Ministry for Primary Industries
Manatū Ahu Matua

Whangarei Harbour sediment and *E. coli* study: catchment economic modelling

MPI Technical Paper No: 2017/15

Prepared for the Ministry for Primary Industries

ISBN No: 978-1-77665-504-5 (online)
ISSN No: 2253-3923 (online)

November 2015

New Zealand Government

Growing and Protecting New Zealand

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LANDCARE RESEARCH
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Whangarei Harbour sediment and *E. coli* study: catchment economic modelling

Whangarei Harbour sediment and *E.coli* study

Catchment economic modelling

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Landcare Research Contract Report: LC2421

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Glossary

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

Attribute state: The level to which an attribute is to be managed, for attributes 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.

Concentration: The amount of a particular substance per unit of another substance (e.g. grams sediment per cubic metre of water).

Contaminant: Biological (e.g. bacterial and viral pathogens) or chemical (e.g. 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 (e.g. 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 excludes interests and taxes. Used interchangeably with net farm revenue.

***E. coli*:** Bacteria that live in the intestines of people and animals. A primary indicator of pathogenic micro-organisms 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% 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

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 (e.g. kg/ha/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.

Net Farm Revenue: The key measurement of economic output from land-based activities at the catchment scale incorporated in NZFARM. Based on farm earnings before interest and tax (EBIT). Includes wages for management and capital and implementation costs for mitigation practices.

New Zealand Forest and Agriculture Regional Model (NZFARM): A catchment-scale economic land use 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 (i.e., no policy or mitigation).

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 (e.g. from the likes of sewerage, factory and dairy shed outfalls).

Primary contact recreation: Activities likely to involve full immersion in water (e.g. swimming).

Secondary contact recreation: Activities with occasional immersion in water and some ingestion of water (e.g. wading and boating).

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

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

Target: Limit which 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.

Executive Summary

Project and Client

Northland Regional Council (NRC) has identified that sediment and *E. coli* are key water quality challenges in the Northland region. As a result, NRC has engaged in a joint venture with the Ministry for Primary Industries (MPI) to commission the Whangarei Harbour Sediment and *E. coli* (WHSES) study.

Objectives

The aim of the WHSES is to develop a model that will integrate science and economics to assess the potential economic costs of meeting a range of attribute states for sediment and *E. coli* in the Whangarei Harbour and freshwater environments that drain into the Whangarei Harbour. The study also intends to inform further work on sediment attributes for the National Objectives Framework (NOF).

The WHSES comprises two objectives:

1. Develop model frameworks and outputs that will enable the assessment of catchment sediment and *E. coli* loads and the expression of the environmental outcomes of these loads as attributes. MPI has contracted NIWA to deliver this objective.
2. Incorporate the model frameworks and outputs developed in Objective 1 into a catchment economic model that will be used to identify cost-effective ways to manage sediment and *E. coli* loads in the Whangarei Harbour catchment. These include both practice-based approaches (e.g. fencing streams) and outcome-based approaches (e.g. reducing sediment loads by 20%). MPI has contracted Landcare Research to deliver this objective.

This report focuses on objective 2.

Methods

The integrated catchment economic modelling of the Whangarei Harbour catchment (WHC) was completed using the New Zealand Forest and Agriculture Regional Model (NZFARM), Landcare Research's economic land use model. The model incorporated data and estimates from economic and land use databases and biophysical models. Annual sediment loads from various land uses in the WHC were estimated using the SedNet model (Dymond 2015), while the harbour sediment budget was estimated by NIWA (Green 2015), and *E. coli* loads and resulting concentrations were estimated using the CLUES model (Palliser et al. 2015). Land-based mitigation costs and effectiveness in reducing sediment and *E. coli* were obtained from a range of sources.

NZFARM includes several options for managing sediment and *E. coli* loads from land uses, ranging from intensive pasture to native bush. These options include implementing farm plans, fencing streams, and constructing wetlands.

Illustrative model scenarios were conducted to test the utility of NZFARM and assess the possible impacts for a range of management and mitigation approaches to reduce sediment and *E. coli* loads in the WHC (Table ES.1). These include both practice-based approaches such as fencing all streams for stock exclusion, and outcome-based approaches that include meeting harbour-sedimentation reduction targets and decreasing *E. coli* concentrations in key sites to achieve secondary contact recreation targets. We also modelled two large afforestation scenarios to establish the minimum feasible loads and best possible attribute states that could be achieved in the WHC. In all scenarios, mitigation costs estimates are annualised and assumed to be accrued for 25 years.

In addition to assessing the cost and effectiveness for practices and policies that could reduce loads in the WHC, the model also estimated changes in sediment and *E. coli*-related attributes. These included four freshwater sediment attributes: water clarity, euphotic depth, suspended sediment, and embeddedness; one harbour sediment attribute: the annual average sedimentation rate (AASR); and two freshwater *E. coli* attributes: target concentrations for primary and secondary contact recreation.

Table ES.1: NZFARM scenarios for the Whangarei Harbour catchment

Scenario Name	Description	Sediment Target	*E. coli* Target
	Minimum Loads		
Afforestation – all	Afforestation of all non-native land in the catchment to estimate the minimum loads possible	n/a	n/a
Afforestation – pasture	Afforestation of all pasture (dairy, dry stock and lifestyle) in the catchment.	n/a	n/a
	Management Actions		
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/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
	Harbour Sediment Load Reduction below the baseline		
Harbour Sed 20%	20% reduction in total annual sediment to each depositional basin	20%	n/a
Harbour Sed 40%	40% reduction in total annual sediment to each depositional basin	40%	n/a
Harbour Sed 60%	60% reduction in total annual sediment to each depositional basin	60%	n/a
	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%
	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/100 mL	n/a	540 cfu/100 mL
Secondary Contact 'A'	Stream *E. coli* concentrations at all ‘nodes of importance’ meet NPS-FM ‘A’ attribute state of 260 cfu/100 mL	n/a	260 cfu/100 mL

Results

The 16 modelled scenarios produced a wide range of economic and environmental impacts. A summary of the catchment-wide impacts is listed in Table ES.2.

The study showed that, given current land use, Councils need to be realistic about the possible outcomes that can be achieved. The WHC has a great deal 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% of the catchment is in pasture, so management options that only target pastoral enterprises may not be sufficient to achieve large reductions in environmental contaminants.

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

In considering each mitigation practice on its own, the construction of wetlands and sediment ponds is estimated to be the most effective option, as it is the only mitigation that can be applied to all land uses. Sediment loads are estimated to reduce by 61% and *E. coli* loads in streams by 48%. It is also the only mitigation option that has a positive impact on the sediment attributes of water clarity and euphotic depth in all 3 measured sites in the catchment. For example, constructing wetlands near the Hatea River improves water clarity at median flows by up to 39% and euphotic depth by 19%.

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

Fencing all pasture land has an effect on streambank erosion and *E. coli* from pasture, but no impact on landmass erosion (85% 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% relative to the baseline.

Implementing farm plans on pastoral farms are 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 WHSES, the average-annual sedimentation rate (AASR). Estimates varied widely across the four deposition basins, however, as they are all affected differently in terms of the amount of sediment they receive annually from both land and marine sources. The suggested ‘high’ attribute state of 1 mm/yr may therefore not be achievable for all harbour basins.

There was wide variation in impacts on the freshwater sediment attributes estimated at three sites in the catchment. Changes in sediment loads were estimated to have a noticeable impact at the Otaika river site that was surrounded with a variety of pastoral and other land uses that could implement a range of mitigation practices. However, the other two sites were located in areas of the catchment mostly comprised of 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.

Implementing mitigation practices in the WHC can lead to reductions in *E. coli* concentration that allow many, and sometimes all, the important sites in the catchment to reach at least the ‘B’ state of 540 cfu/100 mL for secondary contact recreation (this is based on a median estimate). None of the modelled scenarios result in the catchment reaching the ‘A’ stage of 260 cfu/100 mL, with the exception of full afforestation.

Achieving *E. coli* targets for primary contact recreation is not possible in the WHC. 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 minimum of 540cfu/100 mL) in any of the 11 key sites. This target is based on the 95th percentile measurements. Additional work is required to assess whether there are other methods to estimate 95th percentile concentrations in the catchment, perhaps under different flow assumptions.

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% reduction in sediment can also reduce *E. coli* loads in the catchment by 15–23%, while a policy that targets a 40% reduction in *E. coli* can reduce sediment by 15%. This suggests mitigations that focus on simultaneously reducing both *E. coli* and sediment (e.g. wetlands) are likely to be the most cost-effective option for many landowners in the catchment. It also emphasises 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.

Table ES.2: Key model scenario estimates

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 Deposition (t/yr)	*E. coli* Load - Stream (peta)	*E. coli* Load - Harbour (peta)
No Mitigation	$16.6	$0.00	26883	4472	31355	19968	84.0	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%
Max Mitigation	–12%	$1.92	–71%	–36%	–66%	–65%	–62%	–58%
Harbour Sed 20%	–0.3%	$0.04	–23%	–3%	–20%	–20%	–12%	–23%
Harbour Sed 40%	–1%	$0.19	–45%	–4%	–39%	–40%	–15%	–23%
Harbour Sed 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%

1 Introduction

Northland Regional Council (NRC) has identified that sediment and *E. coli* are key water quality challenges in the Northland region (e.g. Ballinger et al. 2014). Previous sediment studies indicate that sediment loads are not high in Whangarei and Kaipara, but that the turbidity of the water is high and water sources are dominated by bank erosion, sub-soil erosion, mass movement, and land disturbing activities. There are also challenges with *E. coli* in rivers and in estuaries. As some management practices, such as riparian planting and stock exclusion, are able to reduce both sediment and *E. coli* loadings effectively, economic modelling is able to identify the cost efficient mitigation options and target locations to reduce the loads of both contaminants.

As a result, the Ministry for Primary Industries (MPI) commissioned the Whangarei Harbour Sediment and *E. coli* Study (WHSES).

The aim of the WHSES is to develop a model that will integrate science and economics to assess the potential economic costs of meeting a range of attribute states for sediment and *E. coli* in Whangarei Harbour and freshwater environments that drain into Whangarei Harbour. The study also intends to inform further work on sediment attributes for the National Objectives Framework (NOF). The study also has a broader goal: to help further develop national understanding of the cost-effective management of both contaminants, especially since both contaminants have typically received less analysis at the catchment-scale, than nitrogen and, to a lesser extent, than phosphorus.

The WHSES comprises two objectives:

1. Develop model frameworks and outputs that will enable the assessment of catchment sediment and *E. coli* loads and the expression of the environmental outcomes of these loads as attributes. MPI has contracted NIWA to deliver this objective.
2. Incorporate the model frameworks and outputs developed in Objective 1 into a catchment economic model that will be used to identify cost-effective ways to manage sediment and *E. coli* loads in the Whangarei Harbour catchment (WHC). MPI has contracted Landcare Research to deliver this objective. These include both practice-based approaches (e.g. fencing streams) and outcome-based approaches (e.g. reducing sediment loads by 20%)

This report focuses on findings from the spatially distributed catchment economic model developed in Objective 2. The integrated model of the WHC consists of three key components: (1) baseline contaminant losses for each hectare of land in the study regions; (2) how these are modified with the use of mitigations (both on- and off-farm); and (3) 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 WHC model is based on the New Zealand Forest and Agriculture Regional Model (NZFARM), Landcare Research's economic land use model. NZFARM 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 WHC version of NZFARM includes several farm- or parcel-level management options for managing sediment and *E. coli* loads: implementing farm plans, fencing streams, and constructing wetlands. While the list of feasible farm management options is extensive, we do not necessarily include all possible options to mitigate losses from diffuse sources into waterways. The results from NZFARM are reliant on input data (e.g. farm budgets, mitigation costs, and contaminant loss rates) from external sources and may vary if alternative data are utilised. NZFARM also does not account for the broader impacts of changes in land use and land management beyond the farm gate.

This report presents results from several 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 outcome-based approaches that include reducing erosion to reach harbour-sedimentation rate targets or decreasing *E. coli* concentrations in key sites to achieve secondary and primary contact recreation targets.

The focus of this portion of the WHSES 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 here should be taken as illustrative examples of how the model works and can be utilised in future analyses, as opposed to a rigorous analysis of a proposed policy or rule change.

2 Methodology

This report presents the assessment of the potential economic and environmental impacts of reducing sediment and *E. coli* in the WHC in Northland. The economic analysis is conducted using the NZFARM model. Baseline estimates of sediment were obtained through the SedNet (Dymond 2015) and CLUES (Paliser et al. 2015) models. Economic impacts are estimated as the cost to landowners of implementing mitigation options relative to their current management practices. Environmental impacts are measured as changes in sediment and *E. coli* loads and related attributes relative to a no mitigation baseline. A more detailed description of the integrated economic model is presented below.

2.1 New Zealand Forest and Agriculture Regional Model (NZFARM)

NZFARM is a comparative-static, non-linear, partial equilibrium mathematical programming model of New Zealand land use operating at the catchment scale developed by Landcare Research (Daigneault et al. 2012, 2013). 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. It can be used to assess how changes in technology, commodity supply or demand, resource constraints, or farm, resource, or environmental policy could affect a host of economic or environmental performance indicators that are important to decisions-makers and rural landowners. The version of the model used for WHC analysis 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.

Simulating endogenous land management is an integral part of the model, which can differentiate between 'business as usual' (BAU) farm practices and less-typical options that can change levels of environmental and agricultural outputs. Key land management options in the NZFARM version used for the WHC include implementing farm plans, fencing streams, and constructing wetlands. Including a range of management options allows us to assess what levels of regulation might be needed to bring new technologies into general practice. Landowner responses to sediment and *E. coli* load restrictions in NZFARM are parameterised using estimates from biophysical and farm budgeting models.

The model's objective function maximizes the net revenue[1] of agricultural production across the entire catchment area, subject to land use and land management options, agricultural production costs and output prices, and environmental factors such as soil type, water available for irrigation, and any regulated environmental outputs (e.g. sediment load limits) imposed on the catchment. Catchments can be disaggregated into sub-regions (i.e. zones) based on different criteria (e.g. land use capability, irrigation schemes) such that all land in the same zone will yield similar levels of productivity for a given enterprise and land management option.

The objective function, total catchment net revenue (π), is specified as:

$$Max\ \pi = \sum_{r,s,l,e,m} \left\{ \begin{matrix} PA_{r,s,l,e,m} + Y_{r,s,l,e,m} - \\ X_{r,s,l,e,m}\left[\omega^{live}_{r,s,l,e,m} + \omega^{vc}_{r,s,l,e,m} + \omega^{fc}_{r,s,l,e,m} + \tau\gamma^{env}_{r,s,l,e,m}\right] \\ -\omega^{land}_{r,s,l} Z_{r,s,l} \end{matrix} \right\} \quad (1)$$

where *P* is the product output price, *A* is the product output, *Y* is other gross income earned by landowners (e.g. grazing leases), *X* is the farm-based activity, ω^{live}, ω^{vc}, ω^{fc} are the respective livestock, variable, and fixed input costs, τ is an environmental tax (if applicable), γ^{env} is an environmental output coefficient, ω^{land} is a land use conversion cost, and *Z* is the area of land use change from the initial (baseline) allocation. Summing the revenue and costs of production across all reporting zones (*r*), sub-catchments (*s*), land covers (*l*), enterprises (*e*), and management options (*m*) yields the total net revenue for the catchment.

The level of net revenue that can be obtained is limited not only by the output prices and costs of production but also by a number of production, land, technology, and environmental constraints.

The production in the catchment is constrained by the product balance equation and a processing coefficient (α^{proc}) that specifies what can be produced by a given activity in a particular part of the catchment:

$$A_{r,s,l,e,m} \leq \alpha^{proc}_{r,s,l,e,m} X_{r,s,l,e,m} \quad (2)$$

[1] Net revenue (farm profit) is measured as annual earnings before interest and taxes (EBIT), or the net revenue earned from output sales less fixed and variable farm expenses. It also includes the additional capital costs of implementing new land management practices.

Landowners are allocated a certain amount of irrigation (γ^{water}) for their farming activities, provided that there is sufficient water (W) available in the catchment:[2]

$$\sum_{s,l,e,m} \gamma^{water}_{r,s,l,e,m} X_{r,s,l,e,m} \leq W_r \tag{3}$$

Land cover in the catchment is constrained by the amount of land available (L) on a particular soil type in a given zone:

$$\sum_{e,m} X_{r,s,l,e,m} \leq L_{r,s,l} \tag{4}$$

and landowners are constrained by their initial land allocation (L^{init}) and the area of land that they can feasibly change:

$$L_{r,s,l} \leq L^{init}_{r,s,l} + Z_{r,s,l} \tag{5}$$

The level of land cover change in a given zone and sub-catchment is constrained to be the difference in the area of the initial land-based activity (X^{init}) and the new activity:

$$Z_{r,s,l} \leq \sum_{e,m}\left(X^{init}_{r,s,l,e,m} - X_{r,s,l,e,m}\right) \tag{6}$$

and we can also assume that it is feasible for all managed land cover to change (e.g., convert from pasture to forest). Exceptions include urban, native bush and tussock grassland under conservation land protection, which are fixed across all model scenarios:

$$L_{r,s,fixed} = L^{init}_{r,s,fixed} \tag{7}$$

The model also includes a constraint on changes to enterprise area (E), if desired[3]:

$$E_{r,s,l,fixed} = E^{init}_{r,s,l,fixed} \tag{8}$$

In addition to estimating economic output from the agriculture and forest sectors, the model also tracks a series of environmental factors, and in this study focus on sediment and *E. coli* loads. In the case where farm-based loads (γ^{env}) are regulated by placing a cap on a given environmental output from land-based activities (ENV), landowners could also face an environmental constraint[4]:

$$\sum_{s,l,e,m} \gamma^{env}_{r,s,l,e,m} X_{r,s,l,e,m} \leq ENV_r \tag{9}$$

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[2] N.B. For this analysis, we assume there are no irrigated land uses

[3] N.B. The WHC analysis was primarily focused on the effects of land management on sediment and *E.coli* loads. As a result, all the scenarios in this report assume all enterprises are fixed at baseline levels with exception of two that estimate the impacts of afforestation.

[4] N.B. this constraint can be placed on the farm, sub-catchment, or catchment level, depending on the focus of the policy or environmental target.

Finally, the variables in the model are constrained to be greater or equal to zero such that landowners cannot feasibly use negative inputs such as land and fertiliser to produce negative levels of goods:

$$Y, X, L \geq 0 \tag{10}$$

The 'optimal' distribution of land-based activities based on soil type $s_{1\ldots i}$, land cover $l_{1\ldots j}$, enterprise $e_{1\ldots k}$, land management $m_{1\ldots l}$, and agricultural output $a_{1\ldots m}$ are simultaneously determined in a nested framework that is calibrated based on the shares of initial enterprise areas for each of the zones. Detailed land use maps of the catchment are used to derive the initial (baseline) enterprise areas and a mix of farm surveys and expert opinion is used to generate the share of specific management systems within these broad sectoral allocations.

The main endogenous variable is the physical area for each of the feasible farm-based activities in a catchment ($X_{r,s,l,e,m}$). In the model, landowners have a degree of flexibility to adjust the share of the land use, enterprise, and land management components of their farm-based activities to meet an objective (e.g. achieve a nutrient reduction target at least cost). Commodity prices, environmental constraints (e.g. nutrient cap), water available for irrigation, and technological change are the important exogenous variables, and, unless specified, these exogenous variables are assumed to be constant across policy scenarios.

NZFARM has been programmed to simulate the allocation of farm activity area through constant elasticity of transformation (CET) functions. The CET function specifies the rate at which regional land inputs, enterprises, and outputs produced can be transformed across the array of available options. This approach is well suited for models that impose resource and policy constraints as it allows the representation of a 'smooth' transition across production activities while avoiding unrealistic discontinuities and corner solutions in the simulation solutions (de Frahan et al. 2007).

At the highest levels of the CET nest, land use is distributed over the zone based on the fixed area of various soil types. Land cover is then allocated between several enterprises such as arable crops (e.g. process crops or small seeds), livestock (e.g. dairy or sheep and beef), or forestry plantations that will yield the maximum net return. A set of land management options (e.g. fencing streams, reduced fertiliser regime) are then applied to an enterprise which then determines the level of agricultural outputs produced in the final nest.

The CET functions are calibrated using the share of total baseline area for each element of the nest and a CET elasticity parameter, σ_i, where $i \in \{s, l, e, m, a\}$ for the respective sub-catchment, land cover, enterprise, land management, and agricultural output. These CET elasticity parameters can theoretically range from 0 to infinity, where 0 indicates that the input is fixed, while infinity indicates that the inputs are perfect substitutes (i.e. no implicit cost from switching from one land use or enterprise activity to another).

The CET elasticity parameters in NZFARM typically ascend with each level of the nest between land cover, enterprise, and land management. This is because landowners have more flexibility to change their mix of management and enterprise activities than to alter their share of land cover. For this analysis the CET elasticities are specified to focus specifically on the impact of holding land cover and enterprise area fixed, which allows us to focus on the impacts of imposing mitigation practices on existing farms. Thus, the elasticities are as follows: land cover ($\sigma_L = 0$), enterprise ($\sigma_E = 0$), and land management ($\sigma_M = \infty$). An infinite

CET elasticity value was used in the land-management nest to simulate that landowners are 100% likely over the long-run to employ the most cost-effective practices on their existing farm to meet environmental constraints rather than change land use. The CET elasticity parameter for each sub-catchment (σ_S) is set to be 0, as the area of a particular sub-catchment in a zone is fixed.[5] In addition, the parameter for agricultural production (σ_A) is also assumed to be 0, implying that a given activity produces a fixed set of outputs.

We note that this specification, along with equation (7), essentially re-specifies NZFARM to solve without needing to use the PMP-like formulation because it now includes additional levels of constraints. In this case, the only thing that is allowed to change is land-management, which is now assumed to be completely substitutable over the long run. That is, the landowner will choose whatever land management option is most profitable for the farm without any reservation. However, this approach also constrains changes in land use, and thus although a farm may be more profitable if it switches from sheep & beef to forestry, this specification prohibits it from doing so. As a result, the simulated costs of the policy are the same as those estimated using catchment economic modelling methods discussed in Doole (2015).

The economic land use model is programmed in the modelling General Algebraic Modelling System (GAMS) software package. The baseline calibration and scenario analysis are derived using the non-linear programming (NLP) version of the CONOPT solver (GAMS 2015).

2.2 SedNetNZ

Landcare Research was sub-contracted by NIWA under objective 1 of the WHSES to undertake an analysis of baseline erosion rates and sediment yields in the WHC using the SedNetNZ model. The catchment erosion and sediment model simulates several erosion processes, sediment storages, and transfers. For this analysis, SedNetNZ has been calibrated for the WHC and downscaled to the farm scale. Sediment is estimated to come from two sources: hill/landmass[6] erosion and streambank erosion. The estimates are then incorporated into NZFARM river environmental classification level 2 (REC2) sub-catchments, of which there are more than 700 in the WHC. More details on SedNetNZ are available in Dymond (2015).

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[5] Recall that other NZFARM-based catchment models specify *S* as soil type and *R* as the zone or sub-catchment. In this study, we assume that there is just a single soil type and many reporting zones and sub-catchments. As both *R* and *S* are fixed in area, we can keep the same structure and simply replace soil-type with sub-catchment.

[6] N.B. Hill/landmass erosion is represented in NZFARM as an aggregate of landslide, earthflow, gully, and surficial erosion as well as floodplain deposition, which are all measured separately in SedNetNZ as it is assumed certain mitigation practices such as farm plans would address all of these processes at once.

2.3 Harbour Sediment Budget

Green (2015) used estimates from SedNetNZ to estimate the sediment budget for 11 reporting zones within the WHC. The harbour sediment budget is a description of the patterns of catchment sediment yields and sediment deposition in the harbour. For representation in NZFARM, the harbour sediment budget has been described analytically, specifying how the catchment sediment is distributed, on average, among different depositional environments in the estuary at the base of the catchment. Equations presented in Green (2015) that relate catchment sediment runoff and mass of marine sediments transported by waves and currents to sedimentation rates in four estuary depositional basins were incorporated into NZFARM. The reporting zones and depositional basins are shown in Figure 1.

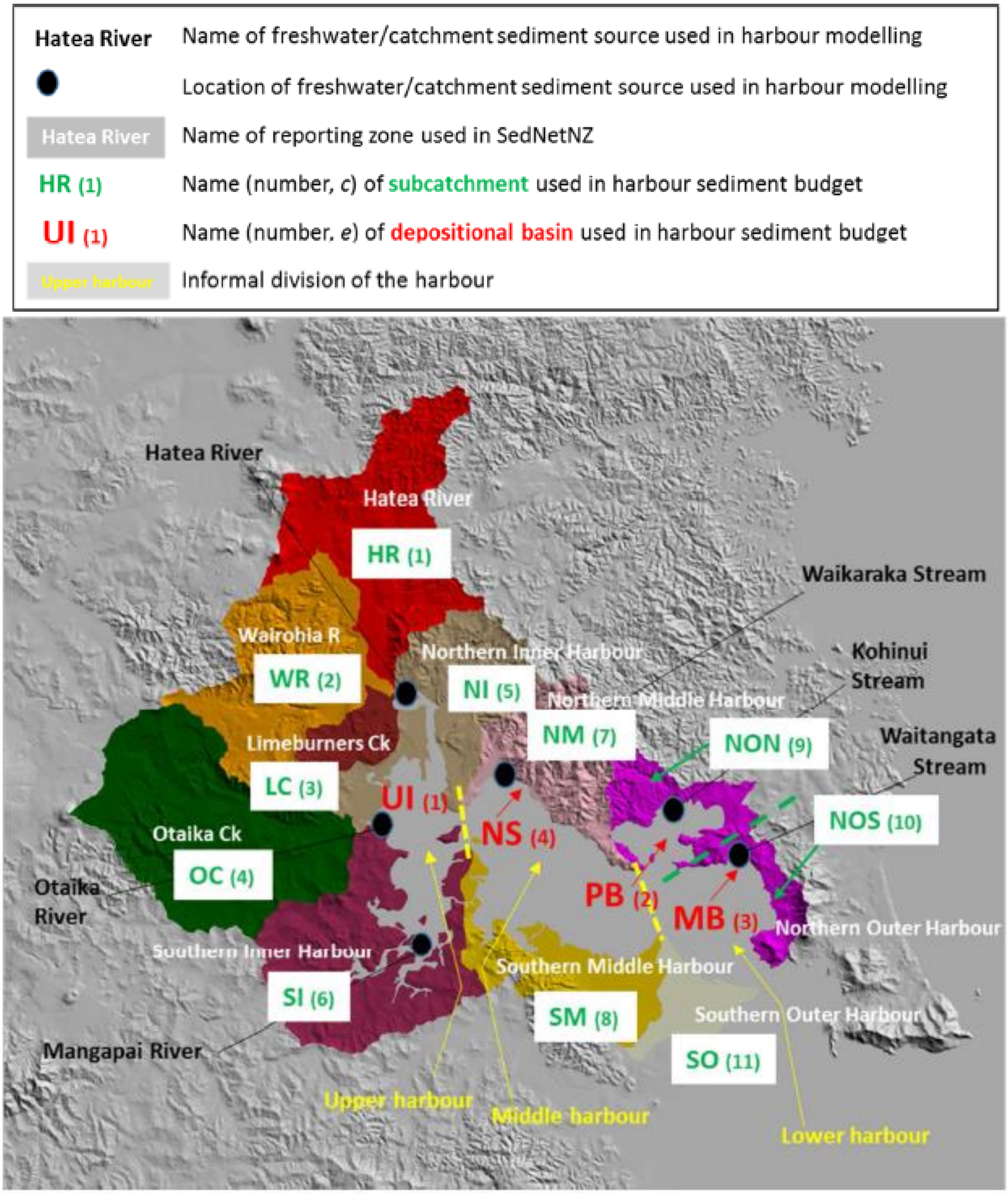


Figure 1: Whangarei Harbour Catchment reporting zones and depositional basins.

2.4 CLUES

NIWA used the CLUES model to estimate baseline annual-average *E. coli* loads in the WHC (Palliser et al. 2015). Attenuation rates throughout the flow network were also estimated as part of this work. The estimated loads are broken down to the scale of land cover (pasture, forest, other) and point sources at the REC2 sub-catchment scale. The estimates also include urban and point-source loading for current conditions; however, these values are very small relative to the total load in the catchment.

The REC2 sub-catchments are displayed in Figure 2. Also included in the figure are the REC2 streams and 11 sites or 'nodes of importance' (more below) located within the WHC. Note that there are areas near the harbour not classified as a REC2 sub-catchment; these have been aggregated and specified as a single sub-catchment.

NZFARM has incorporated the 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 also included the attenuation rates for each sub-catchment to account for the downstream accumulation of *E. coli* in the catchment.

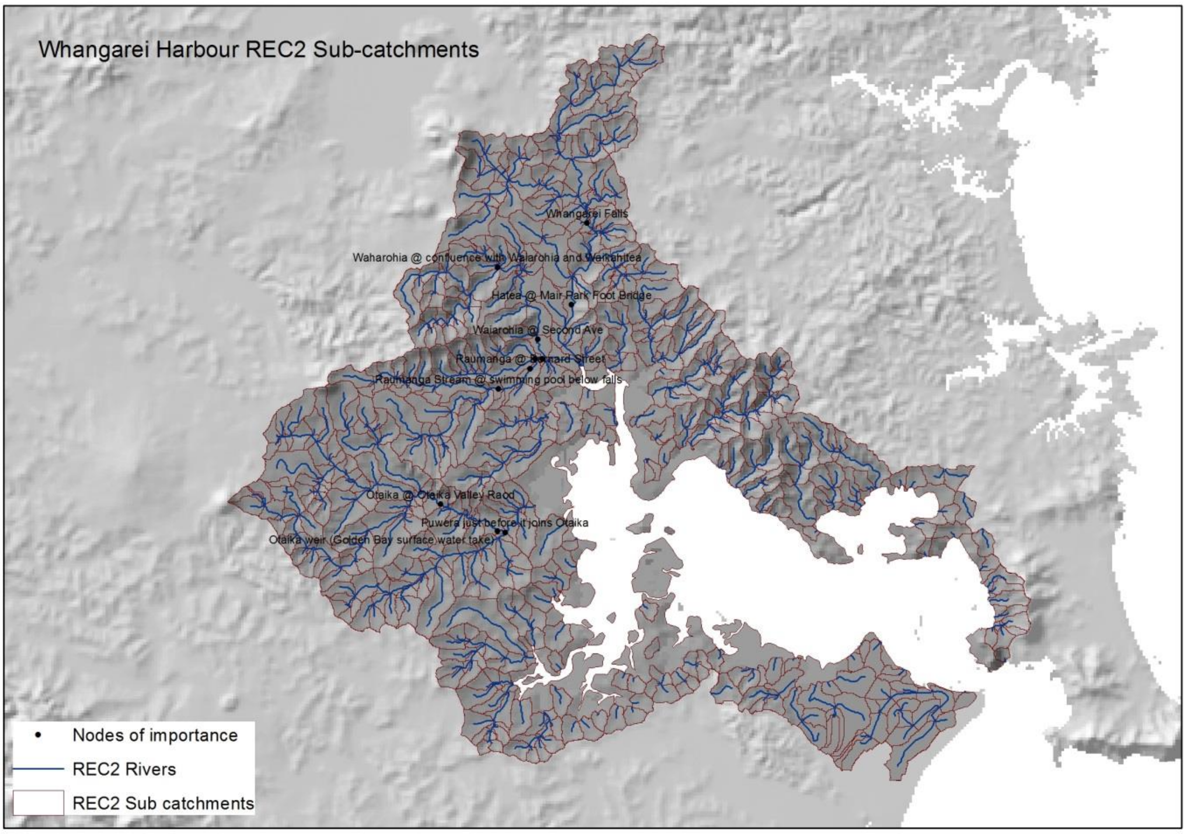


Figure 2: Whangarei Harbour Catchment REC2 sub-catchments and rivers.

2.5 Water quality attributes

This report models the impact of land management on a range of water quality attributes from Green et al. (2015). These include four freshwater sediment attributes: water clarity, euphotic depth, suspended sediment, and embeddedness; one estuary sediment attribute: average annual sediment rate; and two *E. coli* related attributes: concentrations for secondary and primary contact recreation.

2.5.1 Freshwater sediment attributes

The four attributes agreed upon for freshwater sediment attributes in the WHSES are water clarity, euphotic depth, suspended sediment, and embeddedness. Water clarity and euphotic depth are estimated to have an inversely related and non-linear response to changes in sediment loads, while changes in suspended sediment and embeddedness are perfectly correlated. Dymond (2015) provides more details on how these attributes were estimated for 3 sites in the Whangarei Harbour Catchment: the Hatea, Waiarohia, and Otaika rivers.

Due to a lack of knowledge about what the 'appropriate' targets should be, the WHSES did not specify explicit targets for the freshwater sediment attributes as part of this analysis.[7] As a result, this study estimates the impacts to these attributes from specific management practices or sediment loading targets rather than trying to achieve a particular freshwater attribute state. All the scenarios are designed, however, so that these freshwater sediment attributes will always be "maintained or improved".

2.5.2 Estuary sediment attributes

Green (2013) showed how a catchment–estuary sediment budget could be manipulated to calculate catchment sediment load limits that will achieve a target annual-average sedimentation rate (AASR) in an estuary. He also discussed whether managing for just an annual-average sedimentation rate will reduce the broad spectrum of adverse sediment effects and deliver the types of environmental outcomes that are desired. Green (2013) argued that the advantages of managing to meet a simple parameter, such as AASR, including that it is relatively easy to measure, explain and measure progress towards achievement.

Green et al. (2015) view the AASR as a good candidate for a master attribute that is indicative of a wide range of sediment effects in estuaries, including the fact that 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 (AASR before catchment deforestation), and research being conducted at the University of Auckland and NIWA is in progress relating AASR to ecological health. The authors note that using AASR as a sediment attribute might not work for every estuary, and that there will probably be some upper limit to the percentage of the catchment sediment runoff exported to the sea above which AASR would not be valid as a

[7] Recall that sediment attributes are not specified in the NPS-FM.

sediment attribute. Still, they suggest using the AASR as the single estuary sediment attribute in the WHSES on the basis that it is reasonable to assume AASR is indicative of a wide range of sediment related effects in the Whangarei Harbour.

This study includes three scenarios that model the impact of targeting specific estuary sediment reduction loads on the AASR in four estuary depositional basins.

2.5.3 *E. coli* attributes

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 (MfE 2014). 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 provides a National Objectives Framework (NOF) to help regional councils and communities establish freshwater objectives for national values more consistently and transparently. It also sets national bottom lines (i.e. minimum acceptable states) for two compulsory values – ecosystem health and human health for secondary contact recreation. In the NOF, *E. coli* is identified as an attribute that measures water quality for human health for recreation in lakes and rivers. The level to which this attribute is to be managed (i.e. *E. coli* attribute states) is defined in the NOF (Table 1). The WHSES group agreed to use the NOF attribute of *E. coli* median concentration for representing secondary contact in streams (e.g. wading). It also agreed to use the 95 percentile *E. coli* concentration, which is a NOF attribute for representing primary contact in streams. *E. coli* concentrations are typically measured as the number of *E. coli* (cfu) per 100 mL

Table 1: NOF attribute state for various *E. coli* concentrations (cfu/100 mL)

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

Although the Palliser et al. (2015) CLUES modelling only estimated *E. coli* loads, that analysis indicates that *E. coli* concentrations can be measured as a linear response to loads. We have adopted the same assumption in NZFARM; that is, the reference concentration is assumed to decrease proportionally with the estimated reduction in contaminant loadings brought about by mitigation activity. This is an obvious simplification, but is necessary, given a lack of key data regarding the interaction between abatement and in-stream processes.

The WHSES group agreed that the harbour *E. coli* attribute should use the annual harbour *E. coli* load estimate as a proxy for overall microbial contamination risk in harbour. This is modelled in NZFARM as a “maintain or improve” constraint for the aggregate harbour *E. coli* load in the catchment (as opposed to modelling the impact at a specific basin within the harbour).

2.6 Mitigation practices

We track several mitigation options for reducing sediment and *E. coli* loads in the catchment. A description of each option is listed in Table 2. More details on the mitigation options, which were based on an expert workshop held in April 2015, are presented in Appendix 1.

Table 2: Summary of the modelled mitigation options

Option	Description	Landmass Sediment	Streambank Sediment	E. coli
Farm Plan	Specific to individual farms, but can include slope stabilisation, afforestation, channel diversion, and natural wetland remediation.	X		
Stream bank Fencing	Construct fences		X	X
Wetland Construction	3 options that vary across slope and location: • Retention Bund/wetland combination • Sedimentation pond/wetland combination • Mid-catchment constructed wetland intercepting 2nd-3rd order streamflow	X		X
Afforestation	Plant non-native land with pine plantations or native bush	X	X	X
Combination	Includes a combination of the practices listed above. Often more effective, albeit at a higher cost	X	X	X

2.7 Model Data and Parameterisation

NZFARM 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 (e.g. inputs, costs, and prices), production data, and environmental outputs (e.g. sediment loads, *E. coli* loads, etc).

Table 3 lists the key variables and data requirements used to parameterise NZFARM, while Table 4 provides specific elements of the model. More details on the data and parameter assumptions used to populate the WHC version of the model are provided below. All of the figures in the NZFARM are converted to per ha values and 2012 NZD so that they are consistent across sources and scenarios.

Table 3: Data sources for NZFARM's modelling of Whangarei Harbour Catchment

Variable	Data requirement	Source	Comments
Geographic area	GIS data identifying the catchment area	Catchment and sub-catchments based on REC	Provided by 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 LCDBv2	Land use map verified by project partners.
Management practices	Distribution of feasible management practices (e.g., stream fencing, farm, management plan, etc.)	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 NZ 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 & beef, and deer enterprises
Input costs	Stock purchases, electricity and fuel use, fertiliser, labour, supplementary feed, grazing fees, etc.	Obtained using a mix of: pers. comm. with farm consultants and regional experts, MPI farm monitoring report, Lincoln Financial Budget Manual	Verified with local land managers and industry consultants
Product outputs	Milk solids, Dairy calves, Lambs, Mutton, Beef, Venison, Grains, Fruits, Vegetables, Timber, etc.	Used yields for Northland Region, but nothing specific to WHC	Verified with local land managers and industry consultants
Commodity Prices	Same as outputs, but in \$/kg or \$/m3	Obtained from MPI and other sources	Assume 5-year average
Environmental indicators	Soil Erosion/Sediment Stream *E. coli* Harbour *E. coli*	Sediment based on SedNet model *E. coli* sourced from NIWA	Data supplied by project partners

Table 4: List of key components of NZFARM Whangarei Harbour Catchment

Enterprise (E)	Mitigation Practice (M)	Sub-catchment (S)	Reporting Zone (R)	Environmental Indicators (ENV)
Dairy Sheep & Beef Deer Forestry Grapes Horticultural crops Arable crops Scrub Native Urban Other	None Farm Plan Fencing Retention Bund/wetland combo Sedimentation pond/wetland combo Mid-catchment constructed wetland Farm Plan + Fencing Farm Plan + Fencing + Wetland Afforestation	755 REC 2 sub-catchments	11 Whangarei harbour catchment reporting zones	Streambank sediment Hill/landmass sediment Total sediment Stream E. *coli* loads and concentrations Harbour *e. Coli* loads and concentrations Water clarity Euphotic depth Annual-average sedimentation rate

2.7.1 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 GIS-based land use map created by Landcare Research using the latest information from Agribase and the NZ Land Cover Database version 2 (LCDBv2) (Fig. 4). The catchment is approximately 31 000 ha in size, and key land uses include sheep & beef (35%), native (25%), dairy (11%), plantation forestry (10%), and urban (9%). Note that because only 46% 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 WHC, where a noticeable level of both *E. coli* and sediment are found to come from non-pastoral land uses (more below).

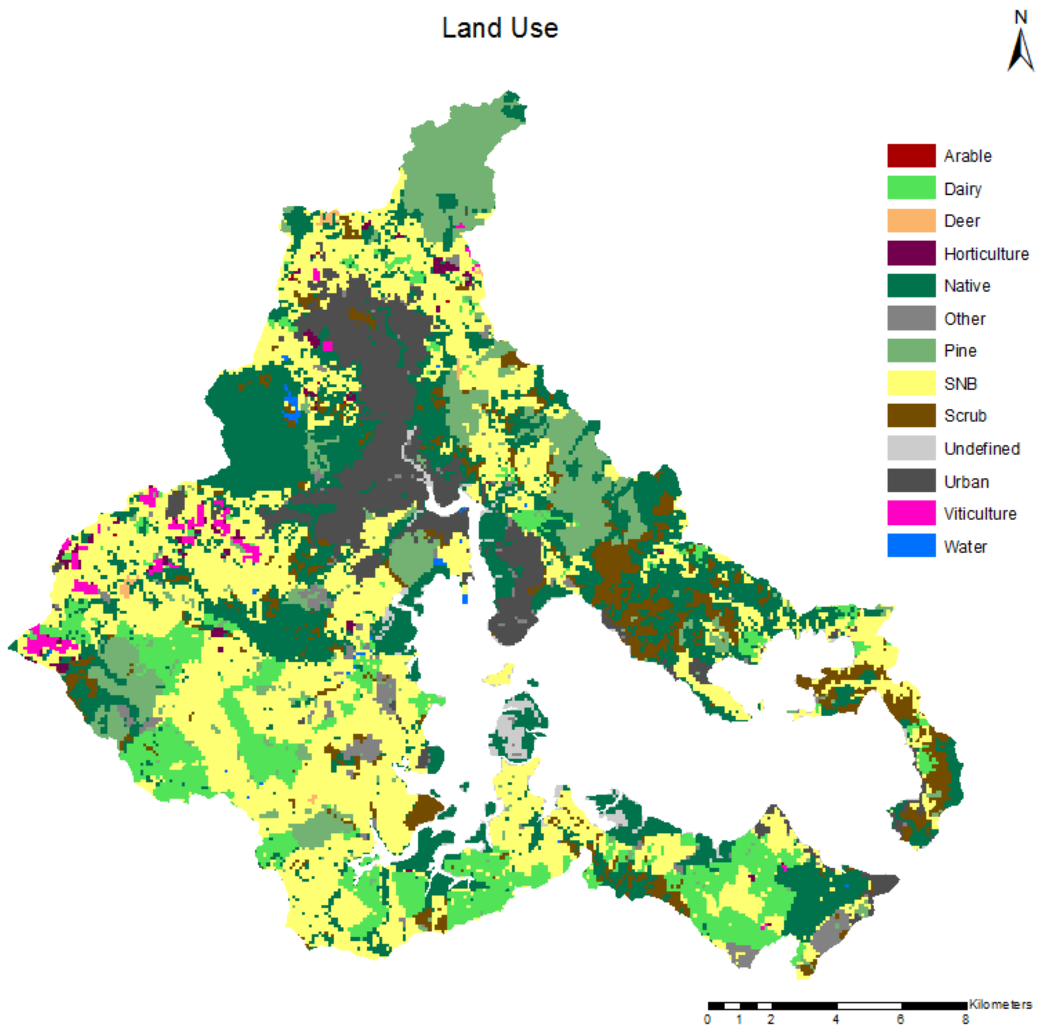


Figure 3: Whangarei Harbour Catchment land use.

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 (e.g. MPI SOPI 2013a; MPI Farm Monitoring 2013b; Lincoln University Budget Manual 2013). These farm budgets form the foundation of the baseline net revenues earned by landowners, and are specified as earnings before interest and taxes (EBIT). These figures assume that landowners currently face no mitigation costs such as fencing streams or constructing wetlands (more below). The national-level figures have been verified with agricultural consultants and enterprise experts, and documented in Daigneault et al. (2015). In addition, the WHC-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 4. Although dairy makes up a relatively small proportion of land use, it produces nearly 60% of farm net revenue in the catchment, followed by horticulture and arable (15%), forestry (15%), and sheep and beef farming (12%).

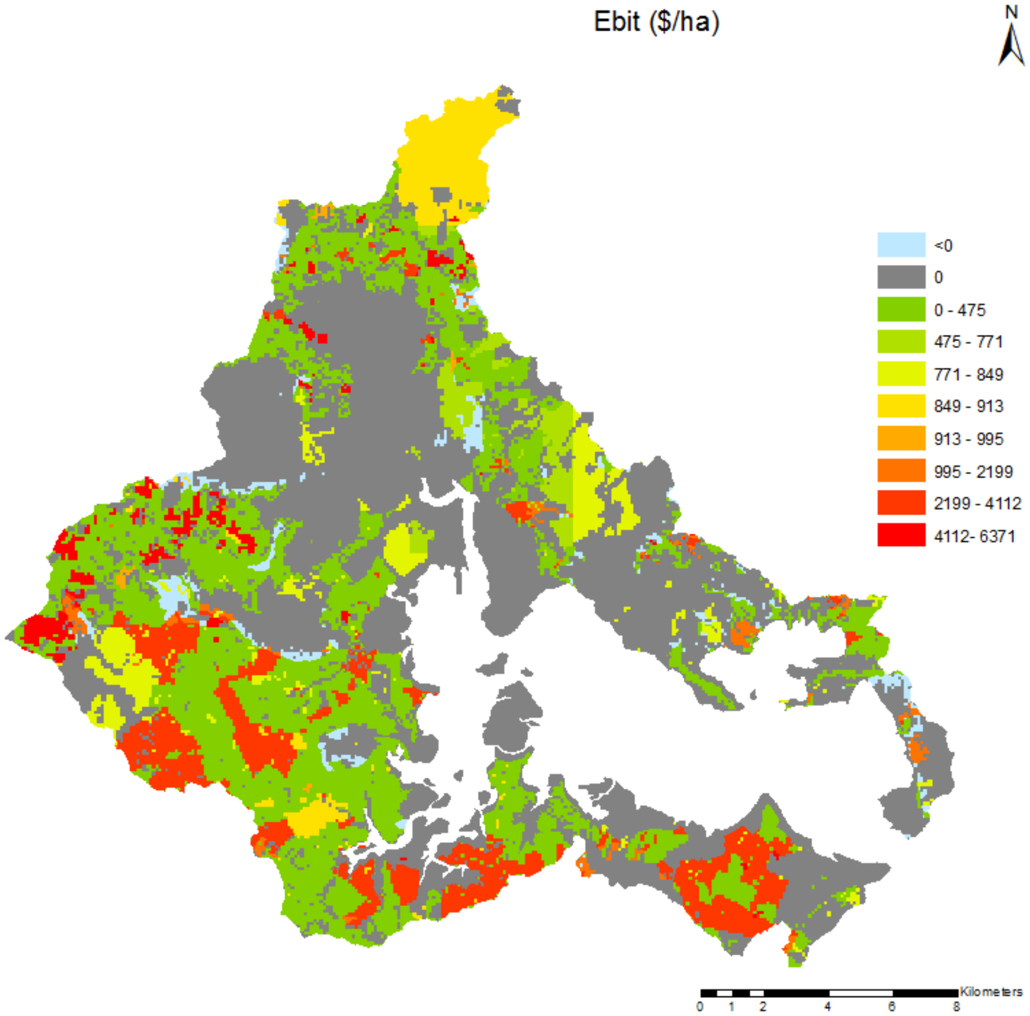


Figure 4: Baseline net farm revenue ($/ha/yr).

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 do not take net revenues into account. In addition, the study is focused on management change within the current land use as opposed to land use change.[8] 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[9] (e.g. nutrients reduction targets in Daigneault et al. 2013).

[8] N.B. We do have two afforestation scenarios to assess the possible lower bound of sediment and *E.coli* loads that could occur in the catchment. All the other scenarios assume no land use change.

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

2.7.2 Nodes of Importance

The project group established that there are 11 sites that could be defined or classified as nodes of importance. These sites were chosen because they are located near environmental monitoring stations and/or popular recreation sites. The locations of the sites are shown above in Figure 2. Table 5 presents the land use distribution, in hectares, at the 11 sites. 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. For example, nearly the entire sub-catchment that includes the site 'Waiarohia at Second Ave' is classified as urban and thus 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 as the model tracks the flow and attenuation of *E. coli* through the stream network.

Table 5: Land use area (ha) of Whangarei Harbour Catchment sites classified as nodes of importance

Site	Dairy	Sheep & Beef	Pine	Horticulture & Arable	Native & Scrub	Urban	Other	Total Area
Whangarei Falls	0	5.3	0	0.3	3.1	5.1	0.2	14
Waharohia @ confluence w/ Waiarohia & Waikahitea	0	50.4	5.2	9.5	33.8	0.4	1.7	101
Hatea @ Mair Park Foot Bridge	0	0	0	0	76.1	35.1	0	111
Waiarohia @ Second Ave	0	0	0	0	0.3	52.1	0	52
Raumanga just before it joins the Waiarohia	0	0	0	0	0	5.3	0	5
Kirikiri just before it joins the Raumanga	0	0.8	0	0	16.5	87.6	1.1	106
Raumanga @ Bernard Street	0	0	0.3	0	6	41.6	0.1	48
Raumanga Stream @ swimming pool below falls	0	0	0	0	11.9	12.4	0	24
Otaika @ Otaika Valley Raod	0	27.3	0.5	0	32.8	0	0.4	61
Otaika weir (Golden Bay surface water take)	0.6	50.6	0	0	24.2	0	0	75
Puwera just before it joins Otaika	0	9.9	0	0	4.1	0	0	14

Note: red text indicates nodes with both *E. coli* and sediment attributes. All other sites only measure *E. coli*; The area figures only account for the REC2 subcatchment that site is immediately located in and not area upstream that it may also contribute to the total load at the node.

2.7.3 Sediment Loads

Sediment load estimates are taken directly from the SedNetNZ model. The land use contribution to sediment are estimated for both hill/landmass and streambank erosion. The sum of these two erosion processes are 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).

SedNetNZ estimates that the total load in the catchment is more than 31 000 tonnes of sediment per year. About 85% of this is estimated to arise from hill and landmass erosion, while the remainder is from streambank erosion (Figure 5–7).

A bulk of the sediment is estimated to come from sheep and beef (36%), native land (26%), and pine plantations (13%). 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. Note that if any of the forested area were converted to pasture, the level of erosion could increase by a factor of 10 (Dymond et al. 2010).

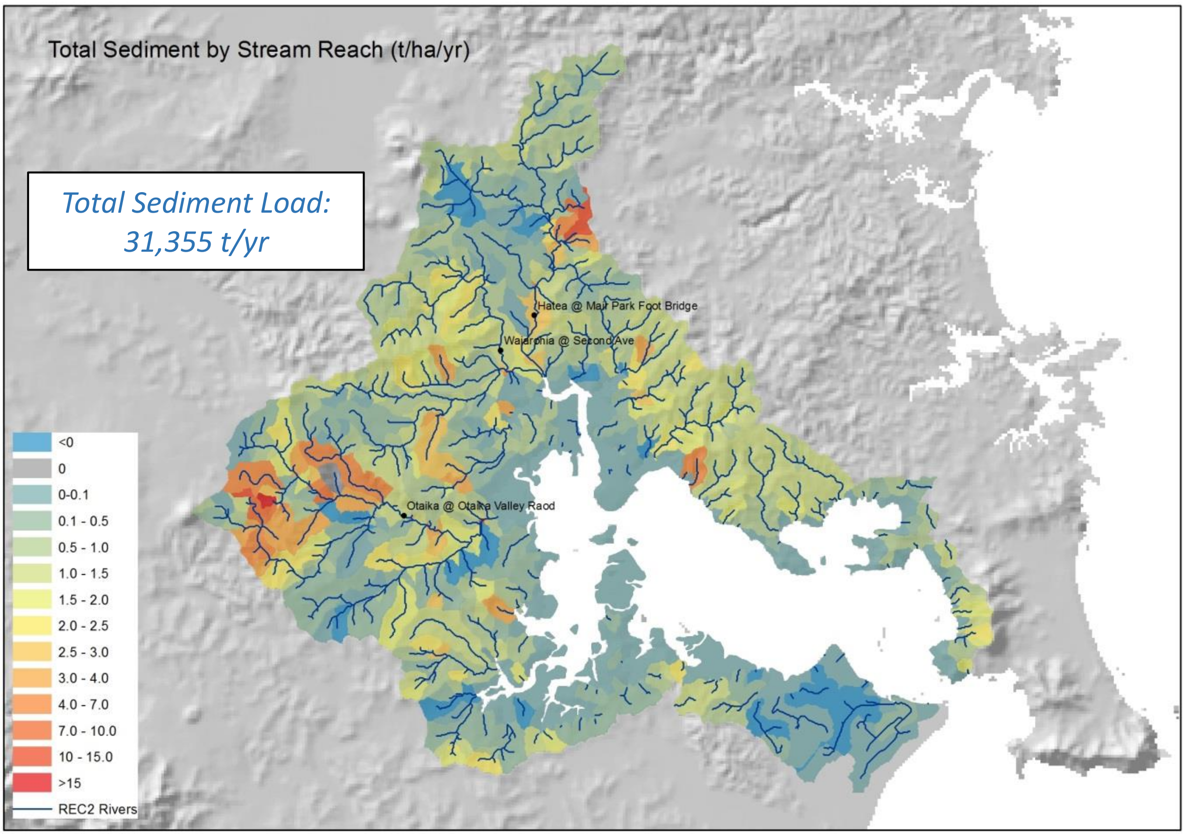


Figure 5: Total sediment load in the Whangarei Harbour Catchment.

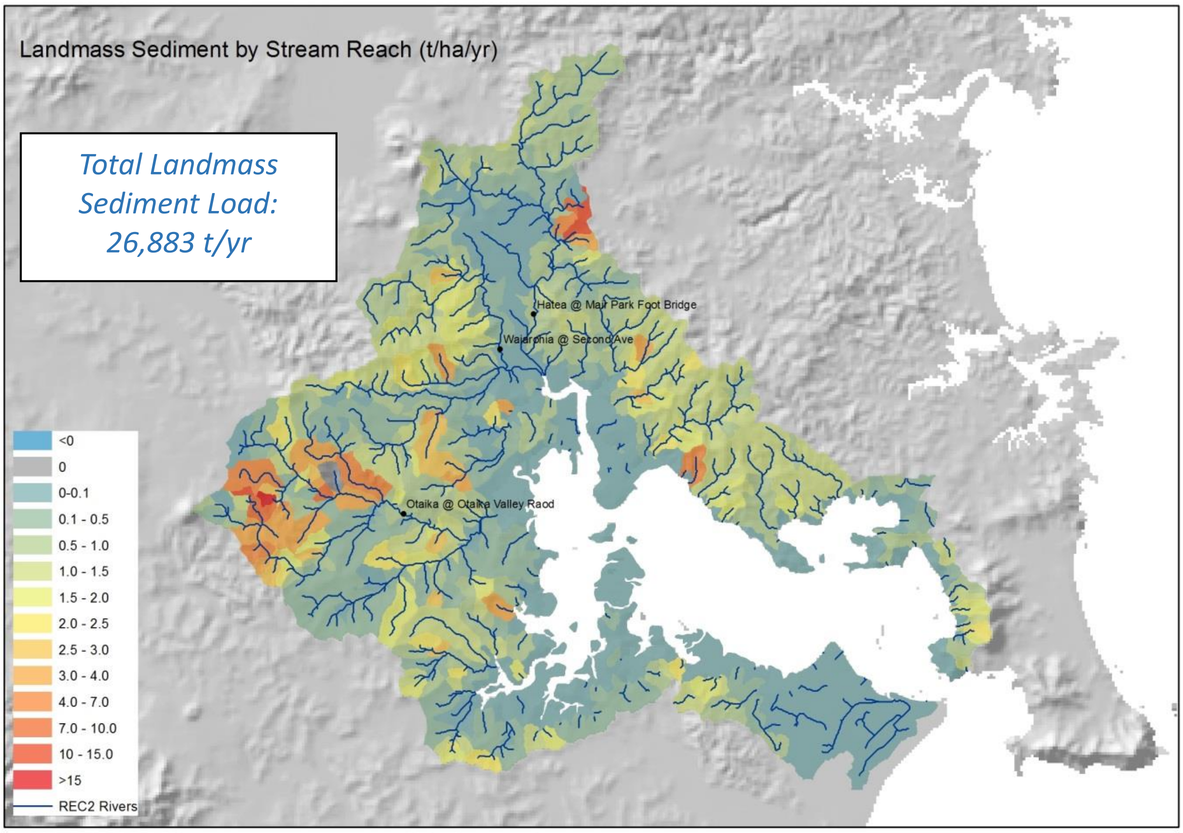


Figure 6: Total landmass sediment load by REC2 stream reach in the Whangarei Harbour Catchment.

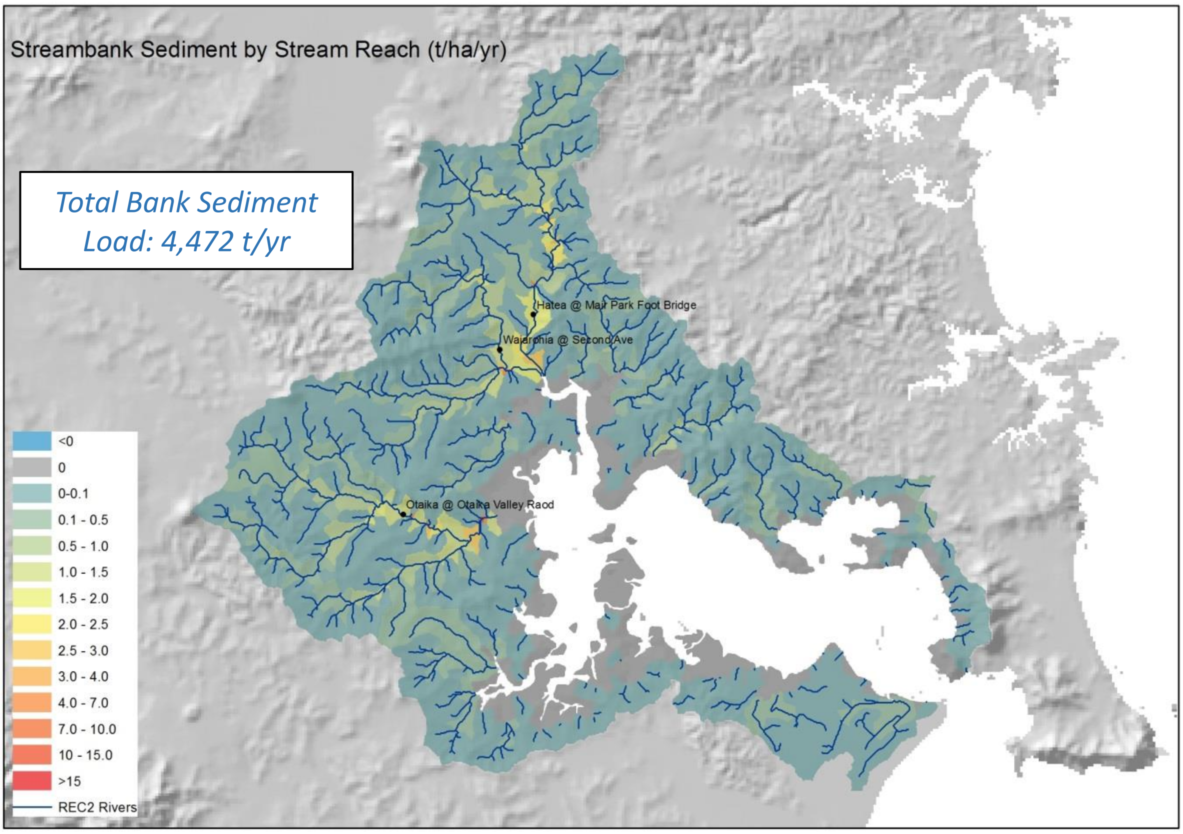


Figure 7: Total streambank sediment by REC2 stream reach in the Whangarei Harbour Catchment.

2.7.4 Freshwater Sediment Attributes

Dymond (2015) estimated relationships between the reduction in sediment loads and resulting freshwater attribute state for 3 sites in the WHC where monitoring and flow data was available (Table 6). Modelled attributes include water clarity, euphotic depth, suspended sediment, and embeddedness. NZFARM has been programmed with all of the equations from Dymond (2015) 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 6: Baseline freshwater sediment attribute estimates for 3 sites in Whangarei Harbour Catchment*[10]

percentile	flow (m3/s)	turbidity (NTU)	suspended sediment (gm/m3)	water clarity (m)	euphotic depth (m)
			Hatea		
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

2.7.5 Harbour/Estuary Sediment Attributes

The harbour sediment attribute of AASR is estimated using methods published by Green (2015), who develops equations that relate catchment sediment runoff and mass marine sediment transported by waves and currents to sedimentation rate in an estuary deposition basin. This approach can be used to estimate the change in AASR (or sedimentation rate) in a depositional basin resulting from either a decrease (e.g. because of mitigation) or an increase in sediment loads from anywhere in the catchment.

[10] N.B. Embeddedness was only estimated for the Waiairohia River as it is the only site that has a gravel-based bed. Embeddedness in the river was estimated to be 122.6 grams of trapped sediment per m3 of water based on a mean annual flood of 30 m^3/s (Dymond 2015).

The baseline values for the AASR in the four harbour deposition basins, as estimated by Green (2015), are shown in Figure 8. The total ASSR is broken out by land and marine sources.

These equations specified by Green (2015) have been programmed into NZFARM. Although the equations include several variables, the only one that has an impact on AASR within NZFARM 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 WHC on the blue portion of the bars in Figure 8. This suggests 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.

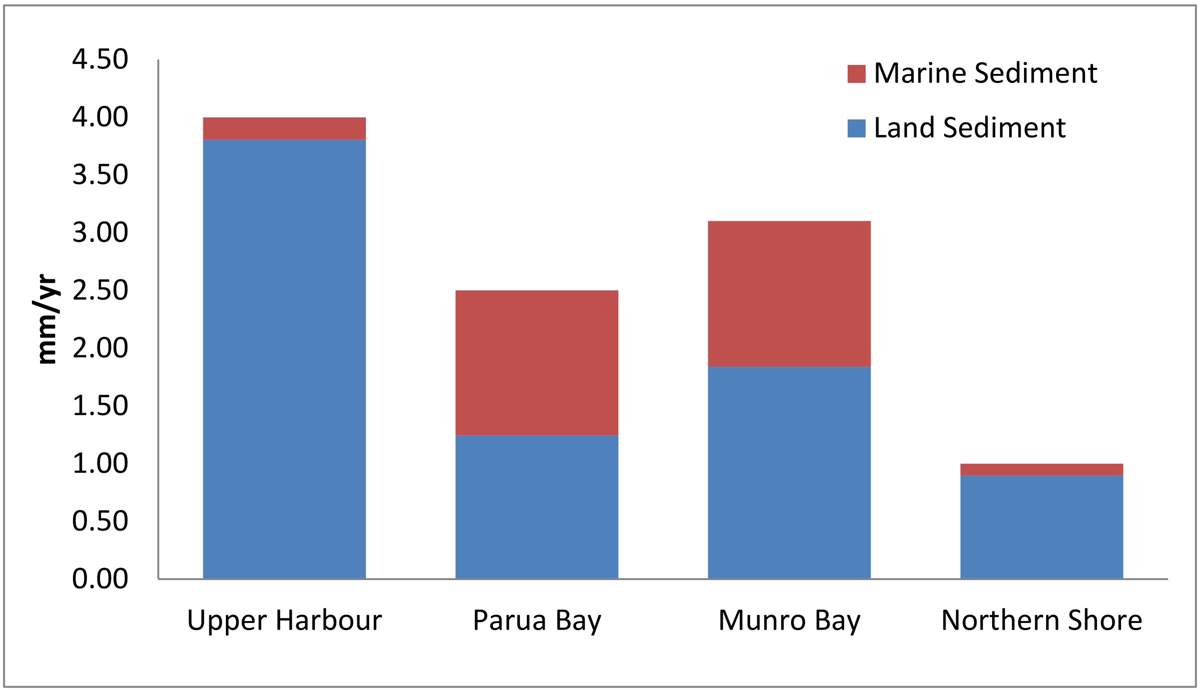


Figure 8: Contribution to baseline AASR for 4 Whangarei Harbour deposition basins of land and marine sources of sediment.

2.7.6 *E. coli* Loads

E. coli loads for the WHC are estimated using a customised version of the CLUES model (Elliott et al. 2005; Semadeni-Davies et al. 2011). The model is calibrated to estimate *E. coli* loads in the Northland region, with a specific emphasis given to the WHC. In order to improve the model predictions for the harbour catchment, it was calibrated to as many suitable sites in the region as possible, rather than just to those sites within the harbour catchment. Water quality modelling focussed on 11 "nodes of importance" in the WHC that were identified by the NRC, as well as *E. coli* loads entering the Whangarei Harbour.

Stream *E. coli* loads were calculated for catchments defined according to the REC2 sub-catchment classification. There were 755 of these sub-catchments within the WHC. Areas of land that discharged directly to the harbour were grouped into a single pseudo-catchment and treated as other catchments.

The CLUES model determines mean annual loads of stream *E. coli* (Fig. 9). The catchment of interest is broken into REC2 sub-catchments, and each sub-catchment has a number of land uses with associated yields, which are modified according to environmental factors such as rainfall. These sources are accumulated and attenuated down the stream network, with the addition of point source loadings. This gives estimated loads (measured in peta *E. coli*/yr) for each REC2 sub-catchment.

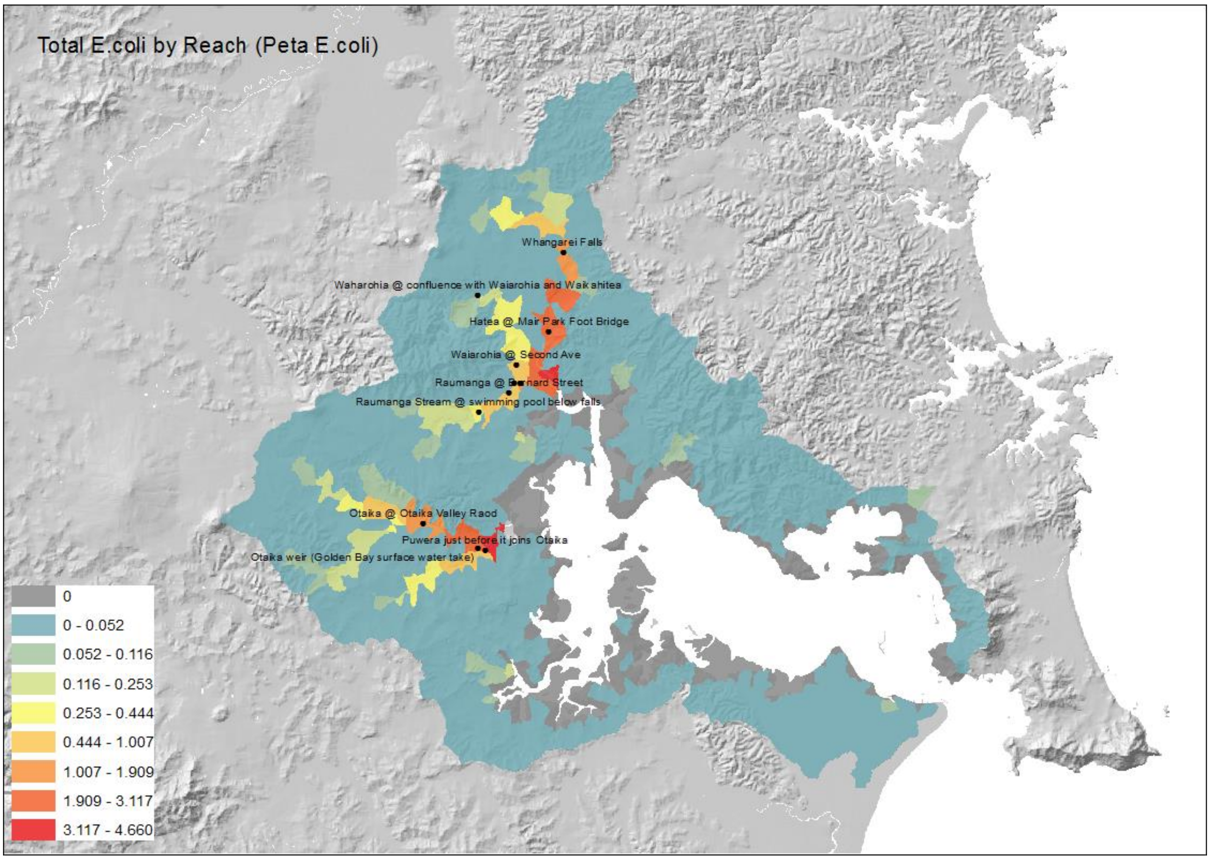


Figure 9: CLUES estimates of annual ***E. coli*** loads (peta ***E. coli***) for individual REC2 sub-catchments.

The *E. coli* load to the Whangarei harbour was also determined in CLUES (Fig. 10) using the same methods as the stream *E. coli* estimation. Most of the sub-catchments in the harbour are grey because they do not contribute *E. coli* to the harbour load (i.e. *E. coli* is fully attenuated). Summing across all the REC2 sub-catchments that do contribute to *E. coli* in the harbour establishes the total annual harbour load of more than 290 peta *E. coli*/yr.

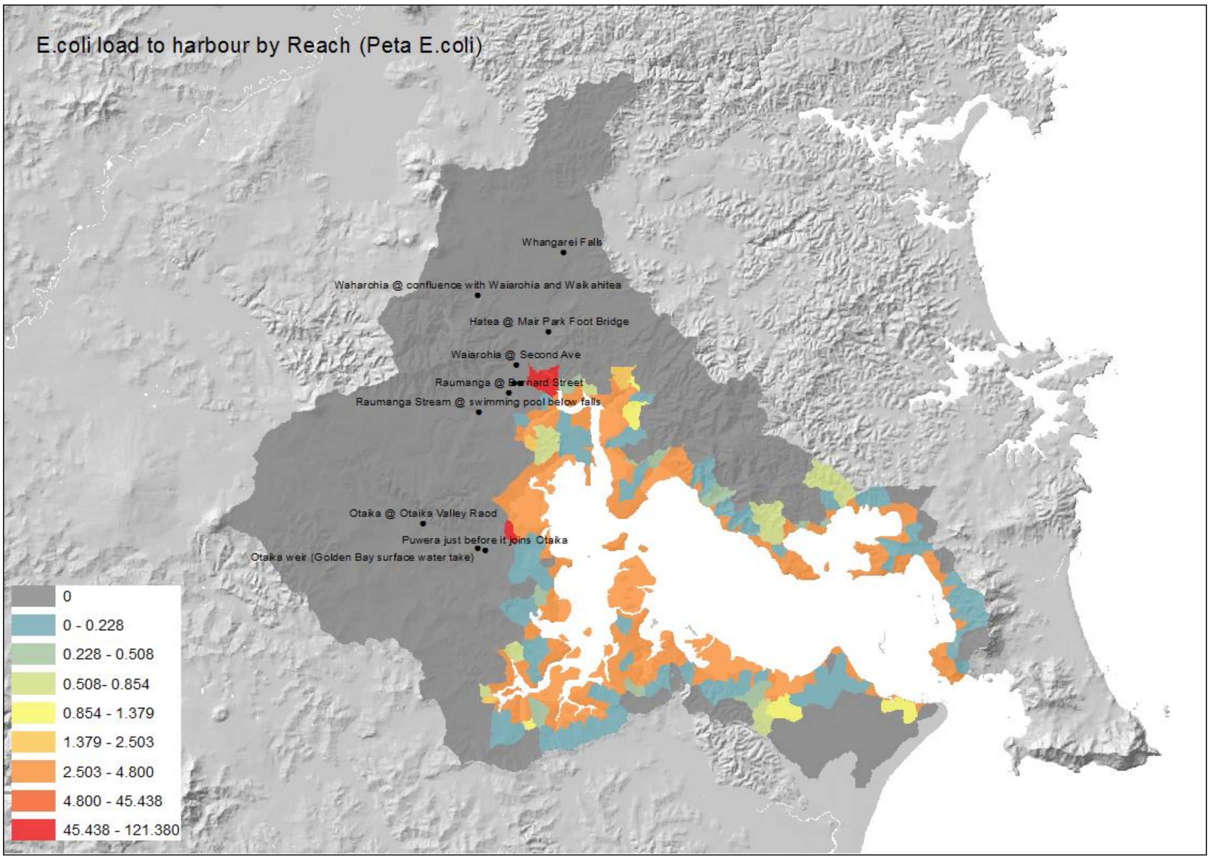


Figure 10: CLUES estimates of annual *E. coli* loads (peta *E. coli*) for sub-catchments flowing out to the Whangarei Harbour.

2.7.7 *E. coli* Concentrations at nodes of importance

The estimated median and 95th percentile *E. coli* concentrations at the 11 nodes of importance, as specified in Palliser et al. (2015) are listed in Table 7. 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' attribute state for both primary and secondary contact recreation, defined by concentrations less than or equal to 260 *E. coli* /100 mL; while the B state is defined by concentrations between 260 and 540/100 mL. C state for secondary contact is defined by concentrations between 540 and 1000 *E. coli*/100 mL. Any concentration greater than the 'National Bottom Line' of 1000 *E. coli* /100 mL 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 7: Outputs at 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)*	Med E.coli Conc (cfu/100mL)	95%ile E.coli Conc (cfu/100mL)
Whangarei Falls	n/a	n/a	n/a	1.3149	439.0	2003
Waharohia @ confluence with Waiarohia and Waikahitea	n/a	n/a	n/a	0.0644	525.0	3485
Hatea @ Mair Park Foot Bridge	98.2	164.3	262.5	2.5247	259.0	6306
Waiarohia @ Second Ave	7.4	59.4	66.8	0.8766	399.0	5421
Raumanga just before it joins the Waiarohia	n/a	n/a	n/a	0.5044	941.7	12844
Kirikiri just before it joins the Raumanga	n/a	n/a	n/a	0.0400	722.3	9852
Raumanga @ Bernard Street	n/a	n/a	n/a	0.6039	903.0	13164
Raumanga Stream @ swimming pool below falls	n/a	n/a	n/a	0.4211	211.0	3076
Otaika @ Otaika Valley Raod	16.9	64.4	81.3	1.3323	484.0	4378
Otaika weir (Golden Bay surface water take)	n/a	n/a	n/a	2.3456	871.5	7883
Puwera just before it joins Otaika	n/a	n/a	n/a	0.7747	1354.2	18470

*na = not applicable because segment not used to estimate changes in sediment attributes

2.7.8 Mitigation Costs

Assumptions about mitigation costs and effectiveness in reducing sediment and *E. coli* loads were established by the project team during a workshop in April 2015 (see Appendix 1), and refined accordingly as new information and assumptions arose. Additional details on the wetland mitigation were provided by Chris Tanner of NIWA (see Appendix 2). 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 are outlined in Table 8.

The costs are converted to an annual figure so that they can be directly comparable to 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%. 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 8: Mitigation cost and effectiveness assumptions

	Mitigation Option	Eligible Land Uses	Max coverage	Cost Component			Mitigation Effectiveness (% from baseline)		
				Initial Capital	Maintenance	Opportunity	Landmass Erosion	Bank Erosion	*E. coli**
1	Farm Plan	Pasture	all farms	Plan: $5000/farm up to 100 ha + $10/ha for each additional ha Implementation: $250/ha	None	None, as plan assumed to identify options where benefits offset production losses	70%	0%	0%
2	Fencing	Pasture	all permanent streams	S&B: $35/m, including materials, construction, and reticulation; Dairy: $7.50/m	None	None	0%	80%	60%
3	Retention Bund/wetland combo	All, including native and urban	1 per 20 ha	$6100/system, including planting and fencing	$6/system/yr, $2000/system for sediment clearing in year 25	40% of farm income in occupied area	70%	0%	50%
4	Sedimentation pond/wetland combo	All, including native and urban	1 per 20 ha	$6000/system, including planting and fencing	$15/system/yr	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/system, including planting and fencing	$300/system/yr	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– 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%

* Assumed to have same effect on median and 95th percentile concentrations

Each mitigation option has the potential to have different impacts based on the size, location, and net revenue of the farm (Figure 11). 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 only needs to fence a short length of stream would likely face higher costs for constructing a wetland as it could take some land out of production.

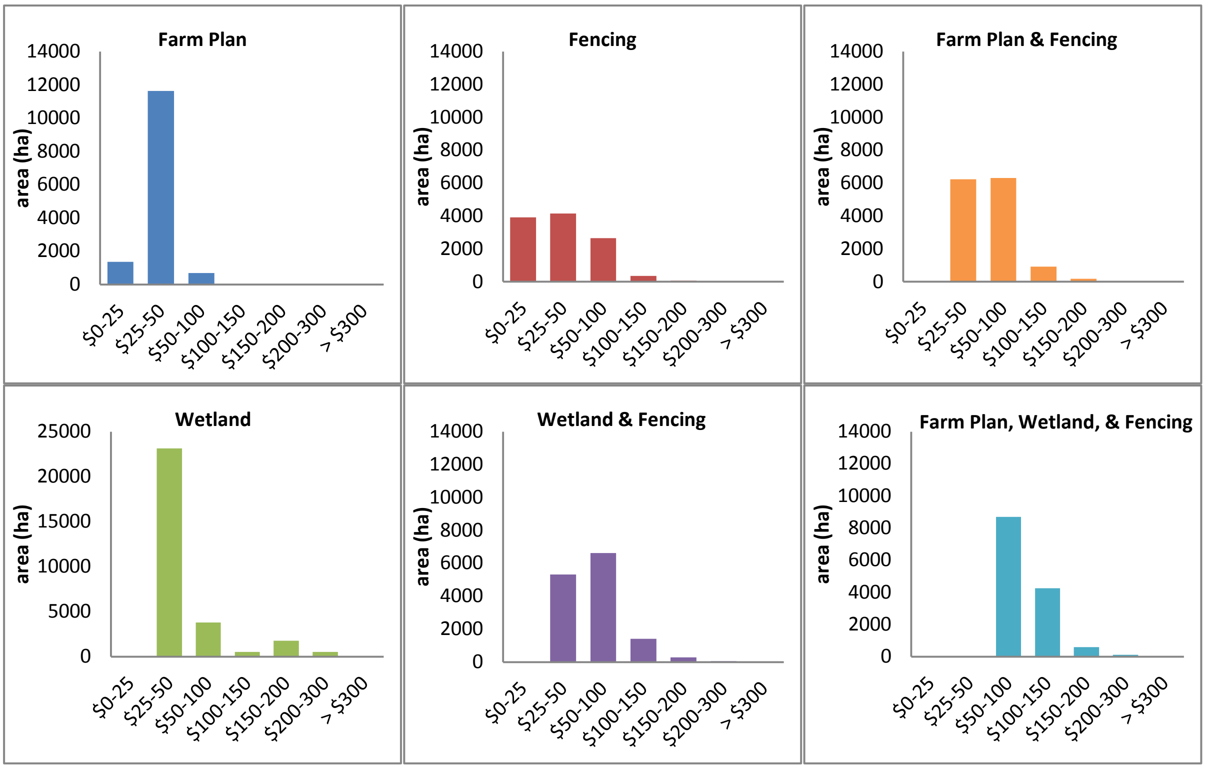


Figure 11: Annual mitigation costs ($/ha) for Whangarei Harbour Catchment landowners, by area (ha).

3 Scenarios

NRC, with input from MPI, has specified a range of mitigation scenarios to be analysed (Table 9). 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 target or decreasing *E. coli* loads and concentrations in key sites to achieve primary or secondary contact 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 but then allowing landowners to collectively select the set of mitigation options that will meet the target.

Table 9: 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
	Management Actions		
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/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
	Harbour Sediment Load Reduction below the baseline		
Harbour Sed 20%	20% reduction in total annual sediment to each depositional basin	20%	n/a
Harbour Sed 40%	40% reduction in total annual sediment to each depositional basin	40%	n/a
Harbour Sed 60%	60% reduction in total annual sediment to each depositional basin	60%	n/a
	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%
	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/100 mL
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

4 Baseline

NZFARM must establish a baseline for the WHC before conducting any scenario analysis. Here we specify that the distribution of enterprise area in each of the model's 700-plus sub-catchments match 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*, Palliser et al. (2015) calibrated the model to empirical data in Northland, which implicitly accounts 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 or how effective that fencing is, we opted not to incorporate this mitigation into the NZFARM baseline.[12] Thus, the NZFARM *E. coli* mitigation figures may be an overestimate of the actual reduction that could occur under the different model scenarios.

A summary of the key economic and environmental outputs is listed in Table 10. Total net farm income from land-based operations with the current land use mix is estimated at $16.6 million/yr or $548/ha for all land and $964/ha for land that is currently earning revenue from farming and forestry. Total sediment load is almost 31 400 tonnes, of which more than 85% comes from landmass erosion. This is about 30% of the total sediment deposited into the Whangarei Harbour. The total stream and harbour *E. coli* loads are estimated to be 84 and 293 peta *E. coli*/yr, respectively.[13]

Table 10: 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 &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
Hort&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

[11] In reality, some 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.

[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.

5 Scenario Analysis

This section reports the economic and environmental impacts of the nine sediment and *E. coli* reduction policy scenario described in Section 3 of this report. The key results reported for each policy scenario include net farm revenue, total annual cost, landmass and streambank sediment loads, average annual harbour sediment deposition rates (AASR), and stream and harbour *E. coli* loads. We also report the policy scenario impact on four freshwater sediment attributes and the two *E. coli*-based recreation attributes at the 'nodes of importance', where applicable. The estimates in this section compare the 'no policy' baseline to 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 2. All values are listed as mean annual figures.

A series of maps showing the spatial distribution of the key findings for each policy scenario is presented in Appendix 4. We also conducted a sensitivity analysis 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 5.

5.1 Catchment-wide Results

The total estimated impacts for the entire WHC are listed in Table 11. The table indicates that the impacts vary widely across scenarios. More insight on each scenario is provided in the next section.

[14] For this analysis, we assume that the policy is fully implemented over a relatively long timeframe of 10 years or more to allow landowners adequate time to adopt new mitigation practices

Table 11: Key model scenario estimates, 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	26883	4472	31355	19968	84.0	292.7
Afforest - All	$0.0	$16.63	13437	2463	15901	10175	22.5	75.8
Afforest - Pasture	$4.6	$12.04	16436	2643	19079	11454	36.7	177.6
Current Fencing	$16.5	$0.11	26883	3995	30878	19689	69.3	233.6
Current Farm Plan	$16.6	$0.03	26495	4472	30967	19715	84.0	292.7
All Wetlands	$15.2	$1.47	7866	4472	12338	7928	43.3	149.7
All Farm Plan	$16.3	$0.35	18429	4472	22901	14731	84.0	292.7
Fence All Streams	$16.2	$0.44	26883	2845	29728	18988	39.8	182.5
Max Mitigation	$14.7	$1.92	7866	2845	10711	6948	32.3	122.1
Harbour Sed 20%	$16.6	$0.04	20705	4357	25062	15975	74.2	224.2
Harbour Sed 40%	$16.4	$0.19	14680	4303	18983	11981	71.3	224.1
Harbour Sed 60%	$16.0	$0.60	9229	3548	12777	7967	47.8	189.7
E. coli 20%	$16.4	$0.19	25366	4077	29443	18751	67.2	234.2
E. coli 40%	$16.2	$0.42	23151	3621	26772	17031	50.4	175.6
E. coli 60%	$15.9	$0.76	20836	2980	23816	15132	33.6	117.1
Second Contact 'B'	$16.6	$0.02	26779	4254	31033	19770	71.1	292.7
Second Contact 'A'	$16.3	$0.31	24017	3770	27787	17754	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%
Max Mitigation	–12%	$1.92	–71%	–36%	–66%	–65%	–62%	–58%
Harbour Sed 20%	–0.3%	$0.04	–23%	–3%	–20%	–20%	–12%	–23%
Harbour Sed 40%	–1%	$0.19	–45%	–4%	–39%	–40%	–15%	–23%
Harbour Sed 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%

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

The distribution of mitigation practices is quite varied (Figure 12). For the practice-based scenarios, the mitigation is prescribed. For the outcome-based scenarios, mitigation is selected within NZFARM to achieve the specified target 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*.

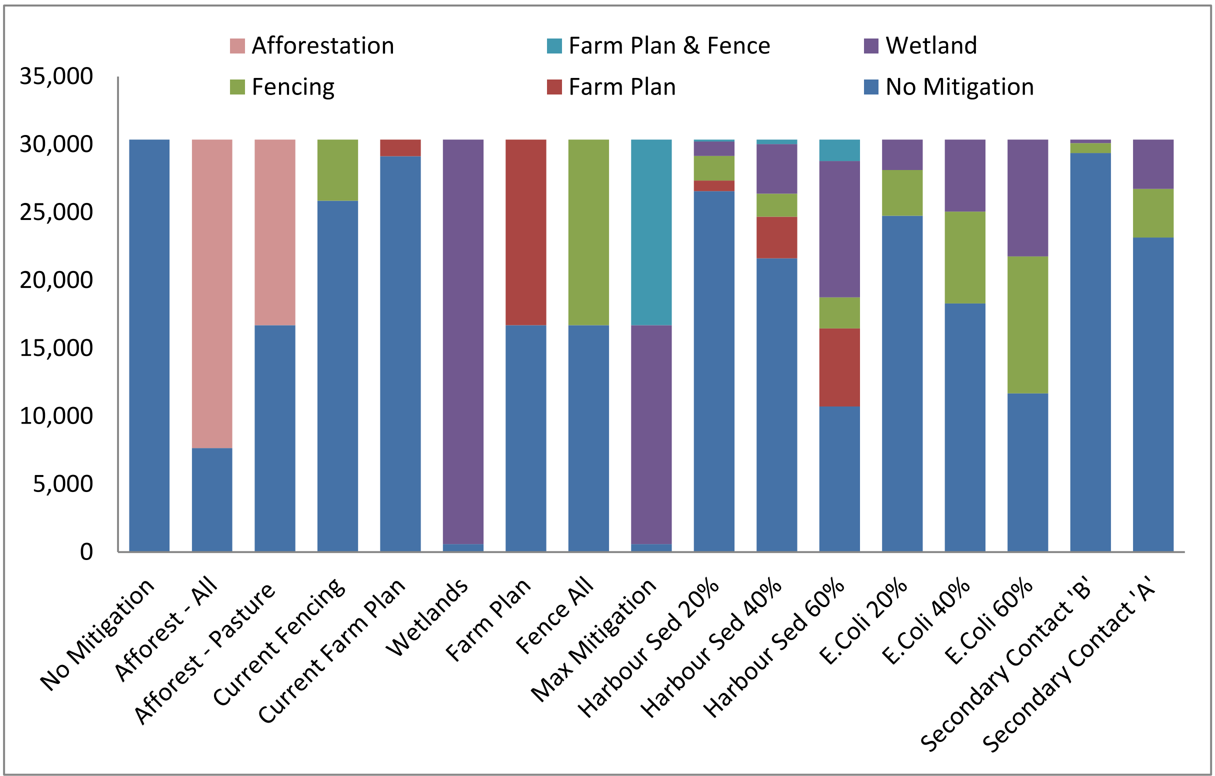


Figure 12: Area (ha) of implemented mitigation option by scenario.

The total costs for the non-afforestation scenarios range from $20,000/yr for achieving the secondary contact target, to about $1.9 million/yr for implementing the maximum amount of mitigation on all land in the catchment (Figure 13). Sheep & beef farms face the largest total and per hectare costs for nearly all scenarios. This is to be expected as this enterprise comprises the largest area of productive land and pasture in the catchment, is often located on land with high erosion rates, and have the greatest length of streams running through them. Note that the total costs for scenarios that include fencing as a mitigation options may be overstated by as much as $107,000/yr as some dairy and sheep & beef farmers have already fenced some or all of their streams (see current fencing scenario).

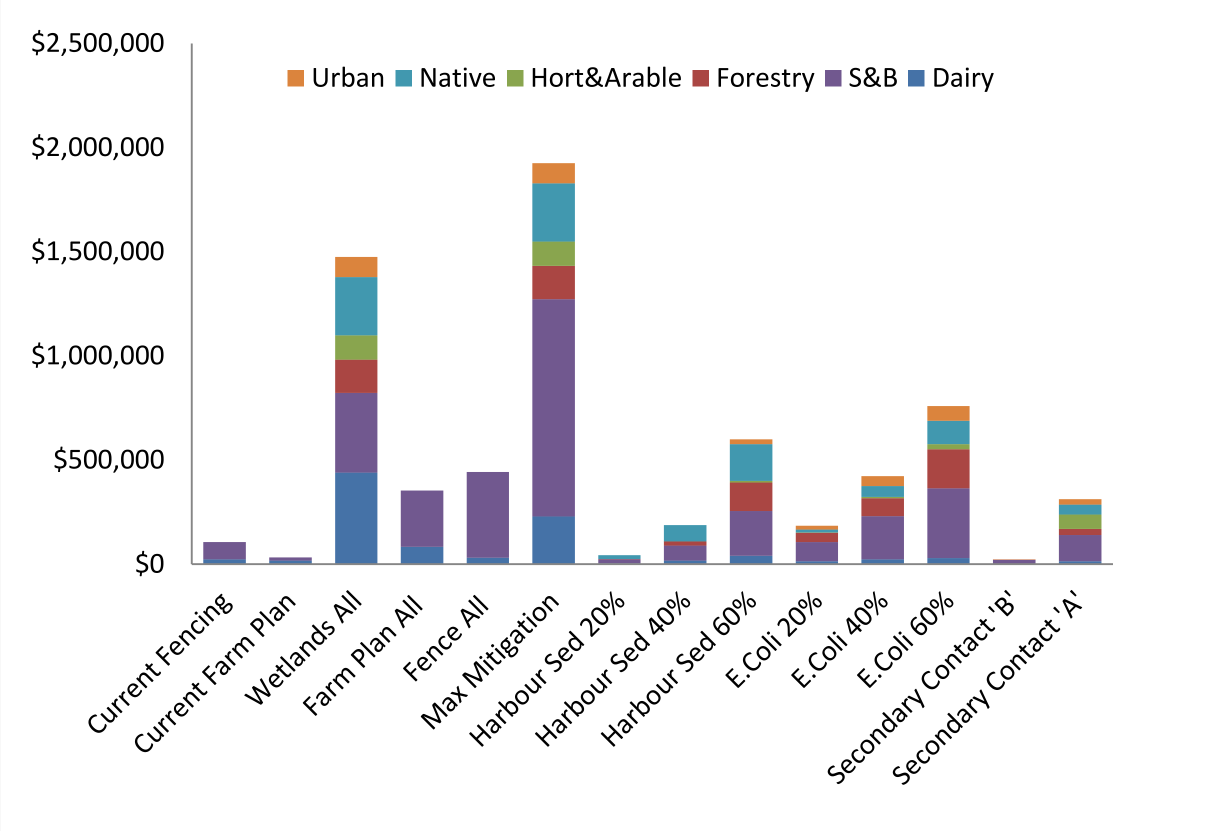


Figure 13: Total annual cost ($/yr), by land uses.

The mean annual mitigation costs figures for each scenario are broken out into per hectare values in Table 12. 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.

Table 12: Mean annual mitigation cost ($/ha/yr)*

Scenario	Dairy	Sheep & Beef	Forestry	Hort & 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
Max Mitigation	$71	$100	$52	$239	$29	$34	$63	$93
Harbour Sed 20%	$2	$2	$0	$0	$2	$0	$1	$2
Harbour Sed 40%	$6	$7	$6	$0	$8	$0	$6	$7
Harbour Sed 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

* Estimated as total mitigation cost divided by total area for each land use

The modelled scenarios estimate a wide-range of impacts to not only total sediment (3–65%), 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 14). 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.

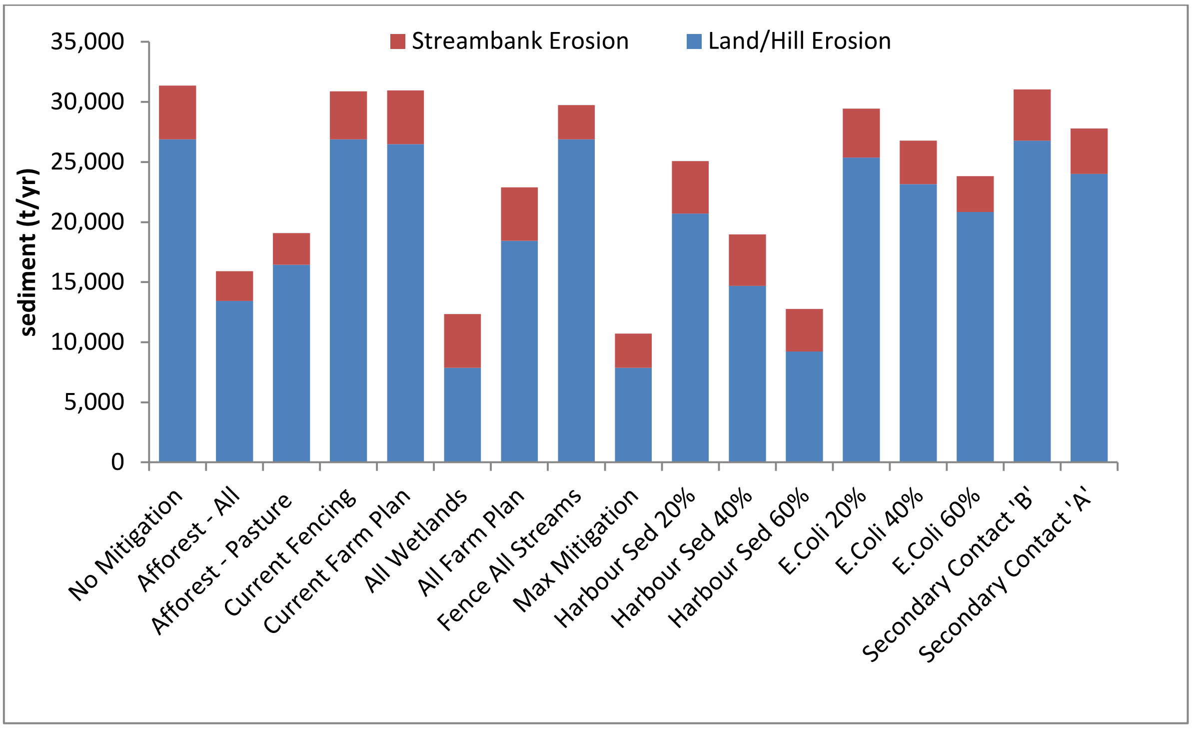


Figure 14: Catchment sources of total sediment (t/yr) by scenarios.

5.2 Scenario-specific findings

This section presents key findings for each set of modelled scenarios. While we provide some estimates here of the spatial impacts for most of the modelled scenarios, additional outputs are provided in Appendix 4.

5.2.1 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. NZFARM estimates that total sediment could be reduced by as much as 49%, while the total *E. coli* loads in the streams and reaching the harbour could be reduced by 73% and 74%, 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 5.3).

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

5.2.2 Current fencing

The current fencing option assumed that 75% of dairy and 20% of sheep, beef, and deer farms have already fenced waterways. We estimate that this option has some effect on reducing streambank erosion (11%) and *E. coli* loads (about 20%) relative to a no-mitigation baseline. As streambank erosion is only about 15% of total erosion in the catchment and fencing is assumed to have no impact on landmass erosion, total erosion is only estimated to be reduced by 2%. The total cost of the current fencing along pastoral streams is estimated to be $107,000 per annum, or about $8/ha/yr. Figure 15 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 impact on some key 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 (e.g. some farms have 100% of their streams fenced) on specific farms.

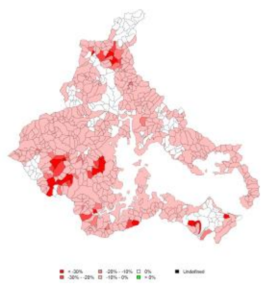
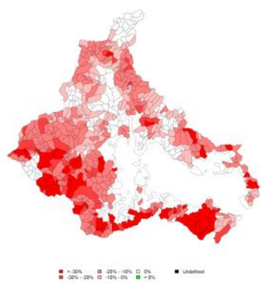
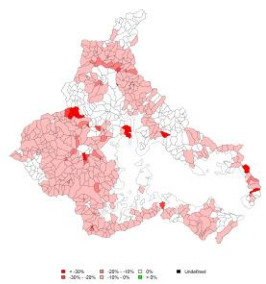
Total Sediment	Stream *E. coli*	Net Farm Revenue
		
< -30% -30% - -20% -20% - -10% -10% - 0% 0%		

Figure 15: Spatial impacts of current fencing scenario (% change from baseline)

5.2.3 Current farm plan

The current farm plan option assumed that just 1240 ha of farm plans that have been implemented by the NRC on pastoral farms are mature and fully effective (Figure 16). Farm plans are only assumed to affect landmass erosion, which is estimated to be reduced by 1% 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 the WHSES. The total cost of the current farm plans, which consist of the cost to prepare and implement the plan, is estimated to be $32,000 per annum, or about $26/ha/yr on the area where they have been implemented.

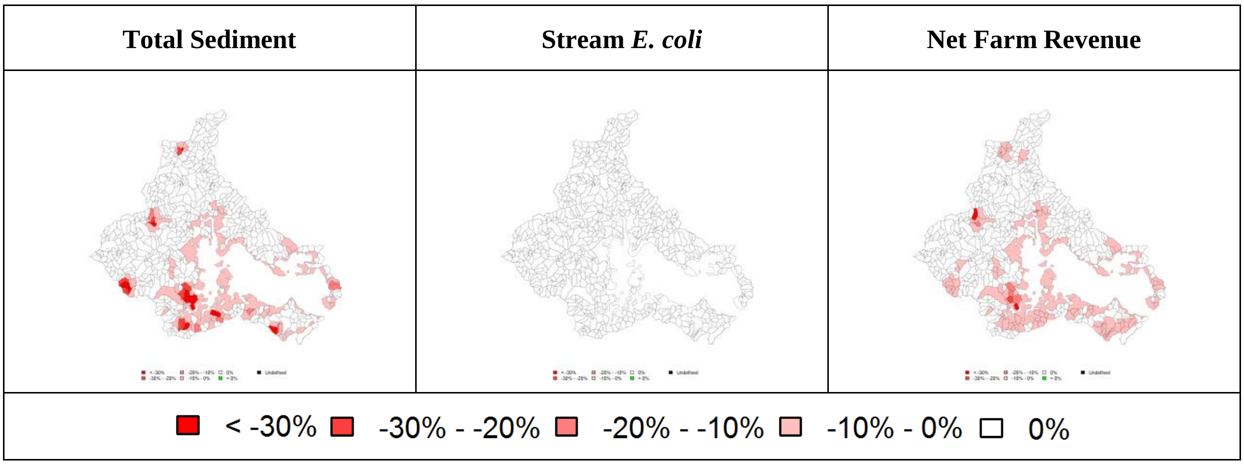


Figure 16: Spatial impacts of current farm plan scenario (% change from baseline)

5.2.4 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 50% relative to the baseline (Figure 17). 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). As Figure 17 indicates where fencing is likely to be most effective, this 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%), so although fencing all streams adjacent to pasture results in a 36% reduction in streambank erosion, that equates to just a 5% reduction in total erosion. Thus, more mitigation may have to be carried out in the WHC to achieve significant improvements in sediment-related attributes.

The total cost of fencing all streams in the catchment is $443,000/yr. This equates to an average of $32/ha/year for pastoral farms.

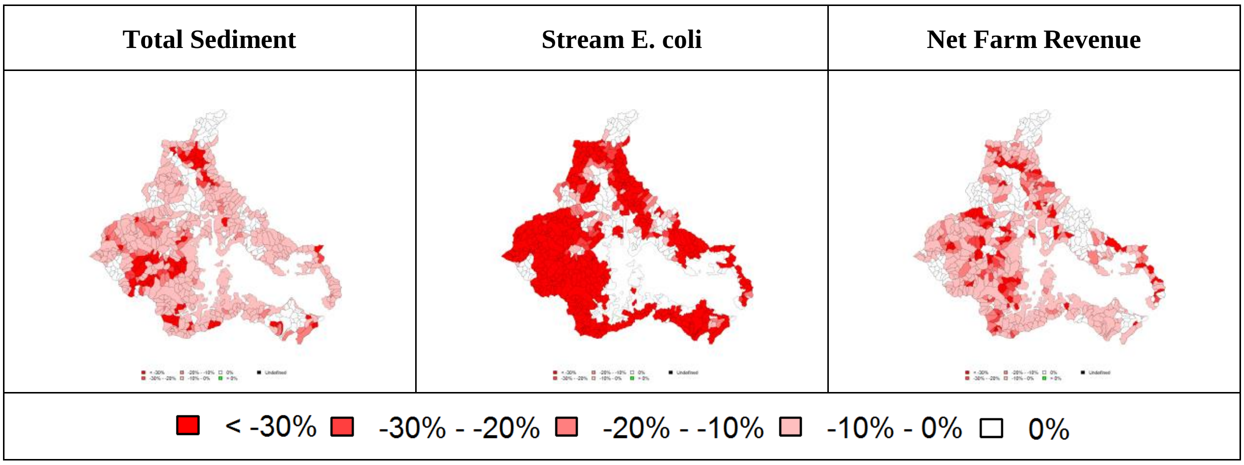


Figure 17: Spatial impacts of fence all pastoral streams scenario (% change from baseline)

5.2.5 Farm Plans on all pasture

Farm plans are assumed to only mitigate landmass sediment from pastoral enterprises but not other land uses. It also is assumed to have no effect on streambank sediment or *E. coli*. As pasture is just 46% 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. NZFARM estimates that implementing farm plans on all pasture results in a 31% reduction in landmass erosion and a 27% reduction in total sediment in the catchment (Figure 18).

Implementing farm plans across all pastoral farms in the catchment can reduce harbour sediment by 26% relative to the baseline, and thus has some measurable impacts 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 as the land surrounding these nodes are primarily native forest, scrub, and/or or urban. This suggests farm plans need to be implemented with wetlands to produce an improvement in some freshwater sediment attributes at the WHC's 'nodes of importance'.

The total cost of implementing farm plans on all pastoral land in the catchment is $354,000/yr. This equates to an average of $26/ha/year for all pastoral farms.

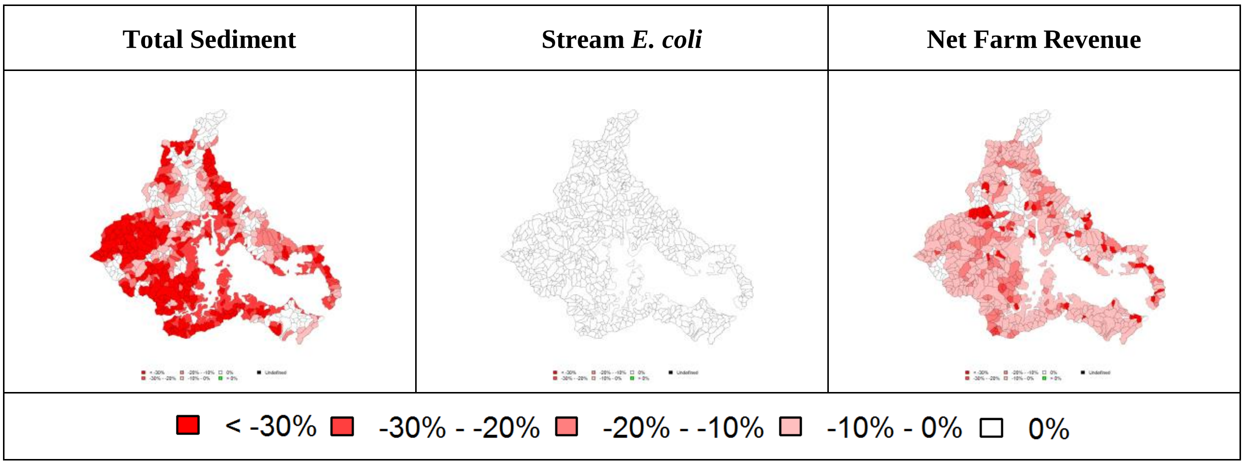


Figure 18: Spatial impacts of farm plans on all pasture land scenario (% change from baseline)

5.2.6 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 as it is the only mitigation that can be applied to all land uses (Figure 19). As a result, total sediment is estimated to be reduced by 61% while stream and harbour *E. coli* are estimated to be reduced by nearly 50%. 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 (e.g. max mitigation scenario).

Wetland-based mitigation is estimated to have a noticeable effect on the entire range of modelled attributes. We estimate that the *E. coli* concentrations target for the A-state secondary contact recreation, is met in 5 nodes of importance, while at least the B-state is achieved in all but 1 node. In terms of harbour sediment, an AASR of 1.9 mm/yr 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, then large changes in sediment and *E. coli* related attributes can be achieved.

We estimated that implementing the maximum amount of wetland mitigation in the WHC results in costs of $1.47 million/yr, or an average of $49/ha/yr. 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 for taking highly profitable land out of production. Coordination and cost constraints could also limit the level of uptake in reality. Note that in Figure 19, many of the sub-catchments are estimated to have high losses in net farm revenues (i.e. 30% 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]

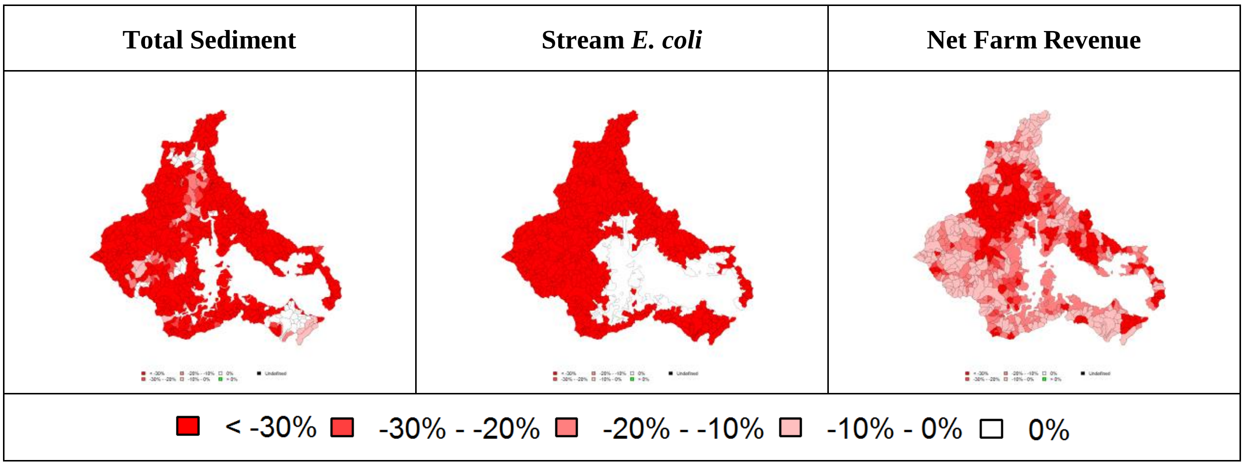


Figure 19: Spatial impacts of wetland mitigation on all land scenario (% change from baseline)

5.2.7 Max Mitigation (Farm Plans, Fencing, & 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%) and *E. coli* loads (58–62%), although at a relatively high cost. The change in the landmass erosion is the same as the farm plan scenario,

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

but adding the fencing reduces streambank erosion as well, thus reducing total erosion by more than either ‘standalone’ mitigation option (Figure 20).

We estimate that the *E. coli* concentrations target for the A-state secondary contact recreation, is met in 6 nodes of importance, while the B-state is met in the other 5 nodes. In addition, an AASR rate of 1.9 mm/yr or less is achieved in all four 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/yr. This equates to an average of $63/ha/yr.

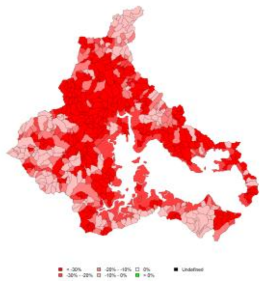
Total Sediment	**Stream *E. coli***	**Net Farm Revenue**
		
■ < -30% ■ -30% - -20% ■ -20% - -10% □ -10% - 0% □ 0%		

Figure 20: Spatial impacts of maximum mitigation on all land scenario (% change from baseline)

5.2.8 Harbour sediment deposition reduction policies

These scenarios estimate the impacts of achieving a 20, 40, and 60% 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 that there is minimal change in certain areas of the catchment (Figure 21). 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 (23–66%) than streambank sediment (3–21%), regardless of the reduction target, highlighting that fencing streams with the sole intent to reduce erosion may be a less cost-effective option.

We estimate that a 20% reduction target results in reducing basin-level AASR rates between 10 and 19% relative to the baseline, while a 60% reduction target is estimated to reduce the AASR by 30–57%. The 20% 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% 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, an unintended co-benefit. As a result, stream *E. coli* loads could be reduced by 12–43% and harbour *E. coli* loads by 23–35%. The 60% reduction target also leads to 8 of the 11 sites achieving at least the 'B' state for secondary contact recreation, 2 more sites than the baseline.

The total cost of these scenarios is estimated to range from $43,000/yr for the 20% target to about $600,000/yr for the 60% reduction scenario. These figures equate to $1/ha/yr and $20/ha/yr, respectively.

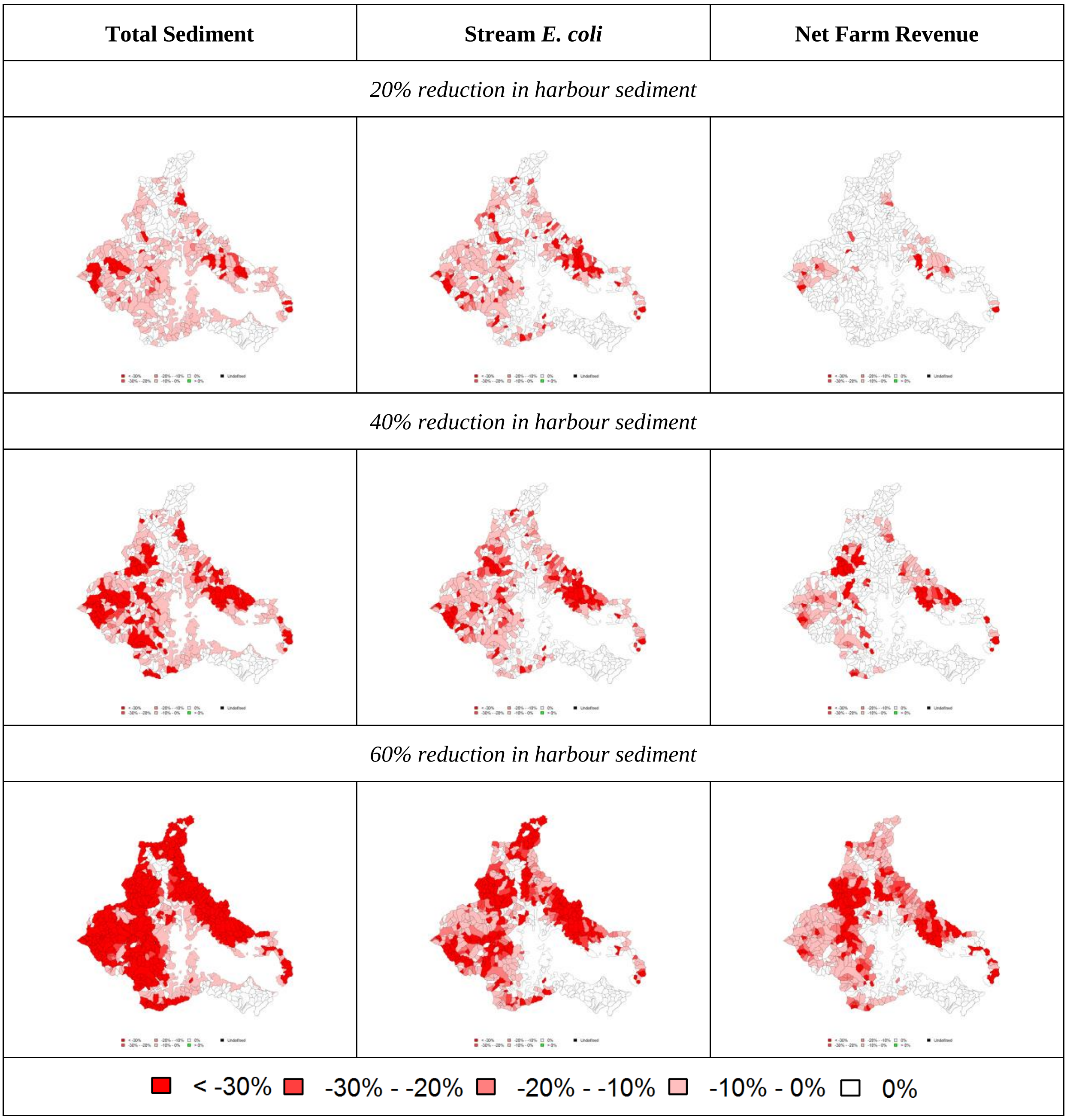


Figure 21: Spatial impacts of harbour sediment reduction scenarios (% change from baseline)

5.2.9 *E. coli* load reduction policies

The scenarios that reduce *E. coli* loads by between 20 and 60% in all REC2 sub-catchments are estimated to lead to reductions in not just *E. coli* loads (20–60%), but total sediment as well (6–24%). Thus, as with the scenarios that only focus on reducing sediment, *E. coli*-specific scenarios can create co-benefits (Figure 22). 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% reduction scenario. However, the 60% reduction scenario results in 6 nodes achieving the A-state of 260 cfu/mL and 4 of the 5 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/yr for the 20% target to about $760,000/yr for the 60% reduction scenario. These figures equate to about $6/ha/yr and $25/ha/yr, respectively.

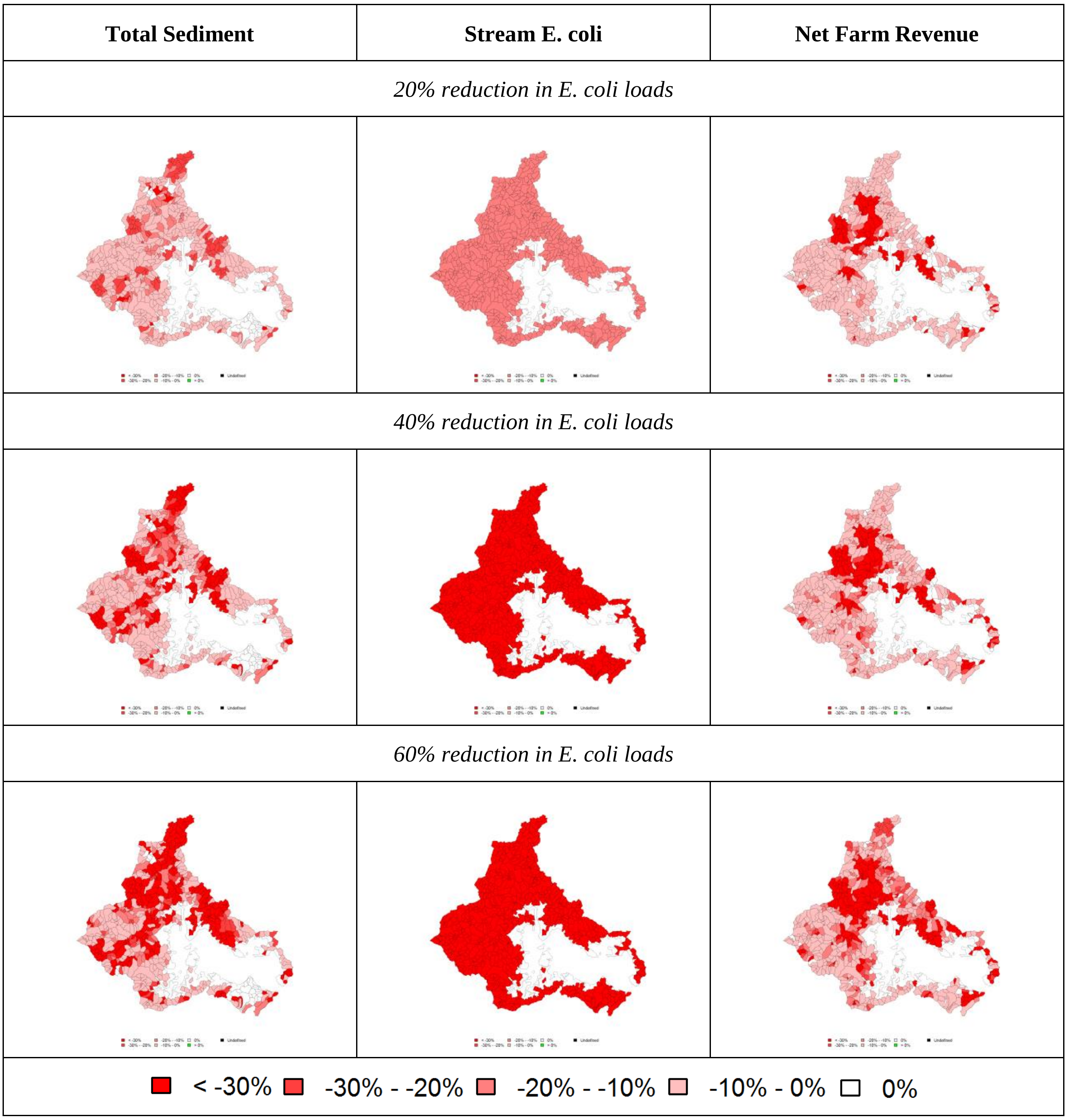


Figure 22: Spatial impacts of *E. coli* load reduction scenarios (% change from baseline)

5.2.10 *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 recreations attribute states at the WHC'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 15–30% and total sediment loads by 1–11%. There is no change in harbour *E. coli* loads as all of the nodes are located towards the middle of the catchment (Figure 23).

The model estimated that implementing practices above each of the nodes can lead to reductions in *E. coli* concentration that allow all of these sites in the catchment to reach at least the 'B' state of 540 cfu/100 mL. However, we also found that the 'A' state concentration of 260 cfu/100 mL could not be achieved at 4 of the 11 sites, although all these nodes had median concentrations of less than 330 cfu/100 mL. This suggests additional research may be necessary to find even more effective mitigation options than those included in this study (i.e. practices that reduce *E. coli* by more than 60%) in order 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 annum. These figures equate to about $1/ha/yr and $10/ha/yr, respectively, if the costs are spread across all 30 000 ha in the catchment. However, if only the area where mitigation is actually implemented is taken into account, the respective costs are $22/ha/yr and $43/ha/yr.

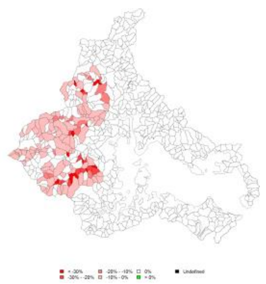
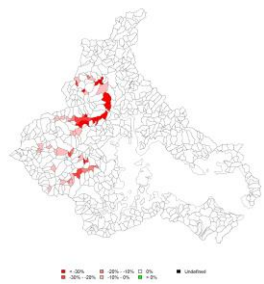
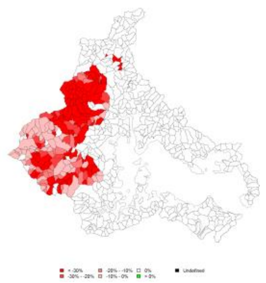
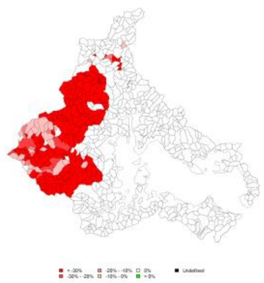
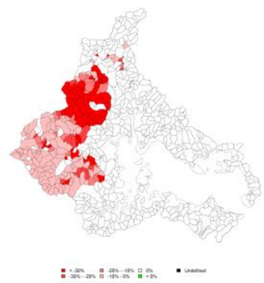
Total Sediment	**Stream E. coli**	**Net Farm Revenue**
'B' secondary contact recreation attribute state		
		
'A' secondary contact recreation attribute state		
		
< -30% -30% - -20% -20% - -10% -10% - 0% 0%		

Figure 23: Spatial impacts of secondary contact recreation attribute state scenarios (% change from baseline)

5.3 Attribute Estimates

5.3.1 Freshwater sediment

There is a wide range of impacts 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 13, while suspended sediment concentration and embeddedness are presented in Table 14.

Impacts in the Hatea catchment are minimal unless there is a large amount of wetland-based mitigation put in place. This is because the site is largely comprised of native and urban land. However, as landmass erosion only constitutes about 37% 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%. 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 Waiairohia 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% urban use with minimal landmass erosion in the baseline and limited mitigation potential (i.e. only wetlands). As with the Hatea, streambank mitigation for urban areas will be required in order to see large reductions in sediment at this site.

Attributes in the Otaika sub-catchment are estimated to have the largest improvement as 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% and 35%, respectively, if maximum mitigation were put in place. NZFARM 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 and 40% estimate no change in load as there is lower cost mitigation that is more effective for achieving the target elsewhere in the WHC. Thus, additional policies may have to be put in place to ensure site-specific attribute objectives are achieved.

Table 13: Water clarity and euphotic depth at 3 WHC sites

Scenario	Hatea River		Waiairohia		Otaika	
	Value	***% Change***	***Value***	***% Change***	***Value***	***% Change***
			Water Clarity (m)			
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%
Max Mitigation	2.29	39%	1.88	6%	1.89	77%
Harbour Sed 20%	1.65	0%	1.77	0%	1.07	0%
Harbour Sed 40%	1.65	0%	1.77	0%	1.07	0%
Harbour Sed 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 (m)			
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%
Max Mitigation	2.64	19%	2.52	4%	2.38	35%
Harbour Sed 20%	2.22	0%	2.42	0%	1.76	0%
Harbour Sed 40%	2.22	0%	2.42	0%	1.76	0%
Harbour Sed 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 14: Suspended sediment concentration and embeddedness at 3 WHC sites

Scenario	**Hatea River**		**Waiairohia**		**Otaika**	
	Value	***% Change***	***Value***	***% Change***	***Value***	***% Change***
			Suspended Sediment (gm/m3)			
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%
Max Mitigation	2.66	–26%	3.32	–8%	2.36	-45%
Harbour Sed 20%	3.60	0%	3.60	0%	4.30	0%
Harbour Sed 40%	3.60	0%	3.60	0%	4.30	0%
Harbour Sed 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 (gm of trapped sediment per m3 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
Max Mitigation	n/a	n/a	113.1	–8%	n/a	n/a
Harbour Sed 20%	n/a	n/a	122.6	0%	n/a	n/a
Harbour Sed 40%	n/a	n/a	122.6	0%	n/a	n/a
Harbour Sed 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

5.3.2 Harbour/Estuary sediment

Nearly all scenarios result in a noticeable reduction in the average-annual sedimentation rate (AASR) in all of the four depositional basins (Figure 24), but impacts vary widely across the scenarios and basins. Green et al. (2015) suggested potential targets of 1, 2, and 3 mm/yr for each basin.

We estimate that the 3 mm/yr 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, however, 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-mm rate, as there is relatively little sediment deposition in that basin from marine sources, with most coming from land-based sources

The optimistic 1 mm/yr AASR target is only reached in the North Shore basin, but note that this basin also achieved that target in the baseline. This finding is not only a result of insufficient 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 20–60% reduction in sediment from land-based mitigation did not result in the same percent reduction in AASR for any of the basins.

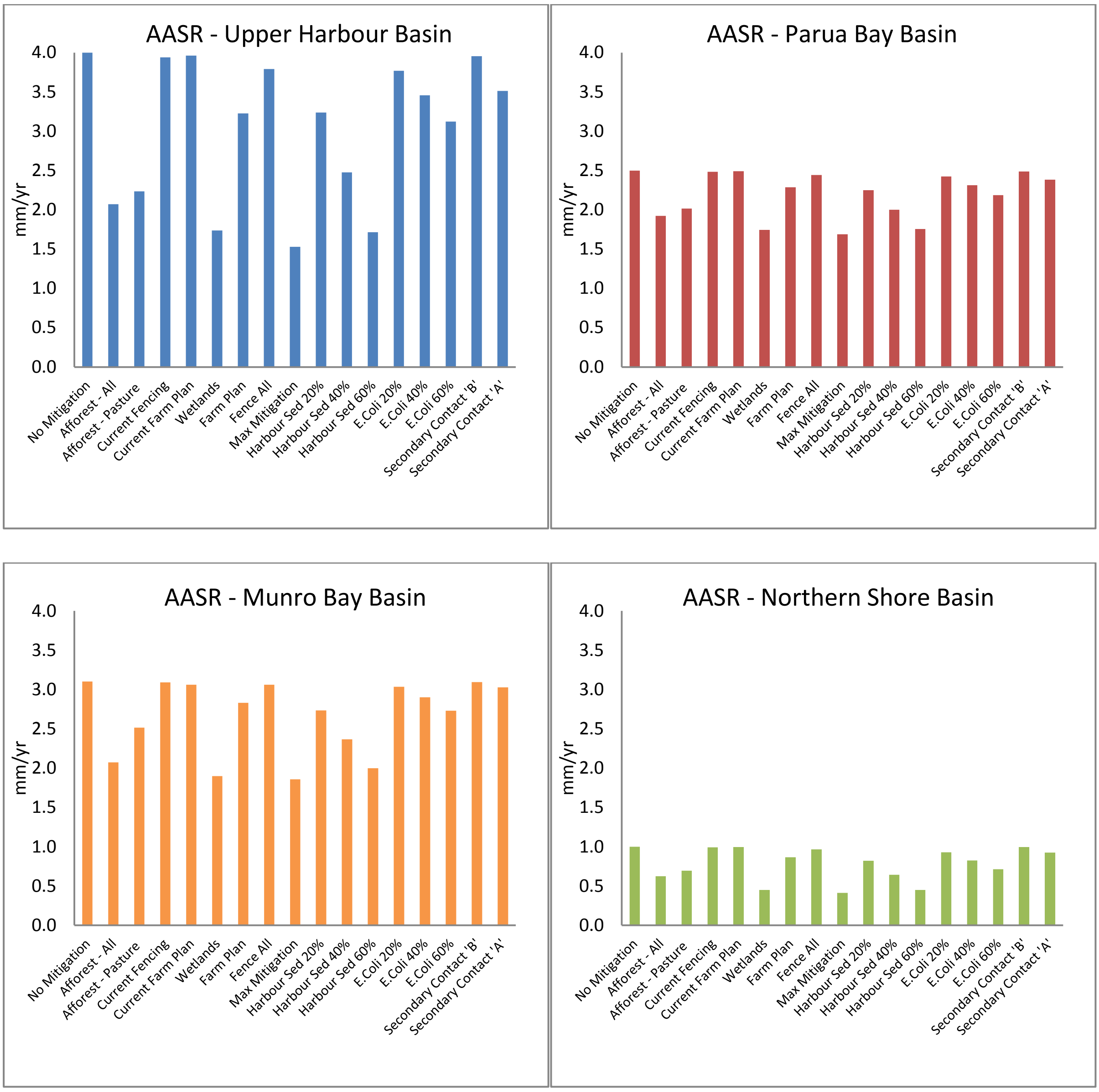


Figure 24: Average annual sediment rate (mm/yr) for 4 WHC depositional basins.

5.3.3 *E. coli* concentrations

E. coli concentration estimates for the median and 95th percentile are listed in Table 15. We find that implementing mitigation practices in the WHC led 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/mL, for secondary contact recreation. None of the modelled scenarios, even the case of full afforestation, results in all the nodes achieving the 'A' state of 260 cfu/mL. This is partly because many parts of the upper catchment are heavily forested and producing relatively low *E. coli* loads, even in the baseline case.

NZFARM 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/mL. 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. 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. Also, it is valuable to reflect on the way 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 15: Estimated *E. coli* concentrations (cfu/100 mL) for WHC's 11 nodes of importance

Scenario	Whangarei Falls	Waharohia @ confluence with Waiarohia and Waikahitea	Hatea @ Mair Park Foot Bridge	Raumanga just before it joins the Waiarohia	Waiarohia @ Second Ave	Kirikiri just before it joins the Raumanga	Raumanga @ Bernard Street	Raumanga Stream @ swimming pool below falls	Otaika @ Otaika Valley Raod	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	1354
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	1354
Wetlands	221	263	130	472	200	365	452	106	244	437	678
Farm Plan	439	525	259	942	399	722	903	211	484	871	1354
Fence All	216	419	127	540	304	491	436	83	135	234	280
Max Mitigation	165	236	97	371	176	307	335	74	156	278	409
Harbour Sed 20%	436	467	248	903	386	558	877	204	474	819	1325
Harbour Sed 40%	409	385	240	896	376	525	872	203	461	806	1188
Harbour Sed 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	1083
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	2003	3485	6306	12844	5421	9852	13164	3076	4378	7883	18470
Afforest – All	652	2541	1937	3089	2185	4360	2978	698	1207	2119	3111
Afforest – Pasture	919	2753	2863	8759	3896	4878	7541	1289	1331	2249	3154
Current Fencing	1771	3344	5596	11701	5163	9220	11739	2686	3459	6166	13379
Current Farm Plan	2003	3485	6306	12844	5421	9852	13164	3076	4378	7883	18470
Wetlands	1009	1743	3166	6431	2713	4977	6586	1539	2203	3955	9246
Farm Plan	2003	3485	6306	12844	5421	9852	13164	3076	4378	7883	18470
Fence All	986	2782	3086	7369	4130	6694	6357	1210	1218	2120	3814
Max Mitigation	754	1568	2361	5063	2391	4187	4885	1073	1413	2515	5582
Harbour Sed 20%	1990	3100	6049	12320	5242	7609	12780	2971	4290	7412	18075
Harbour Sed 40%	1865	2556	5837	12217	5103	7166	12712	2952	4166	7287	16197
Harbour Sed 60%	1187	1841	3771	10897	3222	5339	11328	2573	2237	3909	8765
E. coli 20%	1593	2788	5046	10253	4253	7731	10523	2474	3507	6310	14776
E. coli 40%	1184	2091	3770	7685	3224	5861	7877	1845	2635	4737	11082
E. coli 60%	792	1466	2526	5280	2279	4070	5412	1235	1767	3169	7388
Secondary Contact 'B'	2003	2724	6306	8584	3108	7365	7872	1672	3356	4884	7365
Secondary Contact 'A'	1187	1480	4919	4467	2229	3793	4034	839	1552	2352	3750
NPS-FM Attribute State	A (< 260)			B (260-540)			C (540-1000)			D (>1000)	

6 Model Limitations

NZFARM 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 (e.g. practice v. outcome-based targets), rather than for explicitly modelling the absolute impacts of a single policy scenario, and thus 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 NZFARM 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 WHC. Some of the modelling limitations from the WHSES include:

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 (e.g. 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 WHC that were parameterised based on their physical characteristics (e.g. land use capability, slope, etc.). 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. **Baseline conditions** – The NZFARM 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 5 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.

4. **Management practices** – The model only includes some 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 (e.g. change in farm profit) and effectiveness (e.g. 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.

5. **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 (e.g. 50% 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.

6. **Optimisation routine** – For this analysis, NZFARM 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 WHC. This is assumed to occur over a period of 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, and thus the actual effectiveness of the policy may be overstated.

7. **Regional economic impacts** – NZFARM does not account for the broader impacts of changes in land use and land management beyond the farm gate. The flow-on effects from some of the scenarios investigated in this report could produce some change in regional employment and GDP due to reductions in farm outputs for taking land out of production (e.g. in the case of afforestation with native bush or constructing wetlands). There could also be social and cultural impacts. The estimates produced by NZFARM provide just a subset of possible metrics that could be used to determine the 'best' option to manage sediment and *E. coli* at the catchment-level.

7 Summary and Conclusions

Northland Regional Council has identified that sediment and *E. coli* are key water quality challenges in the Northland region. As a result, the Council engaged in a joint venture with the Ministry for Primary Industries to undertake a sediment and *E. coli* study in the Whangarei Harbour catchment.

The objective of the study 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 analysis was carried out using a catchment economic model based on the New Zealand Forest and Agriculture Regional Model (NZFARM) framework. The model includes several management options for managing sediment and *E. coli* loads from land uses ranging from intensive pasture to native bush.

A range of mitigation scenarios were analysed. These included practice-based approaches such as fencing, farm plans and wetlands, and environmental outcome-based approaches that include reducing erosion to reach harbour sedimentation rate targets or decreasing *E. coli* concentrations in key sites to achieve primary or secondary contact recreation targets.

Two large afforestation scenarios were also modelled to establish the minimum feasible loads that could be achieved in the Whangarei Harbour catchment. This provided a benchmark from which to assess the other scenarios. Afforesting all land could reduce total sediment by as much as 49%, while total *E. coli* loads in streams and in the harbour could be reduced by 73% and 74%, respectively.

The study showed that Councils need to be realistic about the possible outcomes that can be achieved given current land use. The Whangarei Harbour catchment has a great deal of area classified as urban or native, which is managed differently than rural productive land uses such as dairy, sheep and beef, and forestry. Only 46% of the catchment is in pasture, so management options that only target pastoral enterprises may not be sufficient to achieve large reductions in environmental contaminants.

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

In considering each mitigation practice individually, constructing wetlands and sediment ponds is estimated to be the most effective option, as it is the only mitigation that can be applied to all land uses. Sediment loads are estimated to reduce by 61% and *E. coli* loads in streams by 48%. It is also the only mitigation option that has a positive impact on the sediment attributes of water clarity and euphotic depth in all 3 measured sites in the catchment. For example, constructing wetlands near the Otaika River improves water clarity at median flows by up to 77% and euphotic depth by 35%.

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

Fencing all pasture land has an effect on streambank erosion and *E. coli* from pasture, but no impact on landmass erosion (85% 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% relative to the baseline.

Implementing farm plans on pastoral farms are 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 WHSES, the average-annual sedimentation rate (AASR). Estimates varied widely across the four deposition basins though as they are all affected differently in terms of the amount of sediment that they receive annually from both land and marine sources. Thus, the suggested 'high' attribute state of 1 mm/yr may not be achievable for all harbour basins.

There was wide variation in impacts on the freshwater sediment attributes estimated at three sites in the catchment. Changes in sediment loads were estimated to have a noticeable impact at the Otaika river site as it is surrounded by a variety of pastoral and other land uses that could implement a range of mitigation practices. However, the other two sites were located in areas of the catchment mostly comprised of 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.

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/100 mL for secondary contact recreation (this is based on a median estimate). None of the modelled scenarios result in the catchment reaching the 'A' stage of 260 cfu/100 mL, with the exception of full afforestation.

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 minimum of 540 cfu/100 mL) 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.

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% reduction in sediment can also reduce *E. coli* loads in the catchment by 15–23%, while a policy that targets a 40% reduction in *E. coli* can reduce sediment by 15%. This suggests that mitigations that focus on simultaneously reducing both *E. coli* and sediment (e.g. wetlands) are likely to be the most cost-effective option for many landowners in the catchment. 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.

8 Acknowledgements

We would like thank the following for contributing to this report:

John Dymond of Landcare Research for providing land and streambank erosion estimates; Mal Green of NIWA for providing harbour sedimentation estimates; Chris Palliser of NIWA for providing stream and harbour *E. coli* estimates; Graeme Doole of University of Waikato for providing mitigation cost data and reviewing an earlier draft of the report; Darryl Jones and Ben Tait of Northland Regional Council for providing data and information; Jane White of the Ministry for Primary Industries for coordinating this research and providing data and information, and Darran Austin of the Ministry for Primary Industries for providing comments; Ton Snelder of the Ministry for the Environment for providing comments.

Appendix 1 – 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.

It is necessary to keep in mind that we are 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.
- We need to be able to clear these 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 we can think about improving 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 doesn’t 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 we need a much bigger wetland 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 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% 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 were 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.

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-m 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.

60% reduction in baseline (median) flows of microbes from streambank fencing. Of course, high rainfall and flooding will impact on the statistics; rather, achieving a 50% reduction.

There is likely to be a 65% reduction for the 95th percentile. A 3 m buffer might increase efficacy by 10%.

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

Reticulation cost is around 2–3 times the cost of fencing, along with ongoing maintenance costs, pumping, and installation. Implement these water supply costs on a per kilometre of stream length basis.

Northland Regional Council has good costs of fencing that we can attain. These costs are 50% for labour and 50% for materials.

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

Hill stabilisation options

SedNetNZ used to estimate hillside erosion.

We do not have detailed information regarding how to decompose and address the sediment arising from each farm.

Utilise farm plans that achieve a 70% reduction in sediment (once plan is implemented and mature) at a cost of $250/ha (Horizons).

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

We need to check whether this cost includes the option of full afforestation (ask Grant Cooper).

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.

Cost of farm plans will increase in 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. Focus on identifying the benefit associated with switching the farms that currently discharge to water to discharging onto land. This is present in the JEQ paper that focused on 95th percentile efficacy (Muirhead 2015) or the NZIER/Southland work done with CLUES that focused on median efficacy.

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 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%.

Reduces erosion by 80% when harvesting cycle is considered.

8.1.1 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 some 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 2 – Wetland mitigation assumptions

Table A.2.1: 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 @ one per 20 ha	>15 deg	80%	100%	70%	50%	one per 20 ha = 0.05 systems/ha	See 1 below
Sedimentation pond/wetland combination @ 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-ha sub-catchment (based on general assessment of relevant catchment sizes) and storage volume of 120 m^3/ha assuming riser outlet height of 1.8 m, area of 200 m^2/ha to give vol @ 1/3 of surface area (based on EBOP recommendations) so ~0.4 ha per 20 ha catchment = occupy ~2% of contributing catchment when full. Assume 5% of temporarily impounded area is permanent fenced off wetland area (i.e. 0.1% or 0.02 ha (or 200 m^2) /20ha catchment)

2. Expected performance based on modelling studies for Waituna (Tanner et al. 2013) and median performance for International Stormwater 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 ha for partially excavated wetlands utilising the natural contour of the land. This has been converted this to a cost per ha 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% of catchment (1 ha wetland per 400 ha contributing catchment) based on our experience and recent data from Swedish wetlands (Johannesson et al. 2015). There is evidence that smaller wetlands 0.1 % or less can provide significant sediment retention, (e.g. Baskerud and others 2002–5 in Norway and Ockenden et al. 2012 in the UK); 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 A.2.2: Cost of wetland construction (all costs assume activities are permitted and do not incur a resource consent charges)

Mitigation	Construction cost	Planting cost	Fencing cost	Land area occupied cost	Maintenance cost	Ancillary benefits/costs	Notes and References
Retention Bund/wetland combination	$5000 each = $250/ha of land mitigated	0.02 ha wetland planting per system @ $20,000/ha = $400/system =$20/ha of land mitigated	0.02 ha fenced per system, assume need 80-m fencing /system @ $6/m installed and materials = $480 plus gate and hinges @$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 per ha of land mitigated/ yr, plus pipework replacement and some sediment removal @ $2000 after 25 yrs	Only small area taken out of production other areas are temporarily flooded (<3 d). 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 @ 0.25% of catchment area*	0.25% of 20 ha catchment = 0.05 ha = 500 m2 @ $120,000/ha of planting, a gate and fencing = $6000/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 per ha of land mitigated per yr	50% reduction in profit loss due to benefits	
Mid-catchment constructed wetland intercepting 2nd-3rd order streamflow	$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 per ha of land mitigated per yr	Removal of N and P. 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 ha sub-catchment (based on general assessment of relevant catchment sizes) and storage volume of 120 m^3/ha assuming riser outlet height of 1.8 m, area of 200m^2/ha to give vol @ 1/3 of surface area (based on EBOP recommendations) so ~0.4 ha per 20 ha catchment = occupy ~2% of contributing catchment when full. Assume 5% of temporarily impounded area is permanent fenced off wetland area (i.e. 0.1% or 0.02 ha (or 200 m^2) /20 ha catchment)

Appendix 3 – Key baseline estimates by sub-catchment

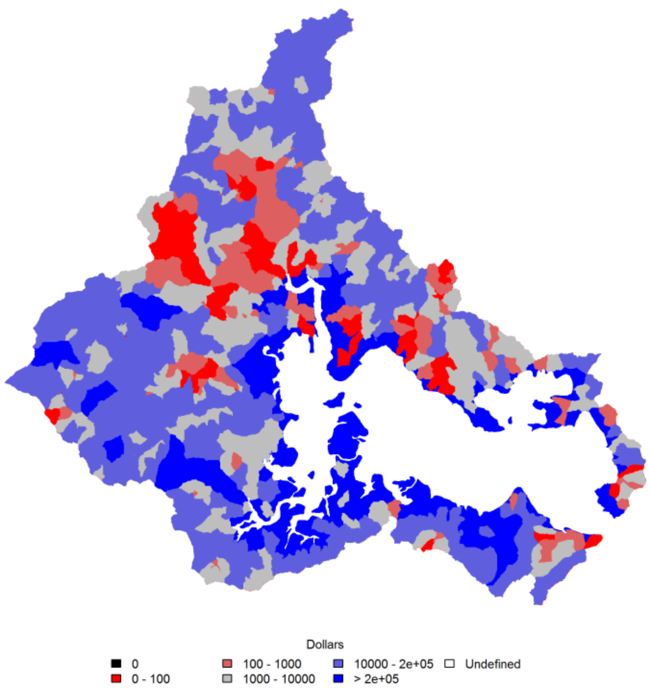


Figure A.3.1: Total net farm revenue ($/yr)

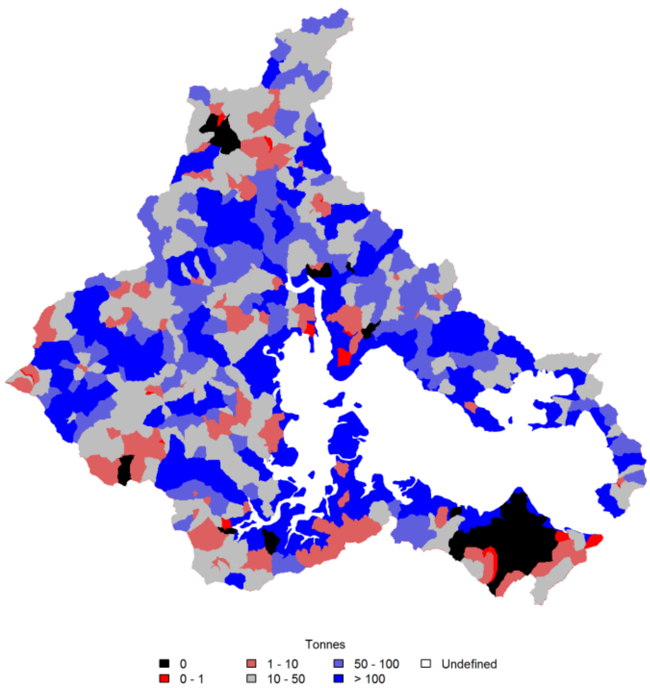


Figure A.3.2: Total sediment (tonnes/yr)

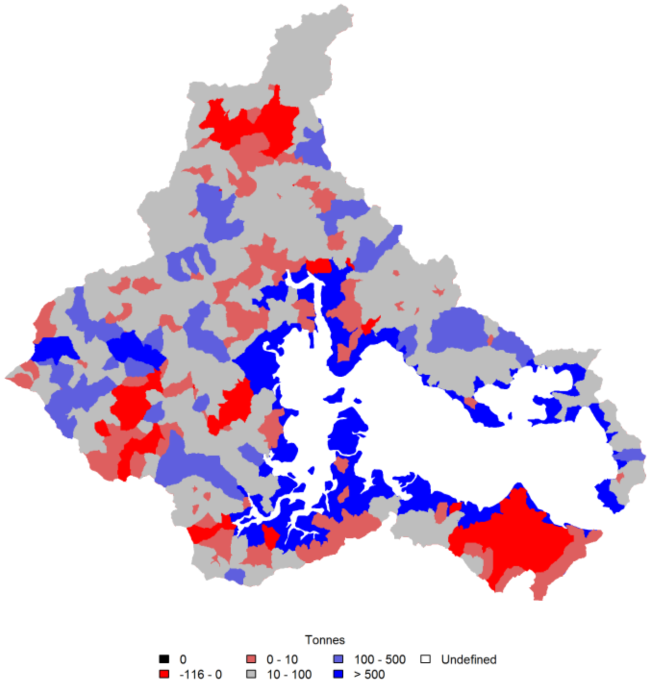


Figure A.3.3: Hill/landmass sediment (tonnes/yr)

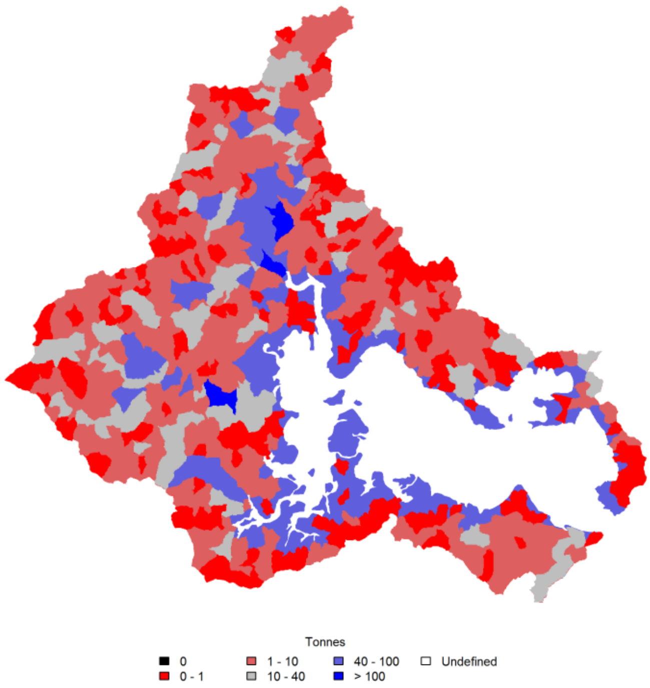


Figure A.3.4: Streambank sediment (tonnes/yr)

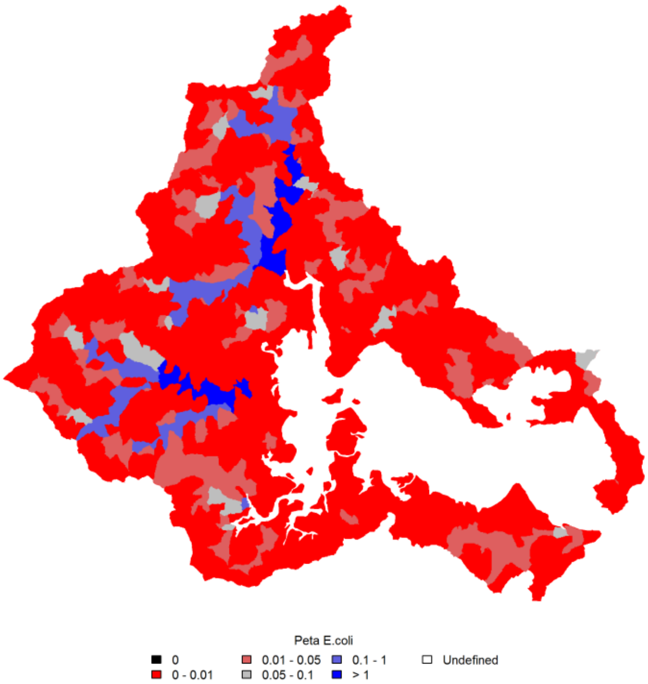


Figure A.3.5: Stream *E. coli* loads (peta *E. coli*/yr)

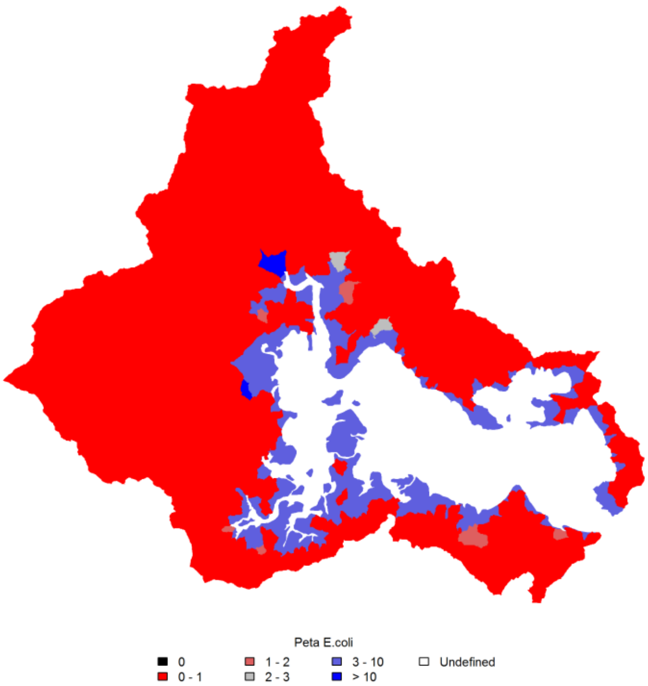


Figure A.3.6: Harbour *E. coli* loads (peta *E. coli*/yr)

Appendix 4 – Key scenario estimates by sub-catchment

We have created spatially explicit maps for each of the policy scenarios for six key outputs: net revenue, landmass sediment, streambank sediment, and 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 NZFARM and overlaying them onto the baseline land use map.

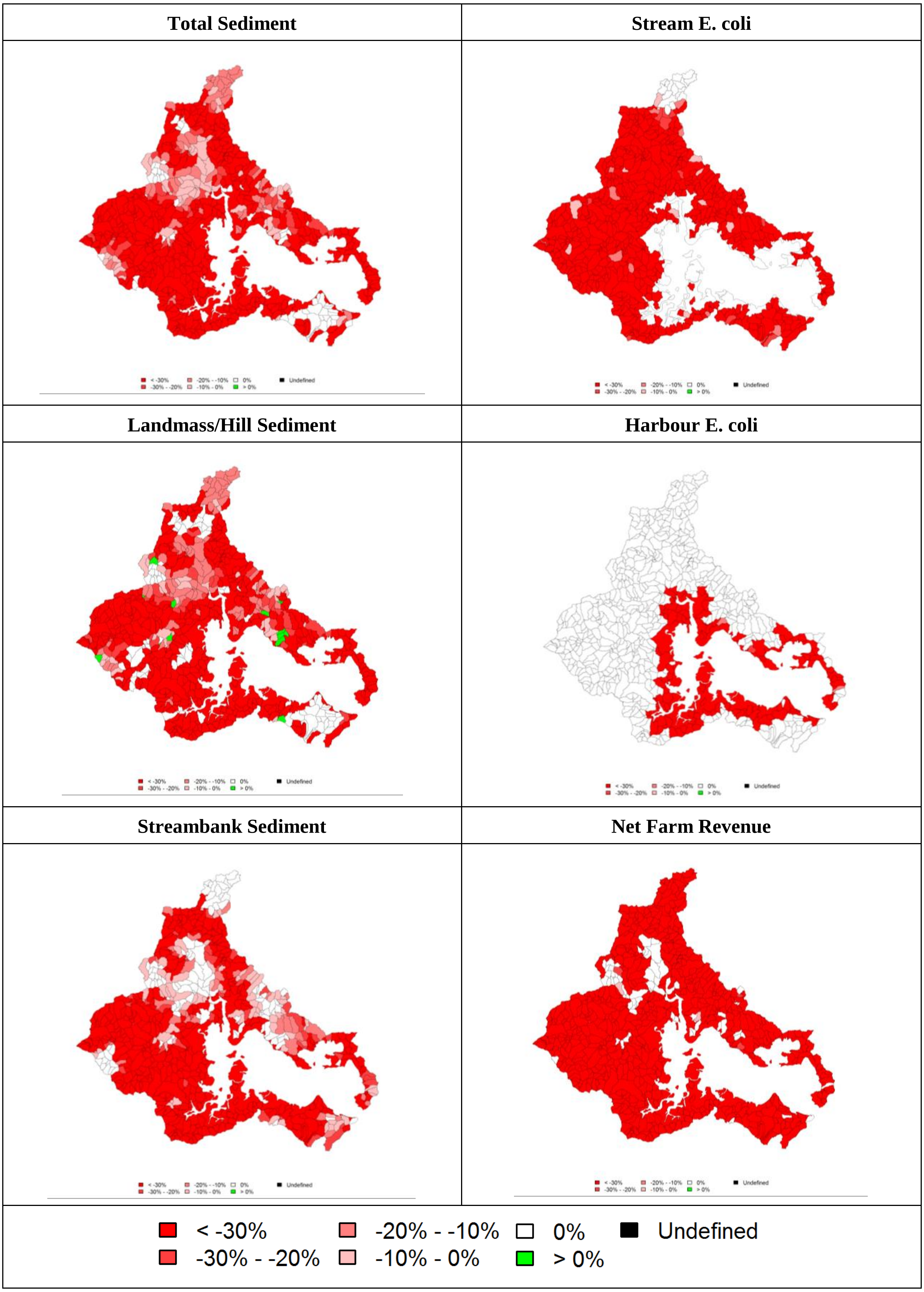


Figure A.4.1: Spatial impacts for Afforestation – All

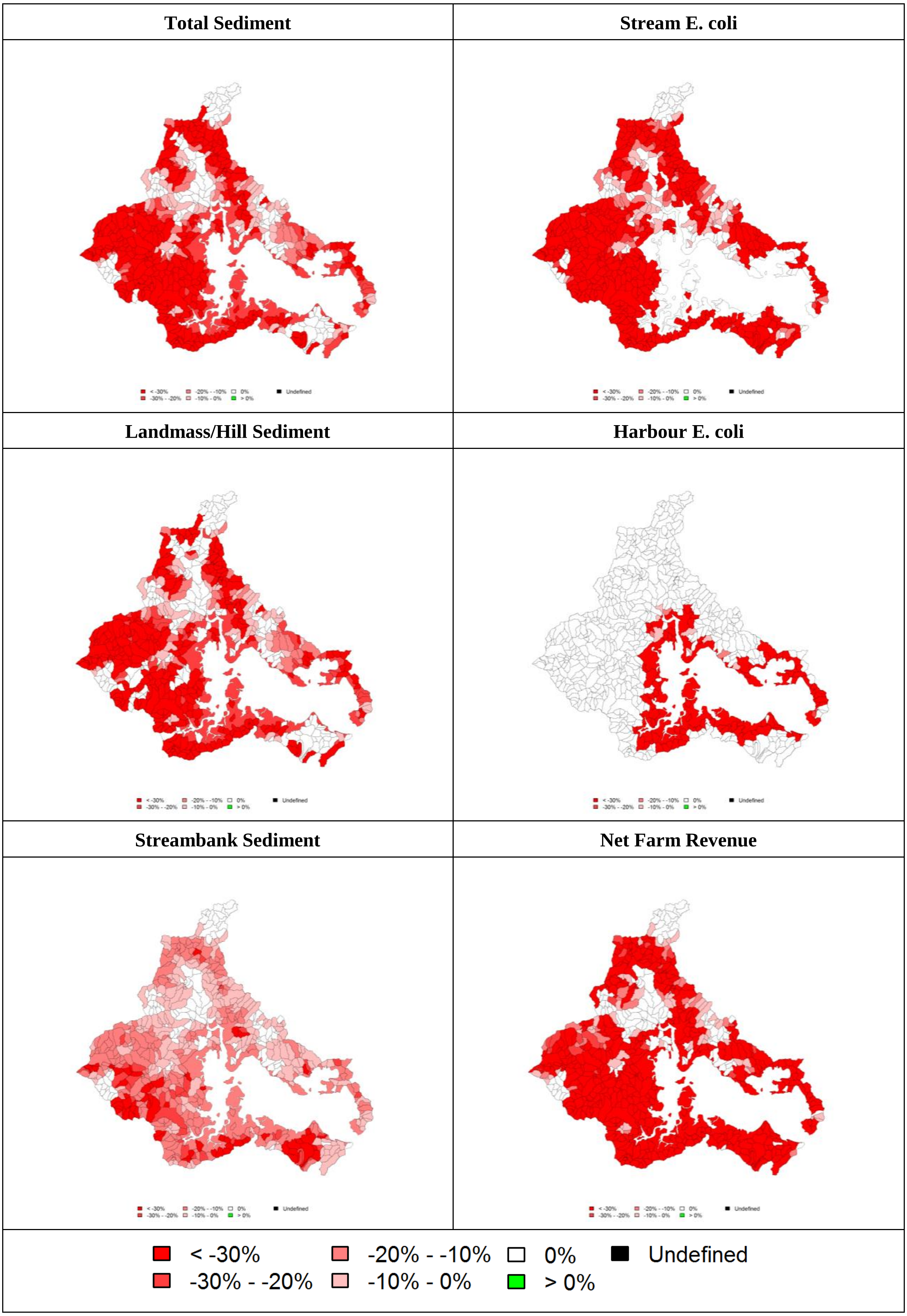


Figure A.4.2: Spatial impacts for Afforestation - Pasture

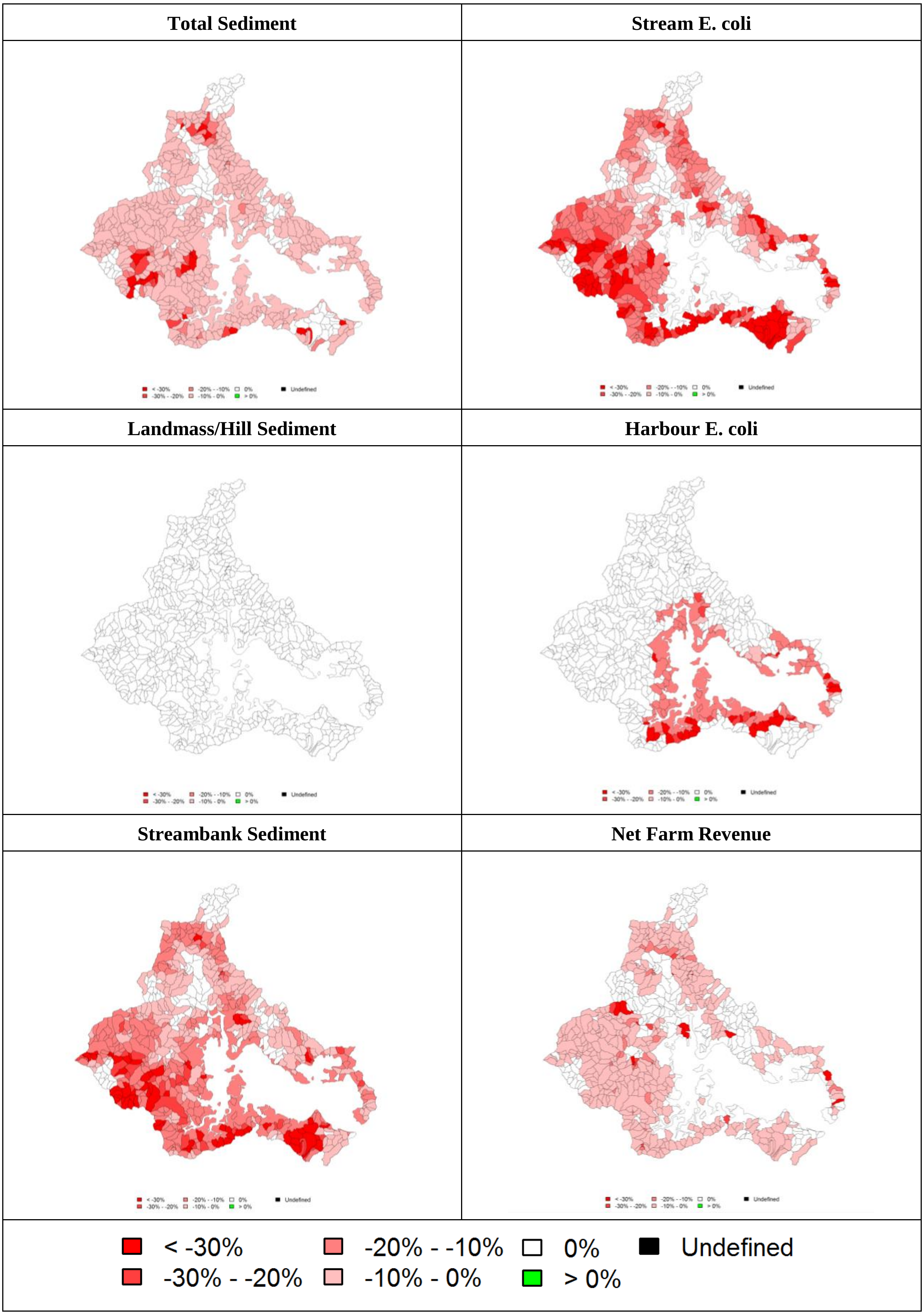


Figure A.4.3: Spatial impacts for Current Fencing

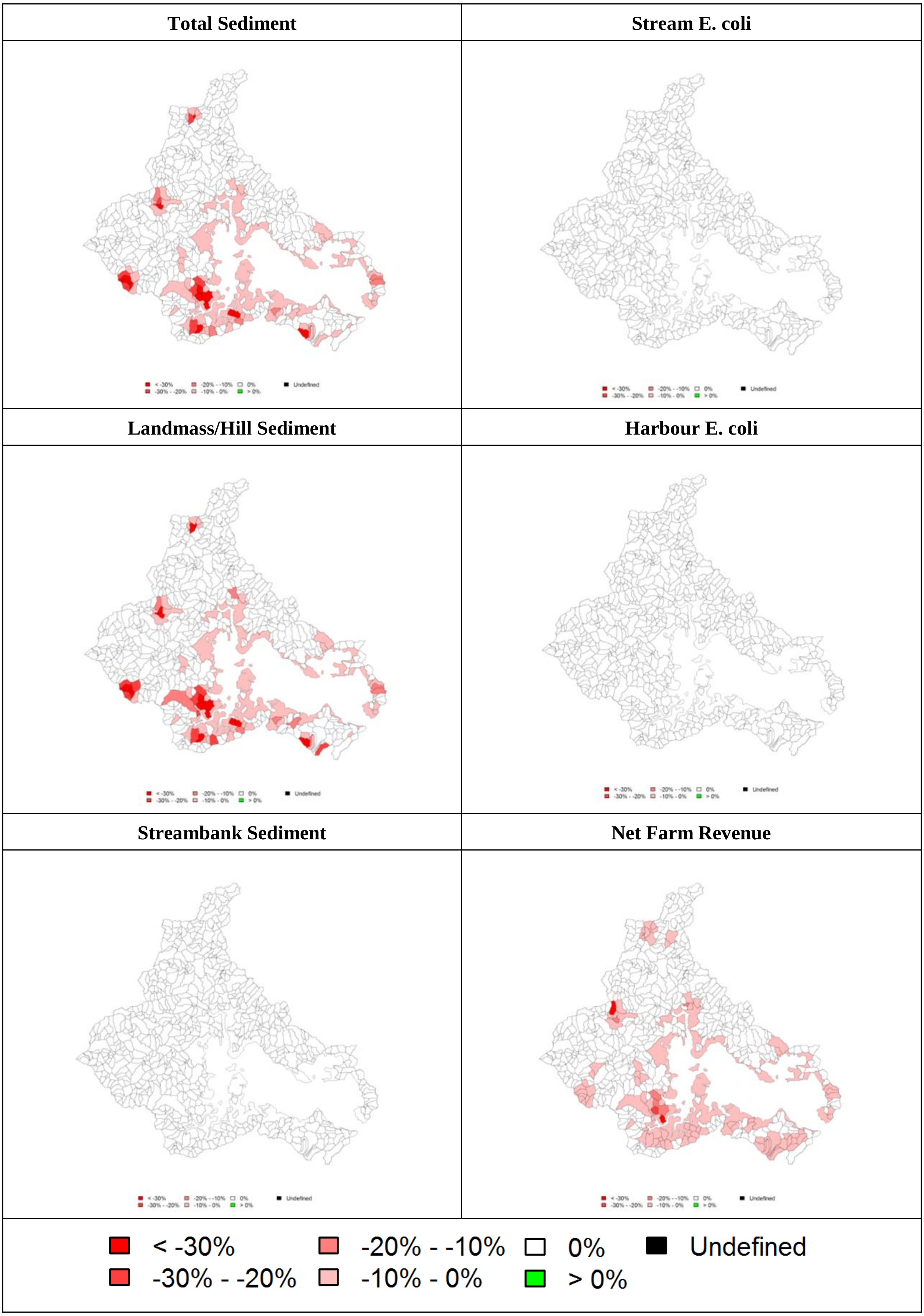


Figure A.4.4: Spatial impacts for Current Farm Plans

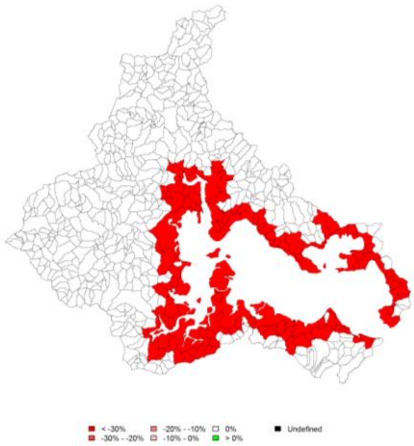
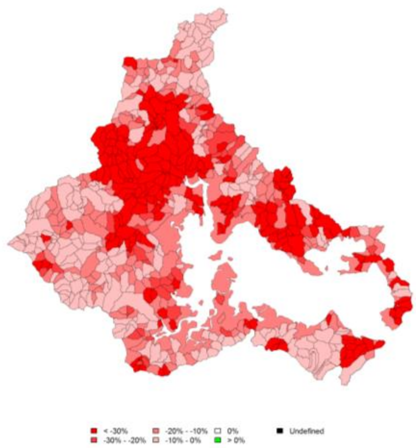
Total Sediment	Stream E. coli
	
Landmass/Hill Sediment	**Harbour E. coli**
	
Streambank Sediment	**Net Farm Revenue**
	

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Figure A.4.5: Spatial impacts for Wetlands - All

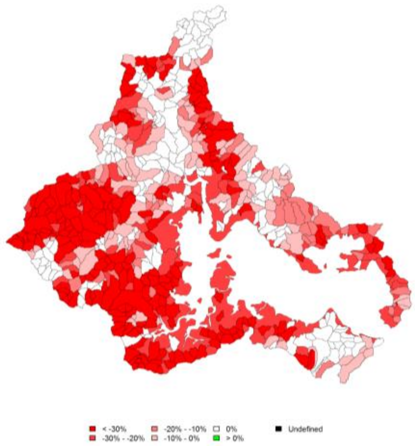
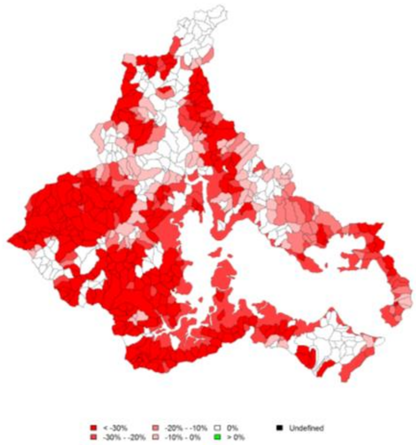
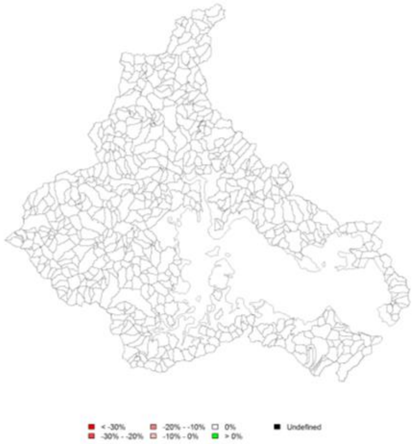
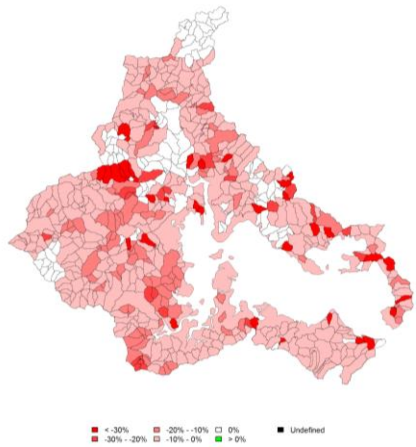
Total Sediment	Stream E. coli
	
Landmass/Hill Sediment	**Harbour E. coli**
	
Streambank Sediment	**Net Farm Revenue**
	

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Figure A.4.6: Spatial impacts for Farm Plan - All

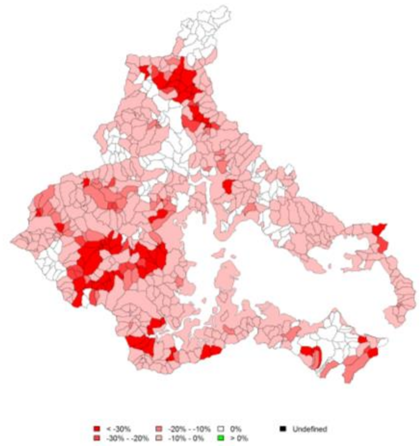
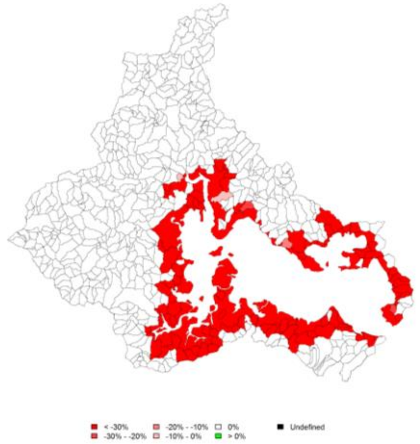
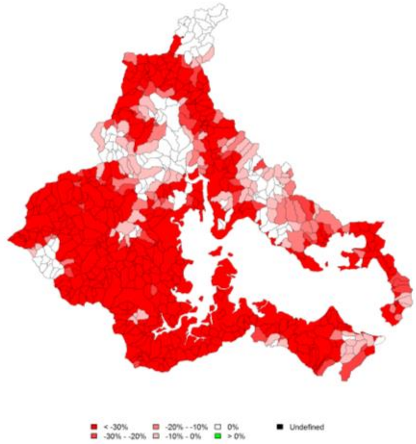
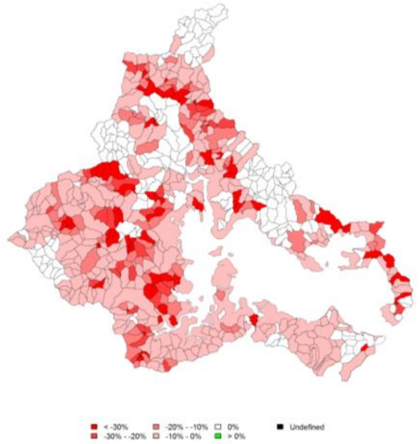
Total Sediment	Stream E. coli
	
Landmass/Hill Sediment	**Harbour E. coli**
	
Streambank Sediment	**Net Farm Revenue**
	

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Figure A.4.7: Spatial impacts for Fencing - All

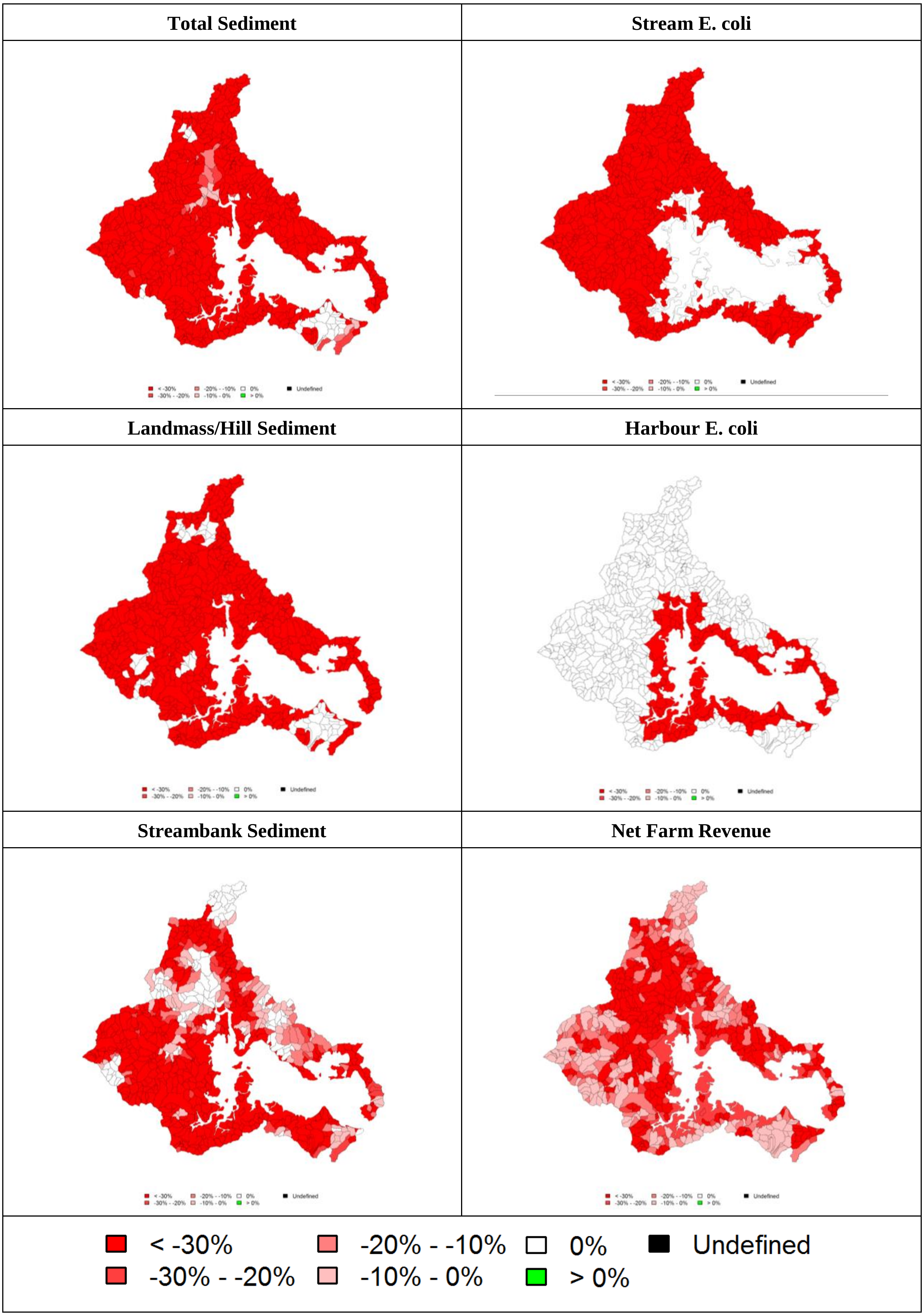


Figure A.4.8: Spatial impacts for Max Mitigation

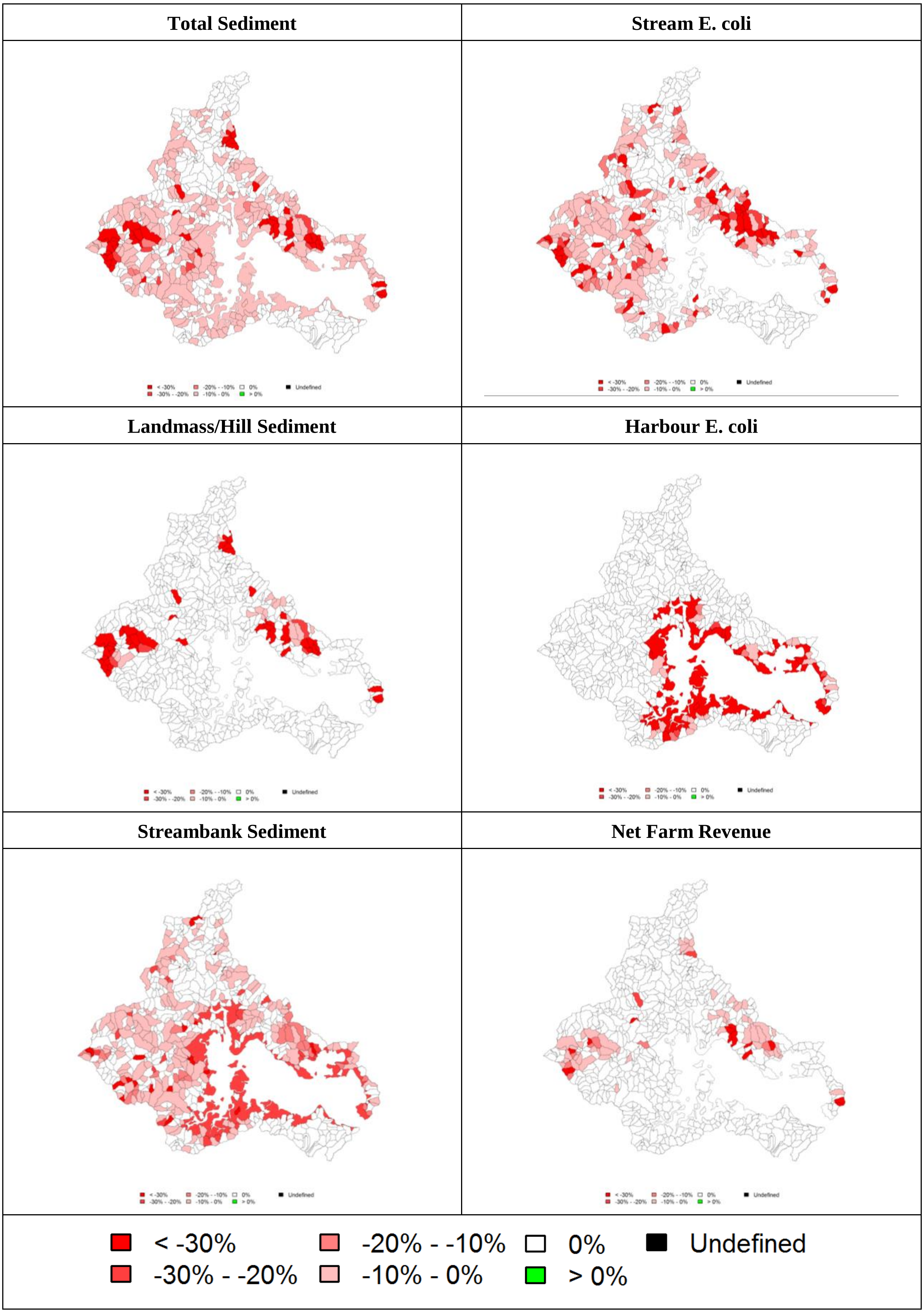


Figure A.4.9: Spatial impacts for Harbour Sediment – 20%

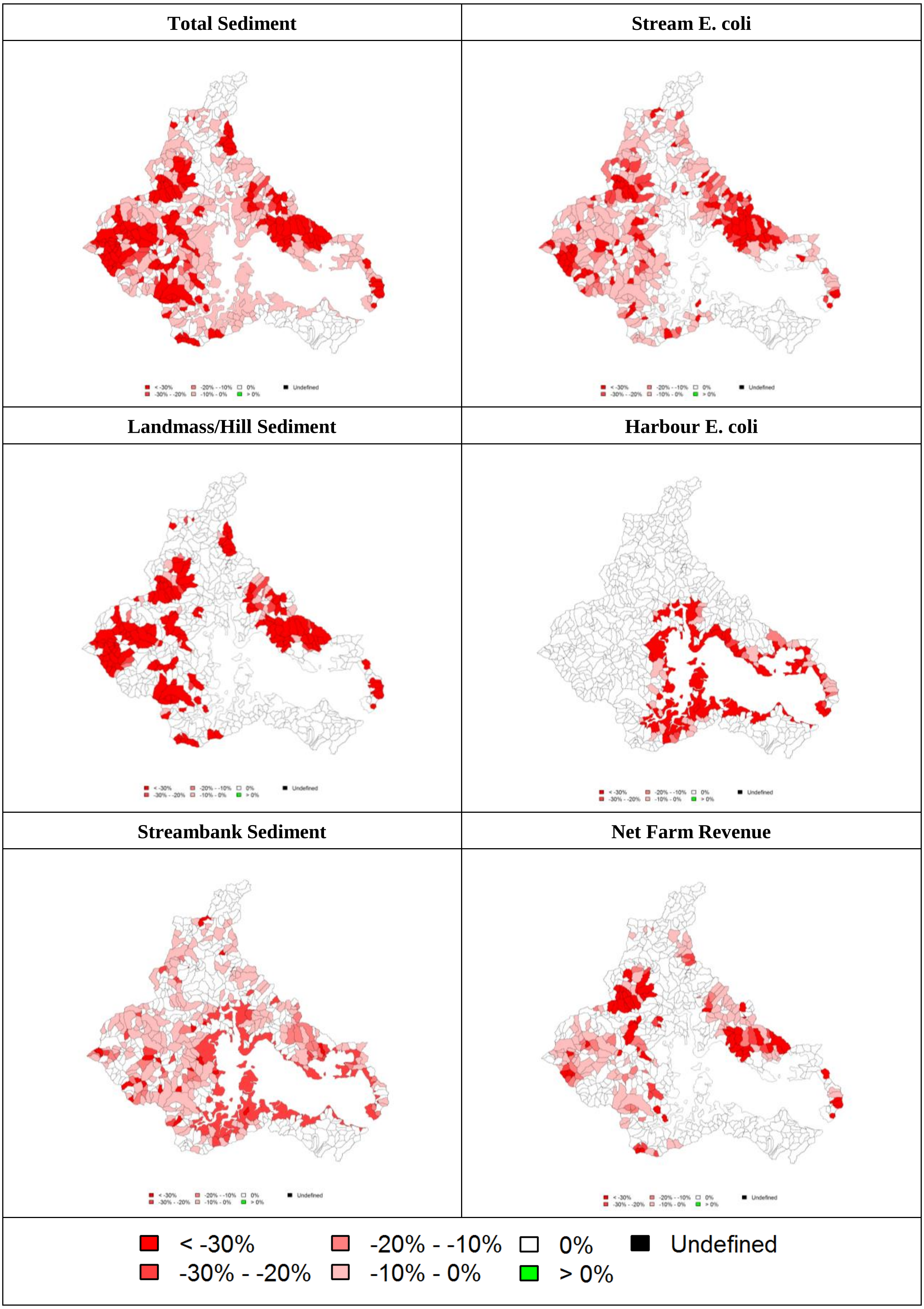


Figure A.4.10: Spatial impacts for Harbour Sediment – 40%

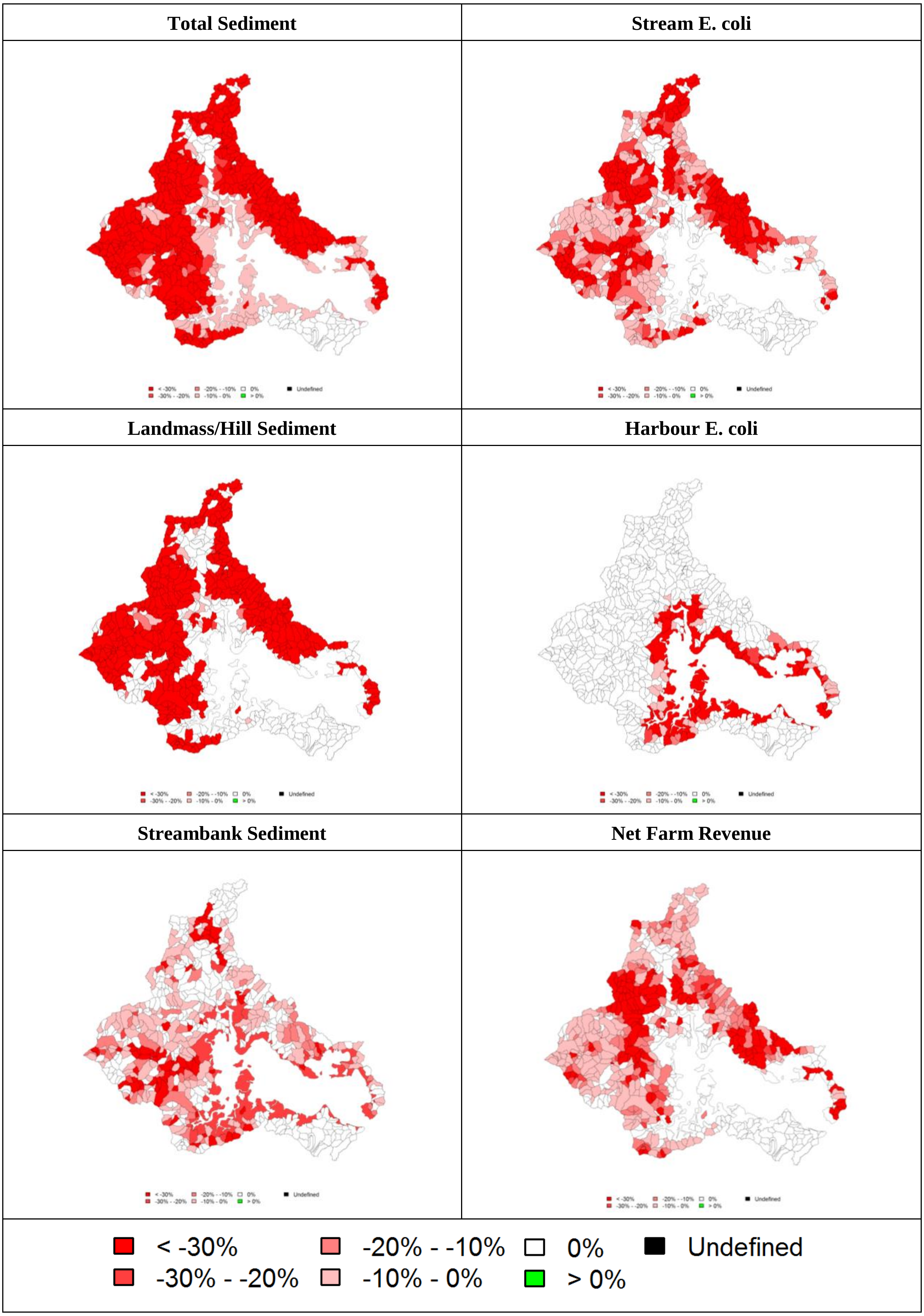


Figure A.4.11: Spatial impacts for Harbour Sediment – 60%

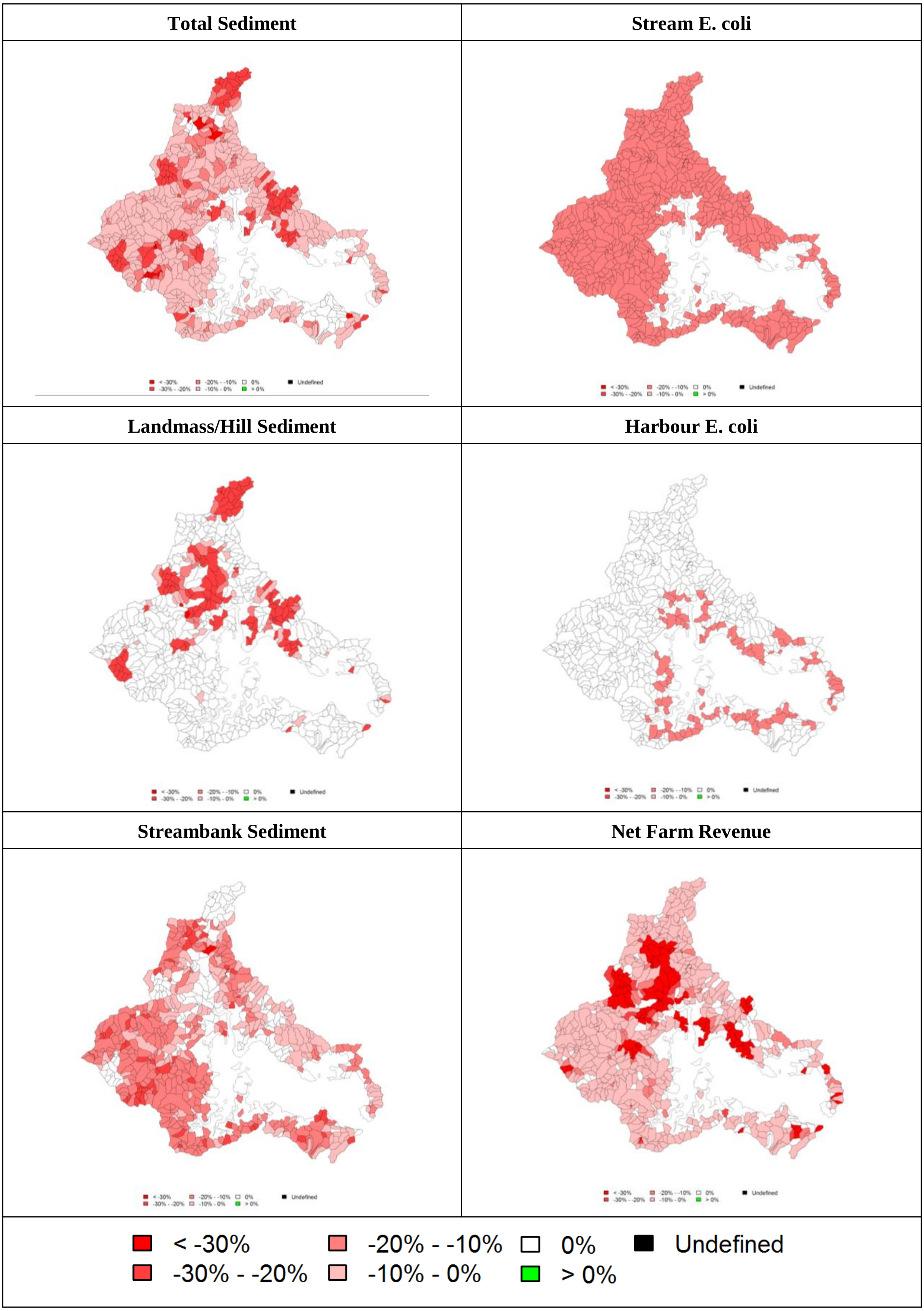


Figure A.4.12: Spatial impacts for *E. coli* load – 20%

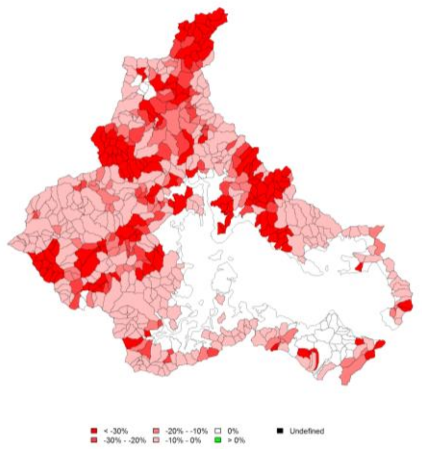
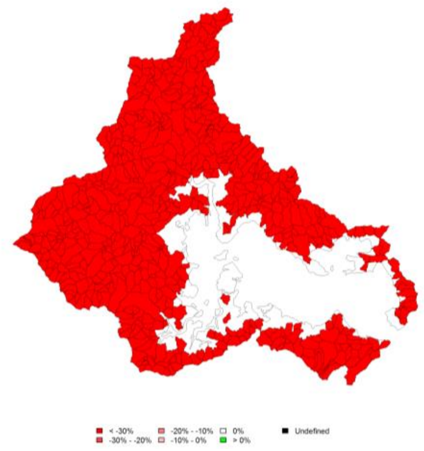
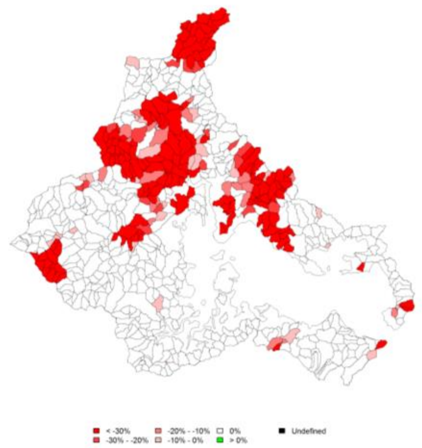
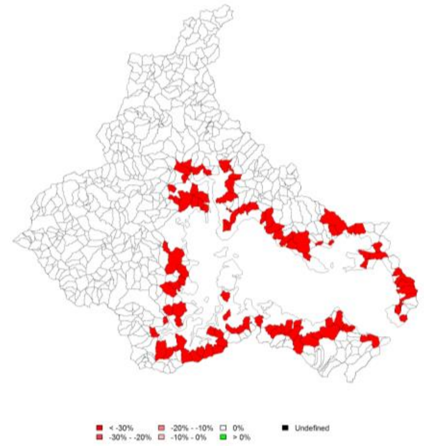
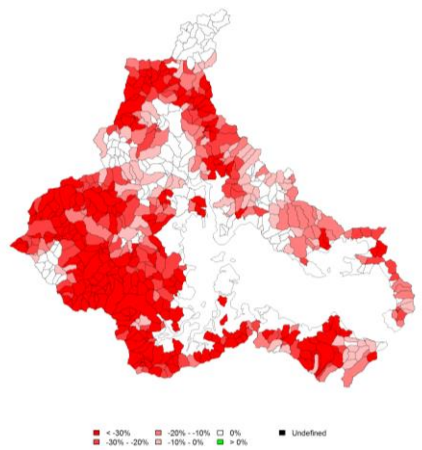
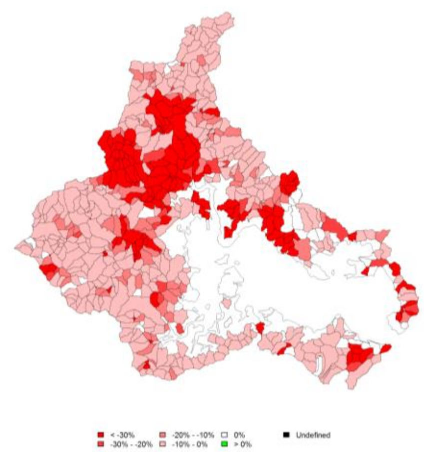
Total Sediment	Stream E. coli
	
Landmass/Hill Sediment	**Harbour E. coli**
	
Streambank Sediment	**Net Farm Revenue**
	
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Figure A.4.13: Spatial impacts for *E. coli* load – 40%

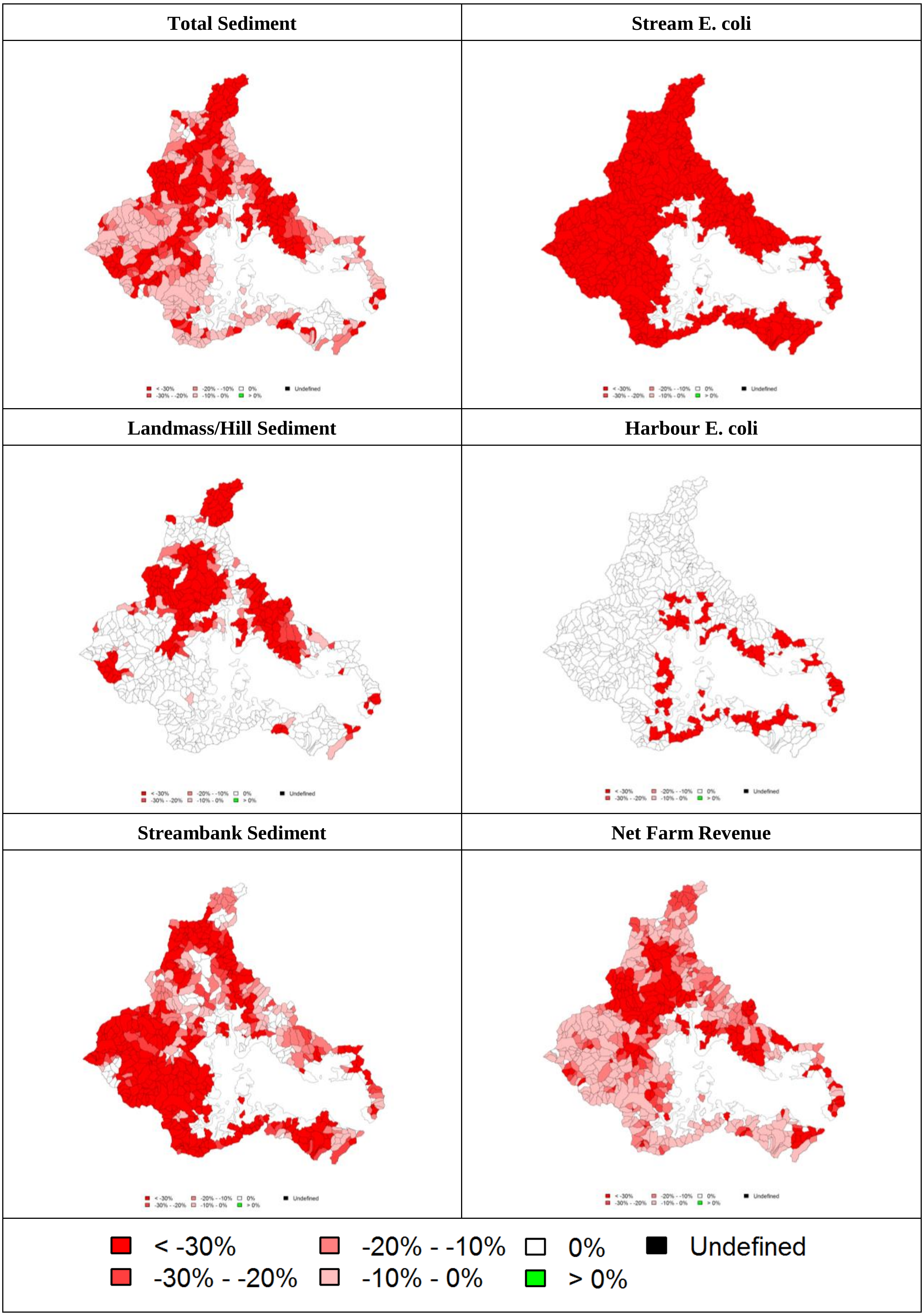

Figure A.4.14: Spatial impacts for *E. coli* load – 60%

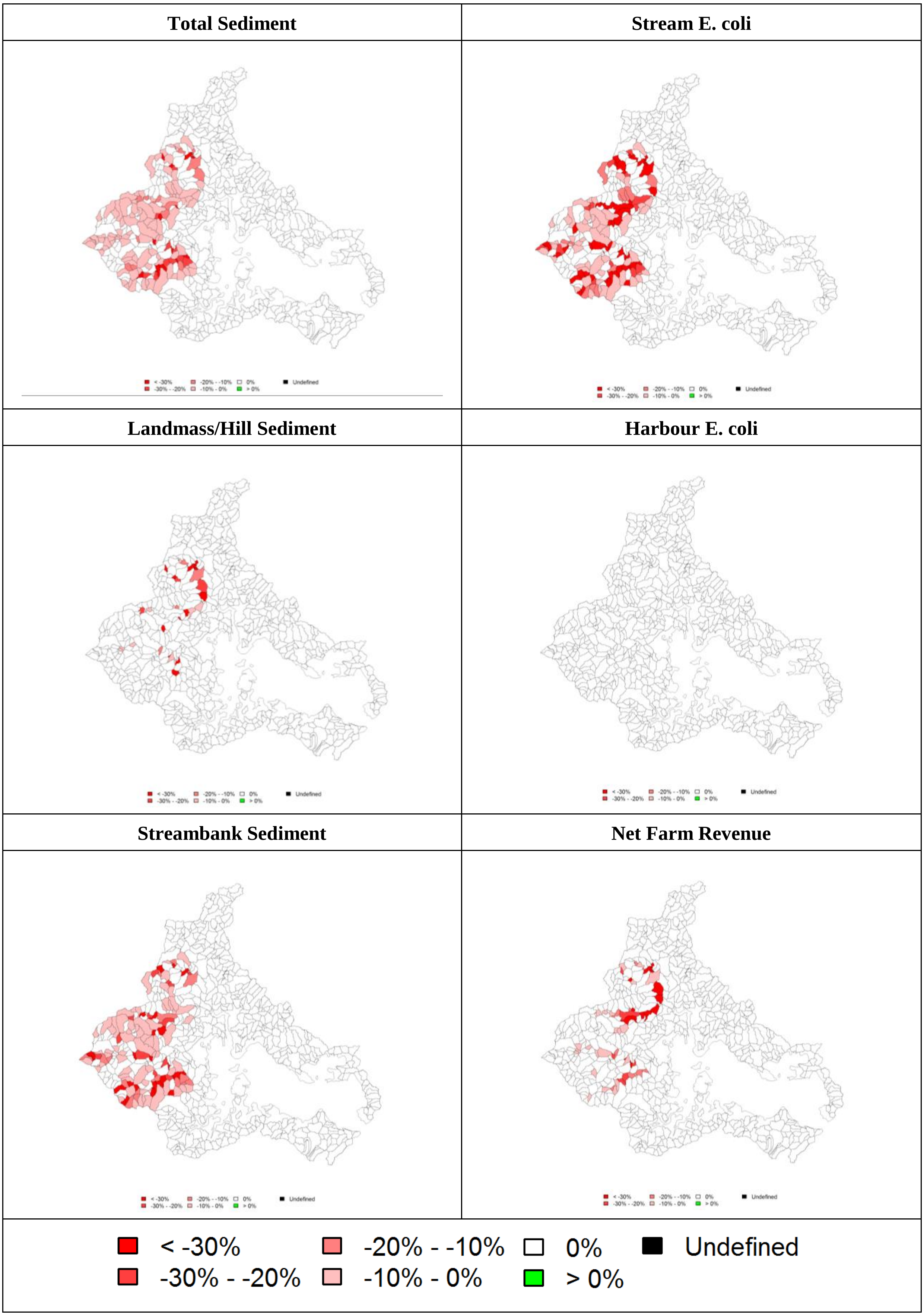

Figure A.4.15: Spatial impacts for Secondary Contact 'B'

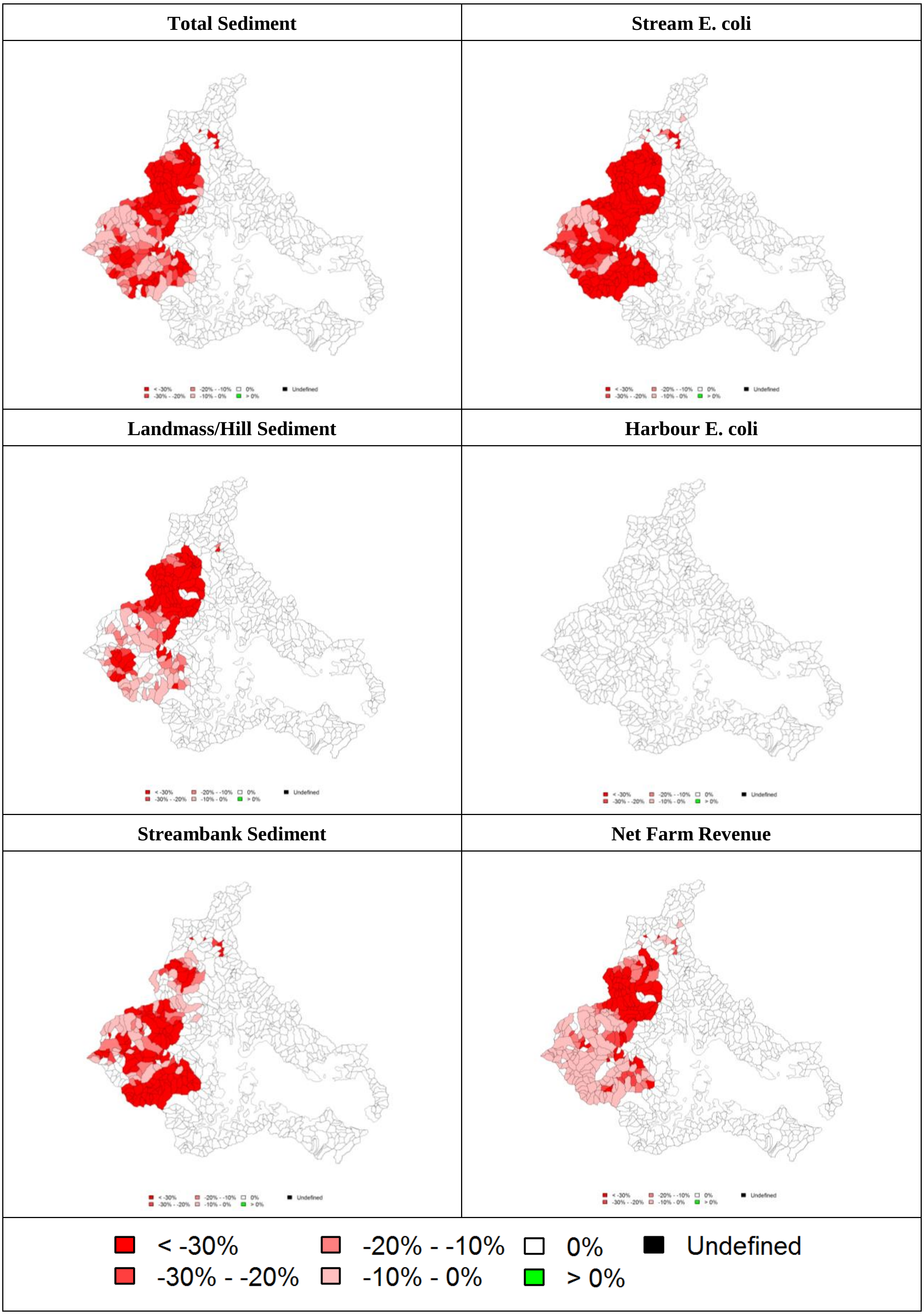

Figure A.4.16: Spatial impacts for Secondary Contact ‘A’

Appendix 5 – Sensitivity Analysis for Lower Effectiveness Rates

Table A.5.1: Mitigation effectiveness assumptions (as % 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 A.5.2: 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	26883	4472	31355	19968	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%

References

Ballinger J, Nicholson C, Perquin J-C, Simpson E 2014. River water quality and ecology in Northland. State and trends, 2007–2011: 133. Available at http://www.nrc.govt.nz/Resource-Library-Summary/Research-and-reports/Rivers-and-streams/River-Water-Quality-and-Ecology-in-Northland---States-and-Trends-2007–2011/

Daigneault A, Greenhalgh S, Samarasinghe O, Jhunjhnuwala K, Walcroft J, de Oca Munguia OM 2012. Sustainable land management and climate change – catchment analysis of climate change: final report. MPI Technical Paper No: 2012/X

Daigneault A, Samarasinghe O, Lilburne L 2013. Modelling economic impacts of nutrient allocation policies in Canterbury – Hinds Catchment. Final report. Landcare Research Contract Report LC1490 for Ministry for the Environment.

Doole GJ 2015. A flexible framework for environmental policy assessment at the catchment level. Computers and Electronics in Agriculture 114: 221–230.

Dymond JR, Betts HD, Schierlitz CS. 2010. An erosion model for evaluating regional land-use scenarios. 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. Landcare Research Contract Report LC2413 for AgResearch. 42 p.

Elliott AH, Alexander RB, Schwarz GE, Shankar U, Sukias JPS, McBride GB 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.

GAMS 2015. GAMS – the solver manuals. GAMS corporation, Washington DC. Available at http://www.gams.com/dd/docs/solvers/allsolvers.pdf.

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. NIWA report HAM2015-042 prepared for Ministry for Primary Industries, November 2015.

Green M, Dymond J, Matthaei C, Elliott, S 2015. Northland sediment study: sediment and *E. coli* attributes. NIWA report HAM2015-013 prepared for Ministry for Primary Industries, March 2015.

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

Ministry for the Environment (MfE) 2014. National Policy Statement – Freshwater Management. Available at: http://www.mfe.govt.nz/fresh-water/freshwater-management-nps

Ministry for Primary Industries (MPI) 2013a. Situation and outlook for primary industries. Policy Publication. Wellington, New Zealand, MPI.MPI 2013b. Farm monitoring report. MPI Publication. Wellington, New Zealand. Available at: http://www.mpi.govt.nz/news-resources/publications?title=Farm%20Monitoring%20Report

Palliser C, Elliott S, Yalden S 2015. Northland sediment study: *E. coli* modelling. NIWA report prepared for Ministry for Primary Industries, August 2015.

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.