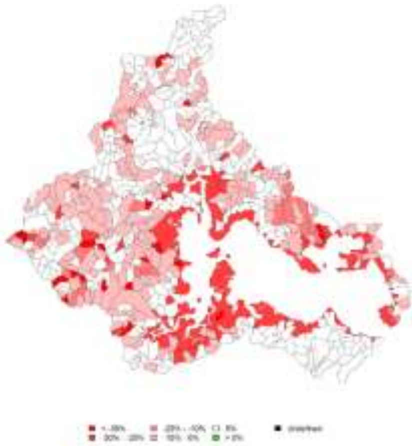
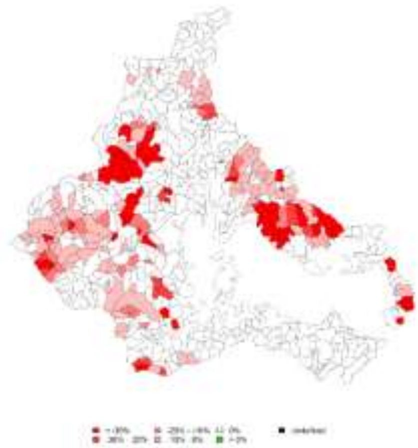
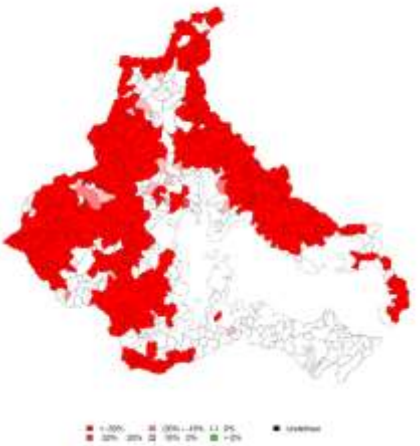
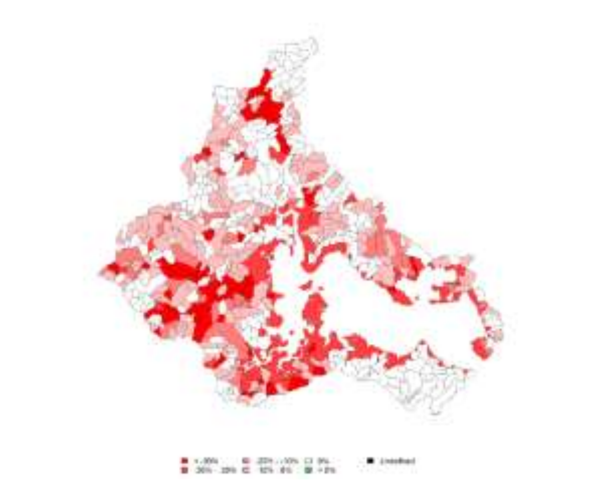
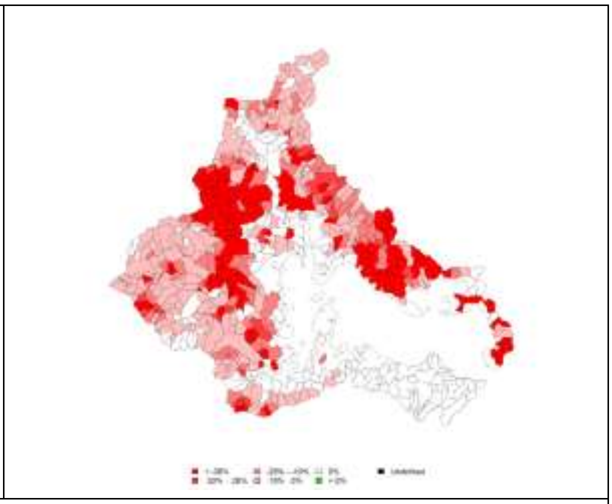
	
< -30% ; -30% - -20% ; -20% - -10% ; -10% - 0% ; 0% ; > 0% ; Undefined	

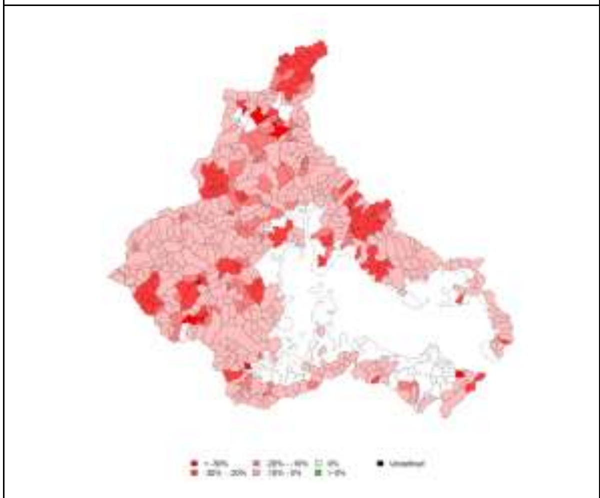
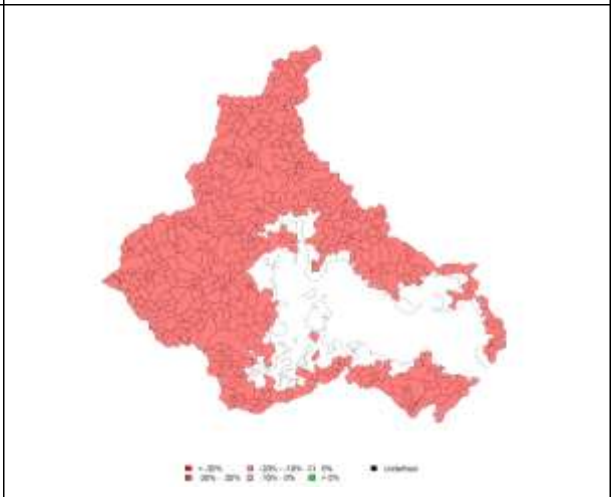
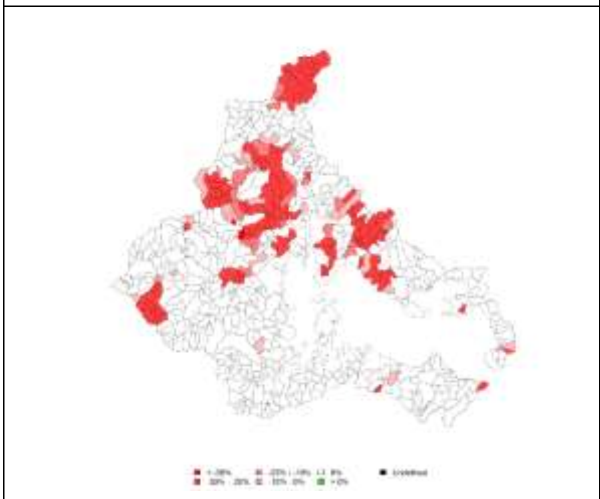
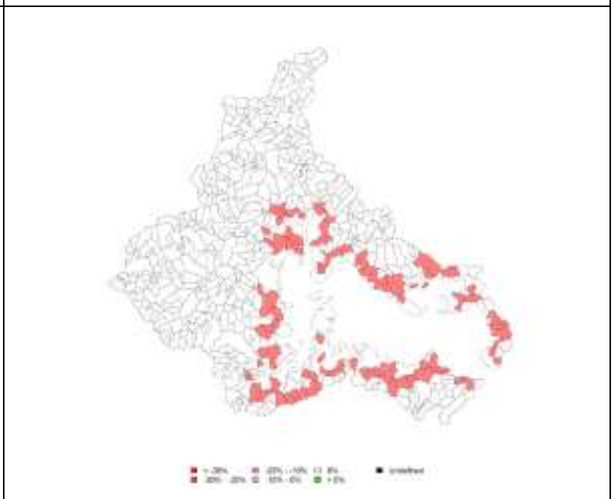
Figure 80: Spatial impacts for harbour sediment – 60 percent

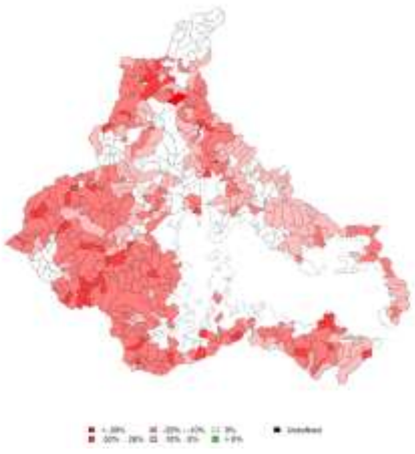
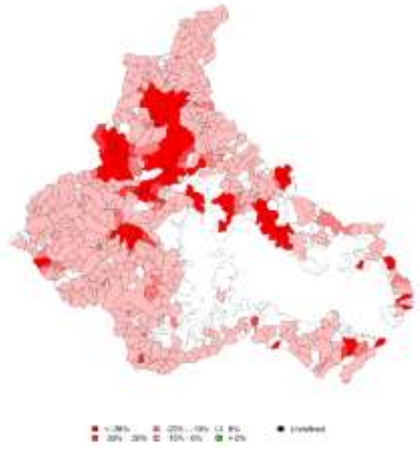
Total sediment	**Stream *E. coli***
	
Landmass–hill sediment	**Harbour *E. coli***
	
Streambank sediment	**Net farm revenue**

■ < -30% ■ -20% - -10% □ 0% ■ Undefined
■ -30% - -20% □ -10% - 0% ■ > 0%

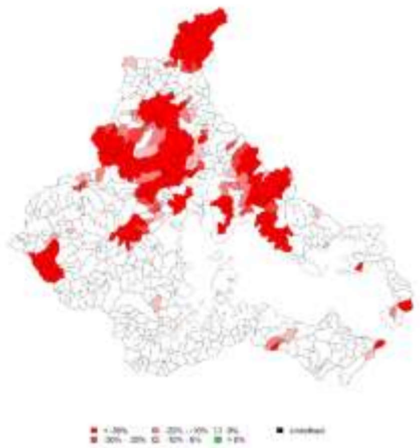
Figure 81: Spatial impacts for *E. coli* load – 20 percent

Total sediment	Stream *E. coli*
	
Landmass–hill sediment	**Harbour *E. coli***
	
Streambank sediment	**Net farm revenue**

< -30%	-20% - -10%	0%	Undefined
-30% - -20%	-10% - 0%	> 0%	

Figure 82: Spatial impacts for *E. coli* load – 40 percent

Total sediment	Stream *E. coli*
	
Landmass–hill sediment	**Harbour *E. coli***
	
Streambank sediment	**Net farm revenue**

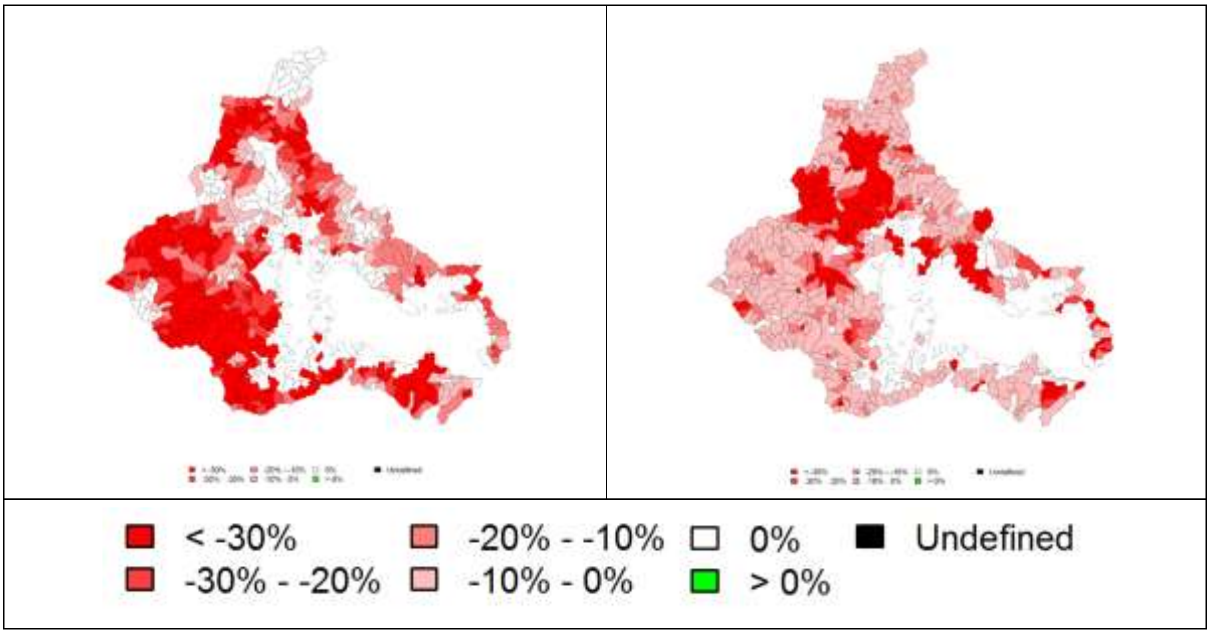
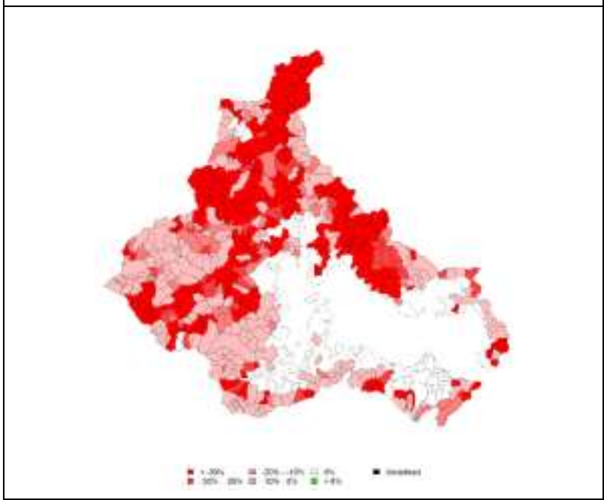
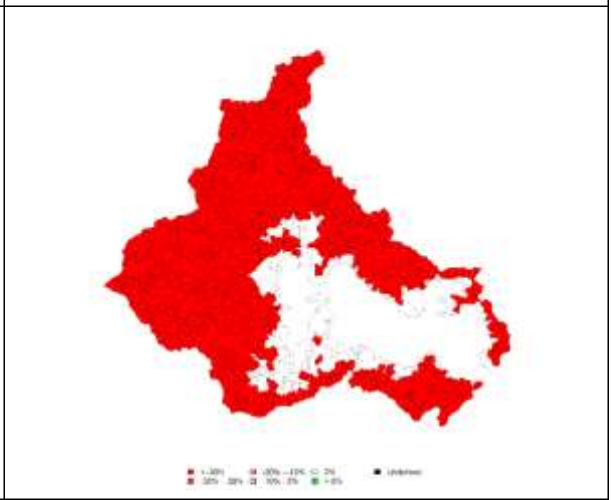
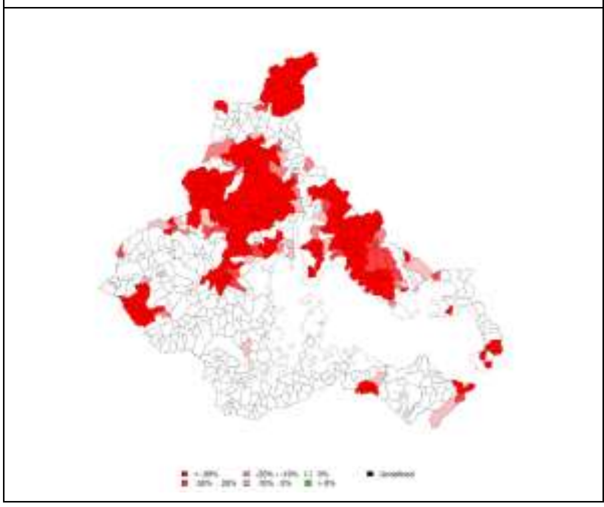
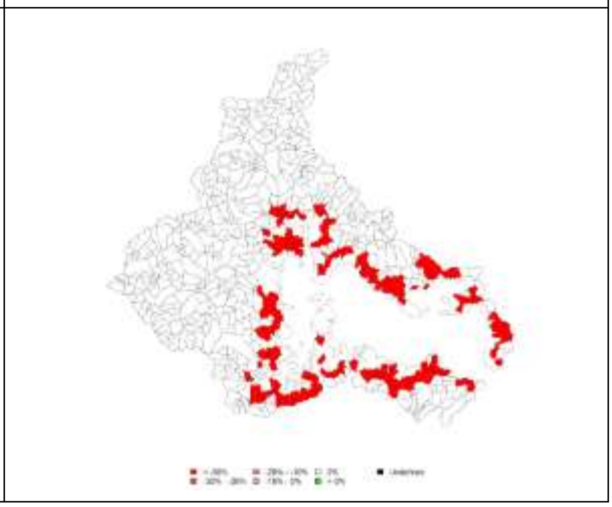


Figure 83: Spatial impacts for *E. coli* load – 60 percent

Total sediment	Stream *E. coli*
	
Landmass–hill sediment	**Harbour *E. coli***
	

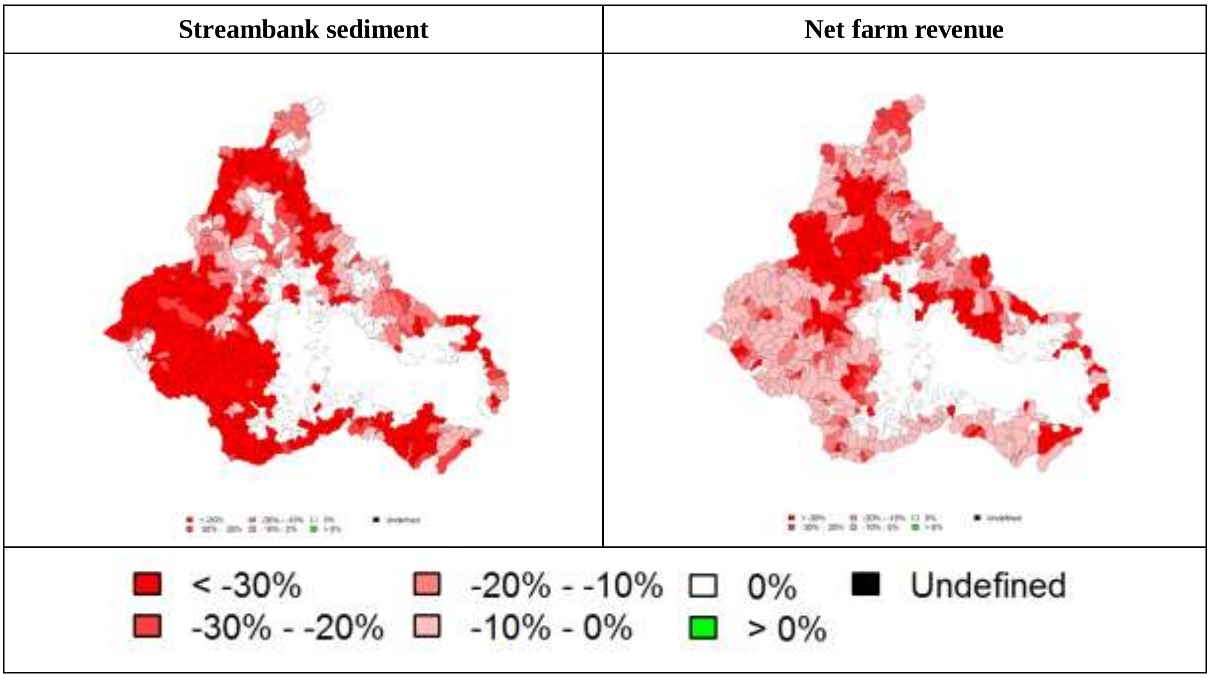
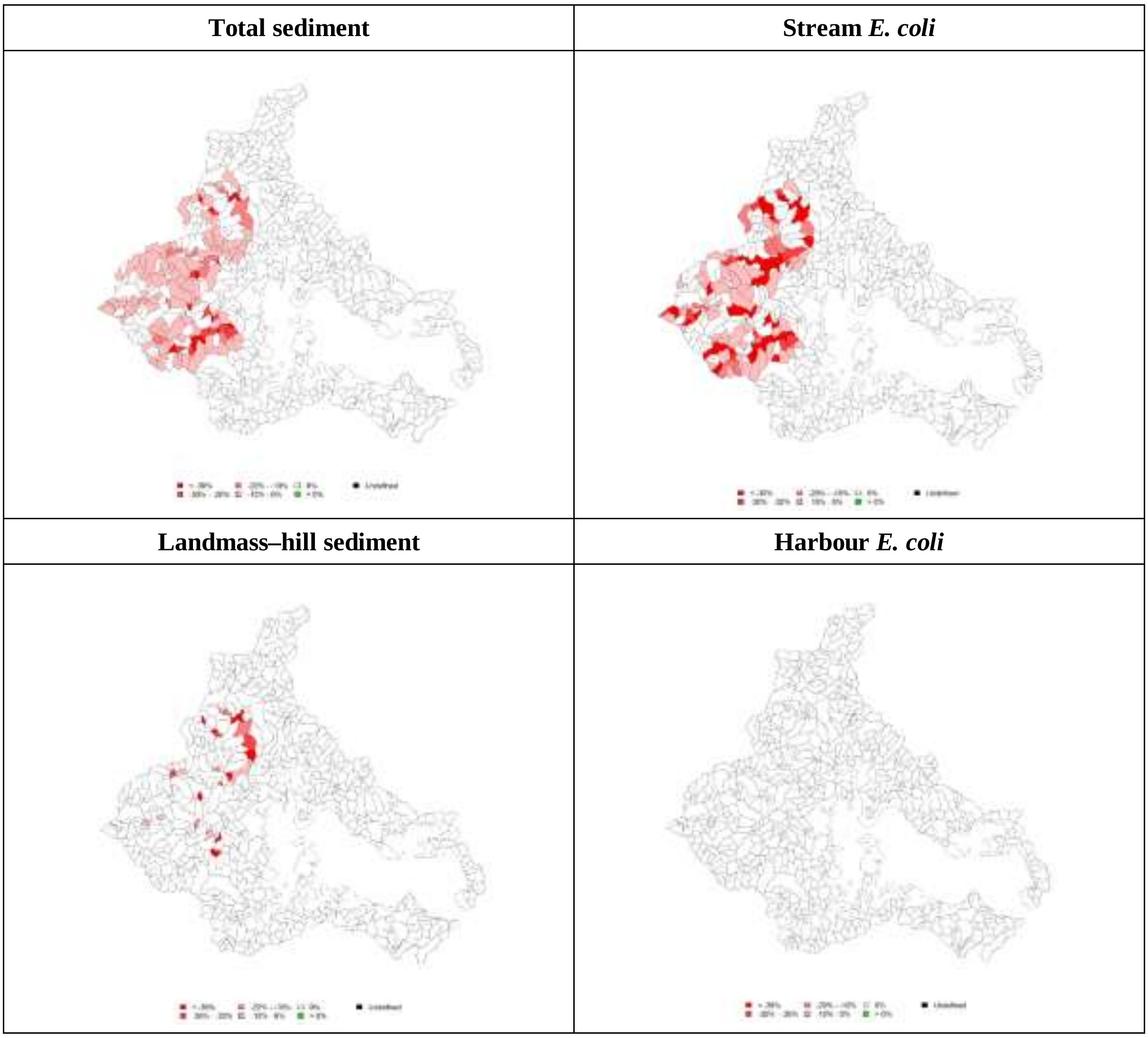


Figure 84: Spatial impacts for secondary contact "B"



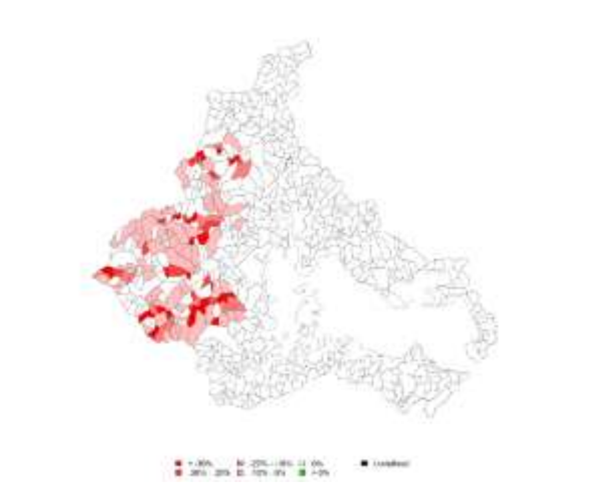
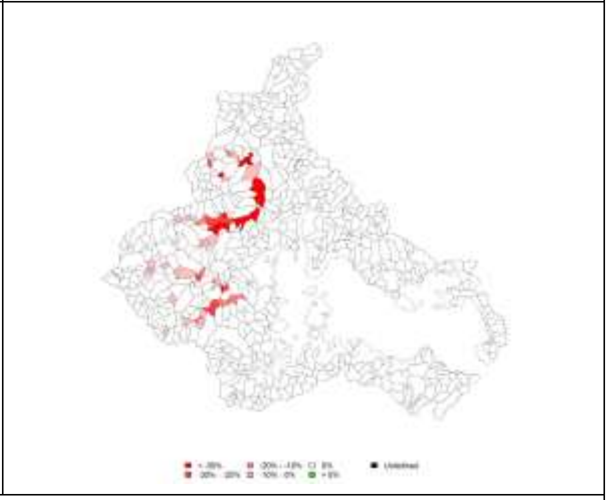
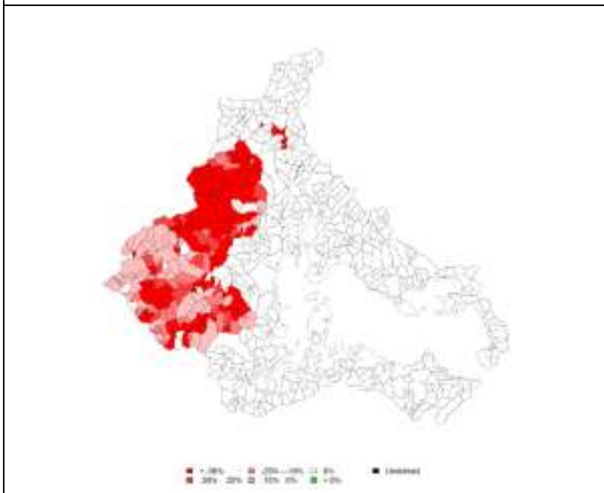
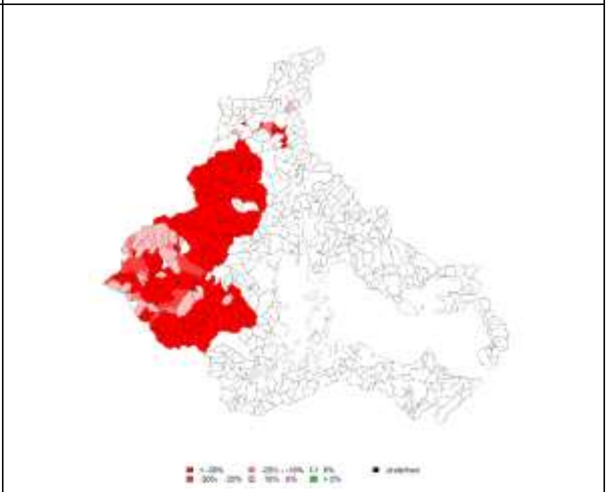
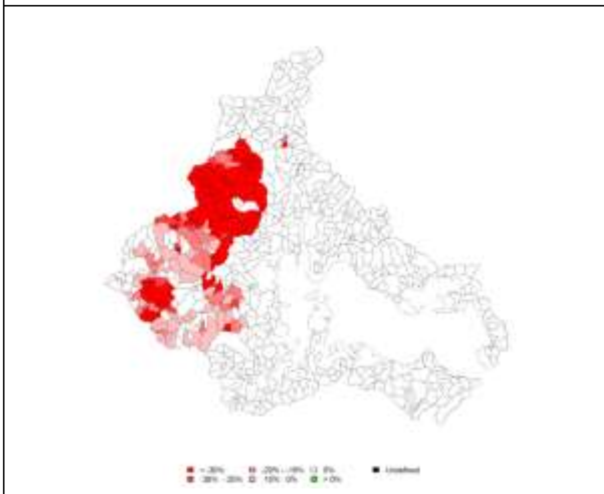
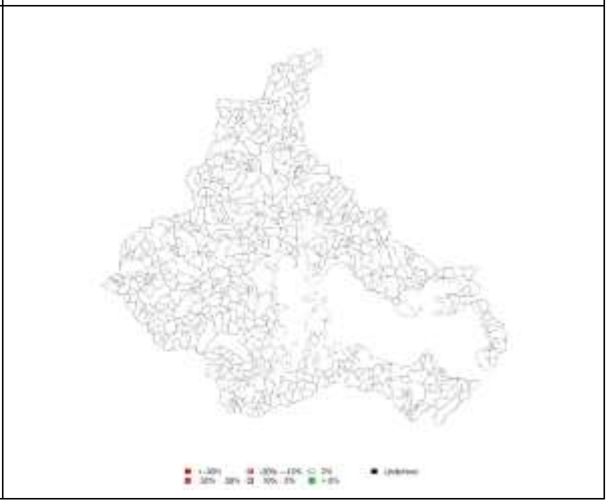
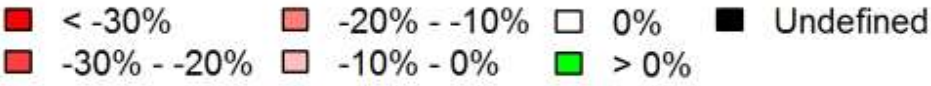
Streambank sediment	Net farm revenue
	
< -30% · -30% - -20% · -20% - -10% · -10% - 0% · 0% · > 0% · Undefined	

Figure 85: Spatial impacts for secondary contact "A"

Total sediment	Stream *E. coli*
	
Landmass–hill sediment	**Harbour *E. coli***
	

Streambank sediment	Net farm revenue
	



Appendix 6: Sensitivity analysis for lower effectiveness rates

Table 46: Mitigation effectiveness assumptions (as a percentage change in load relative to no mitigation)

Mitigation option	Landmass–hill erosion	Streambank erosion	*E. coli*
No mitigation	0%	0%	0%
Farm plan – base effective	–70%	0%	0%
Farm plan – less effective	–50%	0%	0%
Fencing – base effective	0%	–80%	–60%
Fencing – less effective	0%	–50%	–40%
Wetland – base effective	–70%	0%	–50%
Wetland – less effective	–50%	0%	–30%

Table 47: Scenario model sensitivity estimates

Scenario	Net farm revenue (mil $)	Total annual cost (mil $/yr)	Land–hill erosion (t)	Stream-bank erosion (t)	Total erosion (t)	Total harbour deposit (t)	*E. coli* load – stream (peta)	*E. coli* load – harbour (peta)
No mitigation	$16.63	$0.00	26 883	4 472	31 355	19 968	84.0	292.7
				Change from no mitigation baseline				
Farm plan – base effective	–2%	$0.35	–31%	0%	–27%	–26%	0%	0%
Farm plan – less effective	–2%	$0.35	–22%	0%	–19%	–19%	0%	0%
Fencing – base effective	–3%	$0.44	0%	–36%	–5%	–5%	–523%	–38%
Fencing – less effective	–3%	$0.44	0%	–23%	–3%	–3%	–33%	–24%
Wetland – base effective	–9%	$1.47	–71%	0%	–61%	–60%	–48%	–49%
Wetland – less effective	–9%	$1.47	–51%	0%	–43%	–43%	–29%	–29%

Note: mil – million; t=tonnes; yr=year.