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# Kaipara Harbour sediment mitigation study: Catchment economic modelling

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# Contents

## 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).

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

**Earnings before Interest and Tax (EBIT):** Farm profits that excludes interests and taxes. Used interchangeably with net farm revenue.

**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

**Farm Management Plan**: In this study, a farm management plan means predominately planting poplar or willow poles on Highly Erodible Lands that averaged at least 1.0 tonne of sediment per hectare per year. It does not include riparian management.

**Fencing**: In this study, fencing only means riparian fencing. It does not include fencing on Highly Erodible Land to retire grazing.

**Highly Erodible Land (HEL):** Pastoral land with 1.0 t/ha/yr or higher erosion rate.

**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:** Sites within the Kaipara Harbour catchment of particular interest to the Auckland and Northland Regional Councils. They are typically located near environmental monitoring stations and/or popular recreation sites.

**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.

**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) with support from Auckland Council (AC) and Ministry for the Environment (MfE) have contracted a consortium led by Streamlined Environmental Ltd and consisting of Streamlined Environmental, Landcare Research, NIWA, and the University of Otago, to conduct the Kaipara Harbour Sediment Mitigation Study (KHSMS).

## Objectives

The first objective of the KHSMS is to develop a catchment economic model for use in assessing the economic costs and environmental benefits of a range of scenarios for mitigating sediment losses to rivers and estuaries within the Kaipara Harbour catchment. The second aim of the Study is to develop a management tool for use in formulating consistent farm-scale sediment mitigation plans. The tool will be easily usable by land management advisors in the field to identify appropriate actions to mitigate critical source areas of sediment under different land uses at the farm scale.

This report provides an overview of the integrated economic catchment model. It also presents results from a range of scenarios to assess the possible impacts for a range of management and mitigation approaches to reduce sediment in the KHC.

## Methods

The integrated catchment economic modelling of the Kaipara Harbour catchment (KHC) was completed using a spatially explicit economic land use model, New Zealand Forest and Agriculture Regional Model (NZFARM). The model incorporated data and estimates from economic and land use databases and biophysical models. Annual sediment loads from various land uses in the KHC were estimated using the SedNet model (Dymond 2016), while the harbour sediment budget was estimated by Streamlined Environmental (Green et al. 2017). Land-based mitigation costs and effectiveness in reducing sediment were obtained from a range of sources and summarized by Landcare Research (Basher 2017).

NZFARM includes several options and practices for managing sediment from different land uses that range from intensive pasture to native bush. These options include implementing farm management plans, fencing streams, and constructing wetlands and sediment bunds, among other things.

Several model scenarios were conducted to assess the possible impacts for a range of management and mitigation approaches to reduce sediment in the KHC (Table ES.1). For the analysis, these included practice-based approaches such as fencing all streams to exclude livestock as well as outcome-based approaches such as meeting sediment load reduction targets in specific freshwater nodes or marine sediment basins of the KHC. We also modelled full pine afforestation and full native afforestation with constructed and restored wetlands to establish the minimum feasible loads and best possible attribute states that could be achieved in the KHC. In all scenarios, mitigation costs estimates are reported as annual figures[1].

**Table ES.1:** NZFARM scenarios for the Kaipara Harbour catchment

| Scenario # | Scenario Name | Scenario Description |
|---|---|---|
| 0 | Baseline | Current land use with no mitigation practices to match same assumption as SedNetNZ erosion model. |
| | | Practice-based Scenarios |
| 1 | Current Mitigation | Current land use with likely proportion of mitigation practices implemented today. Assumes 80% of streams and rivers on dairy farms and 30% of streams and rivers on other pastoral land are fenced to exclude livestock (dairy cattle, dairy support cattle, beef cattle and deer) and 10% of pastoral land area with 1.0 t/ha/yr or higher erosion rates (i.e., highly erodible land, HEL) has soil conservation measures. |
| 2 | Farm Management Plan on all Highly Erodible Pastoral Land | Current land use with farm management plans (predominately promoting soil conservation by planting poplar or willow poles) implemented on all HEL. |
| 3 | Stock Exclusion Rules | Current land use with riparian fencing of River Environment Classification 2 (REC2) or larger permanent streams for stock exclusion on all pastoral land meeting the NZ Government's proposed stock exclusion regulations (2017). |
| 4 | Stock Exclusion with Riparian Planting | Current land use with riparian fencing for stock exclusion on all pastoral land meeting the NZ Government's (2017) proposed stock exclusion regulations on REC2 or larger permanent streams, but also with 5m stream buffer with planted vegetation. |
| 5 | Stock Exclusion + All HEL Plans | Combination of scenarios 2 and 3. |
| | | Outcome-based Scenarios |
| 6 | Freshwater Node 10% | Total annual sediment load reduced in all seven freshwater zones reduced by 10%. |
| 7 | Freshwater Node 30% | Total annual sediment load reduced in all seven freshwater zones reduced by 30%. |
| 8 | Marine Deposition 15% | Total annual sediment load reduced in all nine marine sediment deposition basins reduced by 15%. |
| 9 | Marine AASR 2mm above 'natural' state | Average annual sedimentation rate (AASR) from catchment-based erosion is no more than 2mm greater than AASR under 'natural' land conditions (Scenario 11). |
| | | Afforestation Scenarios |
| 10 | Full Afforestation (Pine) | All non-forest land (e.g., pasture, arable, lifestyle blocks) is planted with radiata pine. Used to estimate maximum attainable mitigation while maintaining a 'productive' land use. |
| 11 | Full Afforestation (Native) & Wetland Restoration | All non-forest land is planted with native bush and likely extent of pre-human wetlands are restored. Used to estimate 'natural' erosion loads in the catchment and thus maximum attainable mitigation. |

[1] For consistency across mitigation options and scenarios, the annual costs presented in this report are annualized over 25 years using a discount rate of 8%.

In addition to assessing the cost and effectiveness for practices and policies that could reduce loads in the KHC, the model also estimated changes in marine and freshwater sediment attributes. These included three freshwater sediment attributes: water clarity, euphotic depth, and suspended sediment, and one harbour sediment attribute: the annual average sedimentation rate (AASR).

**Results**

The no mitigation 'baseline' and 11 modelled mitigation scenarios produced a wide range of economic and environmental impacts. We choose to use the no mitigation baseline to measure the relative impacts of all other scenarios against because it follows the same assumptions that were used for estimating the long-run average sediment loads in SedNetNZ (Dymond 2016) as well as for the sub-catchment level load levels that were used in Green et al's (2017) marine attribute estimates, both of which are included in NZFARM. This approach was taken to define the baseline as there was no information on the specific farms in the catchment that are currently fenced or how effective that fencing is. Thus, the NZFARM sediment mitigation results may overestimate the actual reduction that could occur under the different model scenarios as well as the cost to achieve certain attribute targets[2]. A summary of the catchment-wide no mitigation baseline is listed in Table ES.2, while the key estimates from the draft mitigation scenarios are listed in Table ES.3. The distribution of mitigation area by scenario is presented in Figure ES.1.

The study showed that, given current land use, sediment sources, and mitigation practices, there is a wide-range of possible outcomes that can be achieved. About 74% of the land area in the catchment is classified as pasture, which contributes about 79% of the total sediment in the KHC. Approximately 52% of sediment in the entire catchment comes from land-based sources (i.e. landslide, gully, earthflow, and surficial erosion), while the remaining 48% is created by streambank erosion (Dymond 2016). This relatively even split suggests that management options that only target one type of erosion process or land use may not be sufficient to achieve large changes in sediment loads and related attributes in the catchment. In addition, sub-catchments within the KHC also have different distributions of land use and sediment sources, and thus may require more or less mitigation to be implemented than others to achieve localised objectives (e.g., minimum water clarity level at a specific point in the river).

**Table ES.2:** Key NZFARM no mitigation 'baseline' estimates

| Land Use | Area (ha) | Net Farm Revenue ($/yr) | Land-based Erosion (t/yr)* | Streambank Erosion (t/yr) | Total Erosion (t/yr) |
|---|---|---|---|---|---|
| Dairy | 140,584 | 289,470,359 | 70,463 | 96,999 | 167,462 |
| Sheep & Beef | 283,999 | 12,543,034 | 216,599 | 146,994 | 363,592 |
| Deer | 3,032 | 3,016,544 | 769 | 766 | 1,535 |

[2] We provide a sensitivity analysis that compares catchment level estimates to the 'current' mitigation scenario in Appendix 6.

| | | | | | |
|---|---|---|---|---|---|
| Lifestyle | 17,021 | 1,203,422 | 4,165 | 7,428 | 11,593 |
| Arable & Hort | 5,488 | 22,202,055 | 155 | 3,261 | 3,416 |
| Forestry | 83,596 | 43,397,500 | 41,675 | 24,173 | 65,848 |
| Native Bush | 53,446 | 0 | 23,161 | 15,103 | 38,263 |
| Other | 14,865 | 274,853 | 1,523 | 38,260 | 39,783 |
| Total | 602,031 | 372,107,767 | 358,510 | 332,982 | 691,492 |

* Includes landslide, gully, earthflow, and surficial erosion, minus floodplain deposition

The most cost-effective (i.e., least average cost per tonne sediment mitigated) practice-based mitigation scenario was the one that focused on implementing farm management plans that largely consist of pole planting on highly erodible land (HEL) that averaged at least 1.0 tonnes of sediment per ha per year (Scenario 2). This mitigation enables a focus on the particular hot spots of sediment in the KHC at an annualized cost of $2.65 million/year, equivalent to a 1% reduction in net revenue in the catchment compared to the no mitigation baseline. As a result, land-based sediment is expected to decline 54%, resulting in total sediment to fall by around 28% relative to the no mitigation baseline.

**Table ES.3:** Key economic catchment model scenario estimates

| Scenario | Net Revenue (mil $) | Total Mitigation Cost (mil $/yr)^ | Average Mitigation Cost ($/t/yr)^ | Land-based Erosion (t/yr) | Stream bank Erosion (t/yr) | Total Erosion (t/yr) |
|---|---|---|---|---|---|---|
| No Mitigation Baseline | $372.1 | $0 | $0 | 358,510 | 332,982 | 691,492 |
| Change from No Mitigation Baseline | | | | | | |
| Current Mitigation | -2.0% | $6.6 | $81 | -5% | -19% | -12% |
| Farm Management Plan - All HEL | -1.0% | $2.6 | $13 | -54% | 0% | -28% |
| Stock Exclusion Rules | -3.0% | $10.5 | $118 | 0% | -27% | -13% |
| Stock Exclusion Rules + Planting | -11.0% | $41.3 | $194 | -25% | -37% | -31% |
| Stock Exclusion + All HEL Plans | -3.0% | $13.0 | $46 | -54% | -27% | -41% |
| Freshwater Node 10% | -0.1% | $0.2 | $5 | -8% | -3% | -6% |
| Freshwater Node 30% | -0.3% | $1.2 | $10 | -24% | -9% | -17% |
| Marine Deposition 15% | -0.2% | $0.6 | $6 | -17% | -13% | -15% |
| Marine 2mm above 'natural' AASR | -2.3% | $8.7 | $84 | -11% | -5% | -8% |
| Full Afforestation (Pine) | -69% | $255.3 | $543 | -66% | -71% | -68% |
| Full Afforestation (Native) & Wetlands | -89% | $330.8 | $546 | -90% | -85% | -88% |

^ Costs annualized over 25 years at a discount rate of 8%.

Implementing the recent NZ government's 'Clean Water' stock exclusion rules (Scenario 3) is estimated to cost about $10.5 million/yr relative to the base case that assumes no fencing at all, equivalent to 3% of net farm revenue[3] (if one accounts for a rough estimate of fencing) . As a result of constructing fences along all permanent dairy streams in the KHC and streams in all other pastoral lands with a slope of 15 degrees or less is estimated to reduce streambank erosion by 27% and total erosion by 13%. The new rules are not as effective as one may expect because it is assumed that riparian fencing only reduces bank erosion by 50% relative to a case where the stream is not fenced (Basher 2017). Extending the stock exclusion rule to require 5m stream buffers with riparian planting (Scenario 4) would reduce total erosion by 31%, but at an added cost, in this case $41 million/yr, equivalent to a 11% reduction in annual net farm revenue compared to the no mitigation baseline.

Combining the option to follow the stock exclusion rules (with fencing but no riparian planting) and implement farm management plans on all HEL (Scenario 5) reduces total erosion in the KHC by 41% at a cost of about $13.0 million/yr over the no mitigation baseline. This cost is equivalent to about $50/ha/yr on farms where the mitigation practices are implemented, although we do highlight that actual costs may be less for farms that have already implemented some mitigation practices that were not accounted for in our 'no mitigation' baseline.

The scenarios that focused on outcomes instead of practices yielded significantly different results than the practice based scenarios. For the two scenarios that focused on reducing sediment loads in the seven freshwater nodes by 10 to 30% (Scenarios 6 and 7), modelling results estimated that the targets could be achieved at very little cost ($0.2 to $1.2 million/yr). This is because reductions can be achieved by specifically targeting the mitigation practices of farm plans, stream fencing, and wetland construction on 6,000 to 32,000 ha of pastoral land with high erosion rates and relatively low implementation costs per tonne of sediment mitigated in each of the seven sub-catchments[4]. Total sediment for the KHC is reduced by 6 and 17%, respectively, relative to the no mitigation baseline, with these reductions being concentrated in the seven target areas.

Reducing the amount of catchment-based sediment that reaches the harbour by 15% in all the deposition areas (Scenario 8) could be achieved for as little as $0.6 million/yr. These reductions could be achieved by targeting about 15,000 ha of farms with a relatively even split of farm plans, stream fencing, and wetland construction in the KHC (Figure ES.1). Note, however, that reducing the catchment-based sediment that contributes to the total harbour load by this specified amount is not likely to have a large impact on marine sediment attributes, which are discussed in more detail below.

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[3] N.B. if one accounts for our estimate of streams that are 'currently' fenced in Scenario 2 then the annual cost is reduced to $3.9 million/yr. However, the additional benefit from stock exclusion is also reduced as well. In this case streambank erosion is reduced by about 26,800 t/yr, or 10% relative to the current fencing scenario.

[4] N.B. while we also included several practices for mitigating land-based erosion from horticulture, arable, and urban land uses (e.g., cover crops, wheel track diking), none of them were estimated to be implemented in any of the model scenarios. This is because the practices primarily targeted surface erosion, which was very small relative to the other erosion processes and land uses. Thus, NZFARM deemed these practices to not be cost-effective options for mitigating erosion in the KHC.

Focusing on achieving an AASR of 2 mm/yr above a 'natural' rate from catchment-based sediment in each of nine harbour deposition basins (Scenario 9) has a much higher cost than the other outcome-based scenarios and is estimated to cost $8.7 million/yr, or about a 2.3% decline in net farm revenue relative to the baseline. This is primarily because three of the nine basins (i.e. Kakarai intertidal flats (KAIF), Makarau intertidal flats (MAIF), Kaipara intertidal flats (KPIF) – see Fig. ES.2) require that the catchment-based erosion component of the AASR be reduced by more than 40%, thereby resulting in mitigation having to be implemented in a significant area of the catchment. The model estimates that most of the mitigation will come in the form of combining farm management plans (i.e. pole planting) and fencing streams, including on many farms with minimal baseline erosion rates.

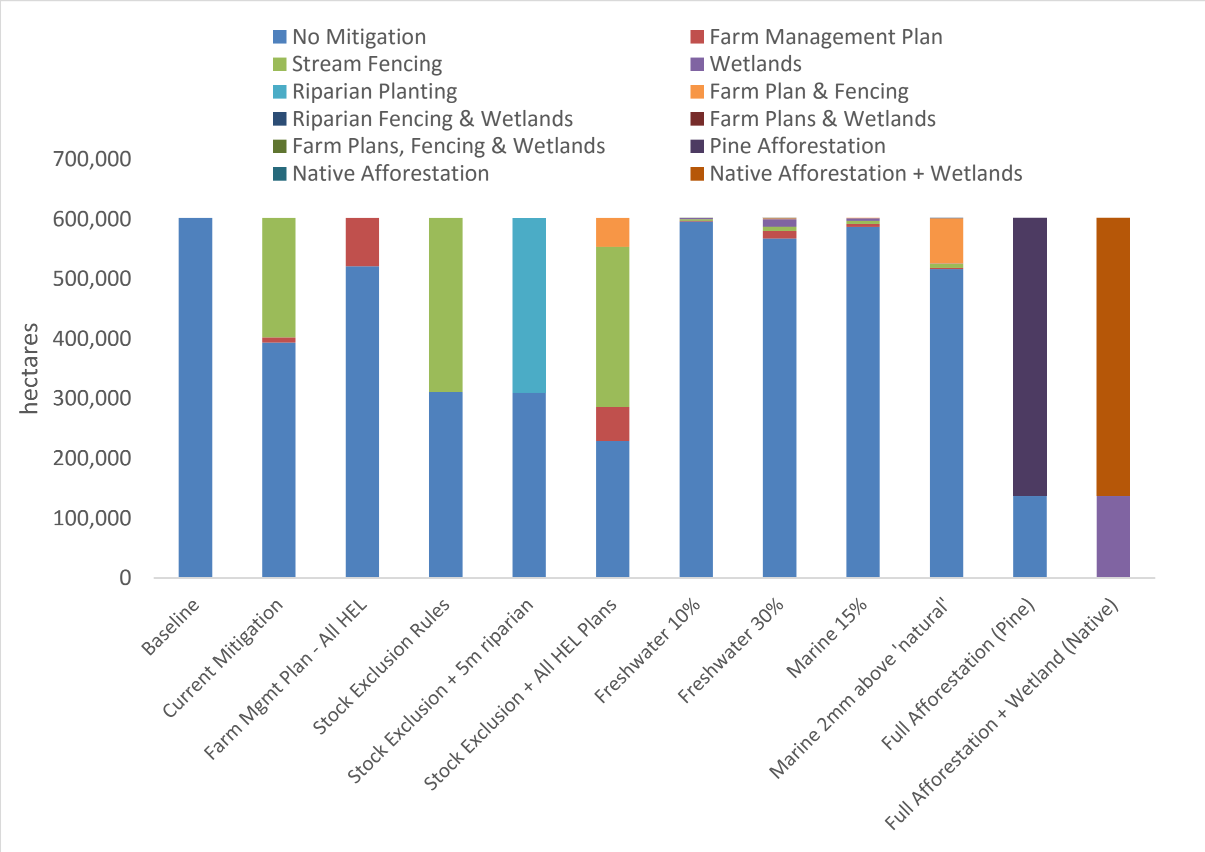



**Figure ES.1:** Mitigation practice area (ha) by scenario.

Afforesting the 77% of the catchment that is currently not covered with woody vegetation (Scenarios 10 and 11) could reduce total erosion in the Kaipara Harbour by 68–88%. However, this is estimated to cost between $255 and $331 million per year, much of which is attributed to lost revenue produced by current land use (i.e. opportunity cost). The full afforestation with restored wetlands scenario indicates that total annual pre-settlement loads were approximately 85,000 t/yr, which resulted in an average 'natural' catchment-based AASR of 0.4 mm/yr.

The modelled scenarios are also estimated to have a range of impacts on freshwater and marine sediment attributes as well. In the case of the marine sediment attribute (AASR), most of the nine modelled deposition areas in the harbour did not have declines in sedimentation rates of more than 1.0 mm/yr unless there large areas of the catchment are afforested (Fig. ES.2). This is because (a) the total reductions in sediment in key areas of the catchment that have the largest effect on AASR are relatively small, and (b) the AASR is a result of both land- and sea-based sediment, for which catchment mitigation only has an impact on the former process (see Figure 11 in main report). Note also that there is wide variation in the AASR for each of the basin across the different scenarios. This is because the proportion of land and streambank sediment deposited into each basin can vary, and thus a mitigation practice that targets one type of erosion may be more effective than another.

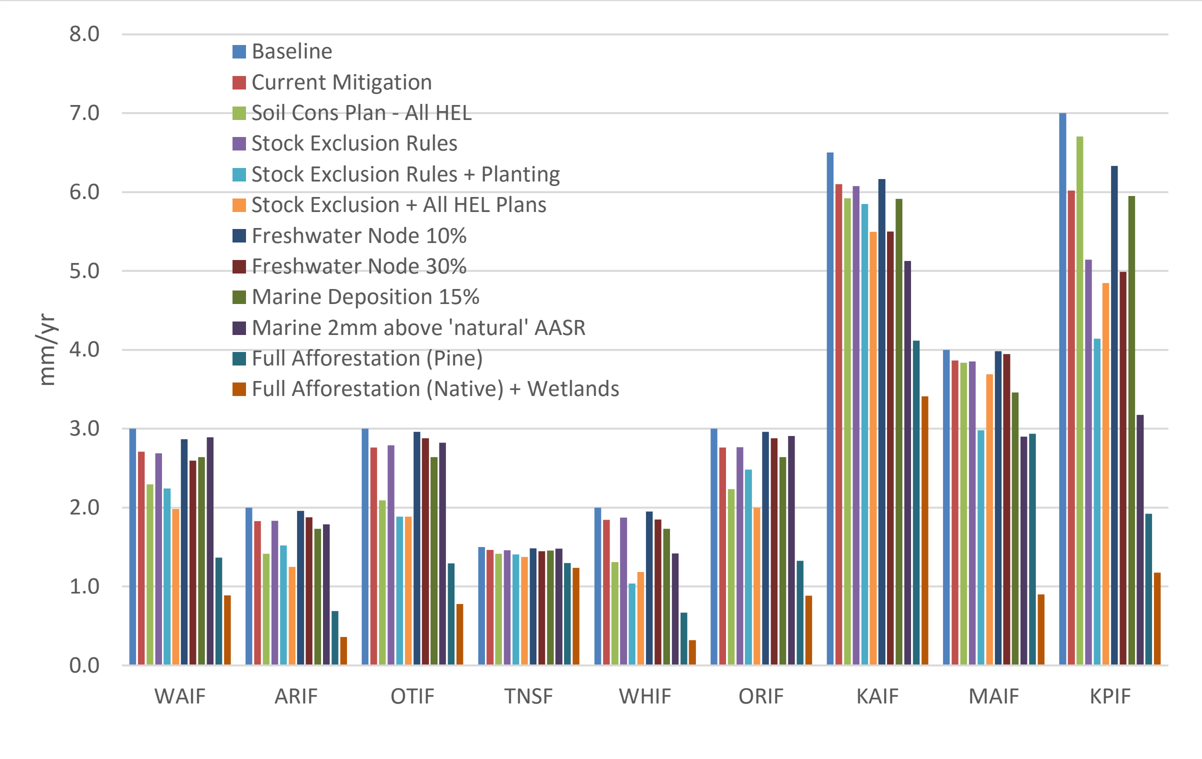
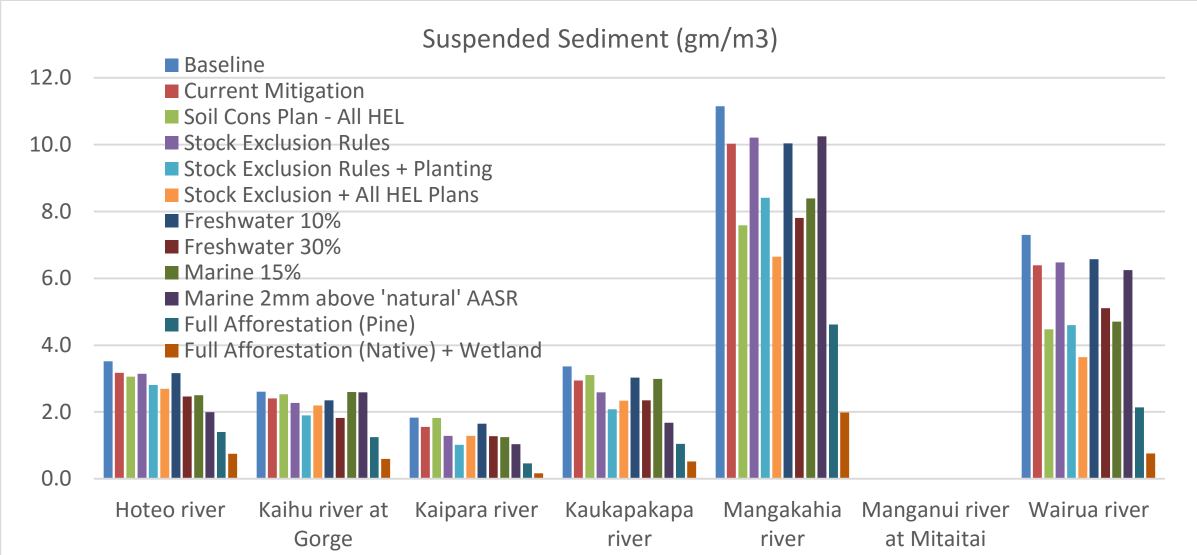
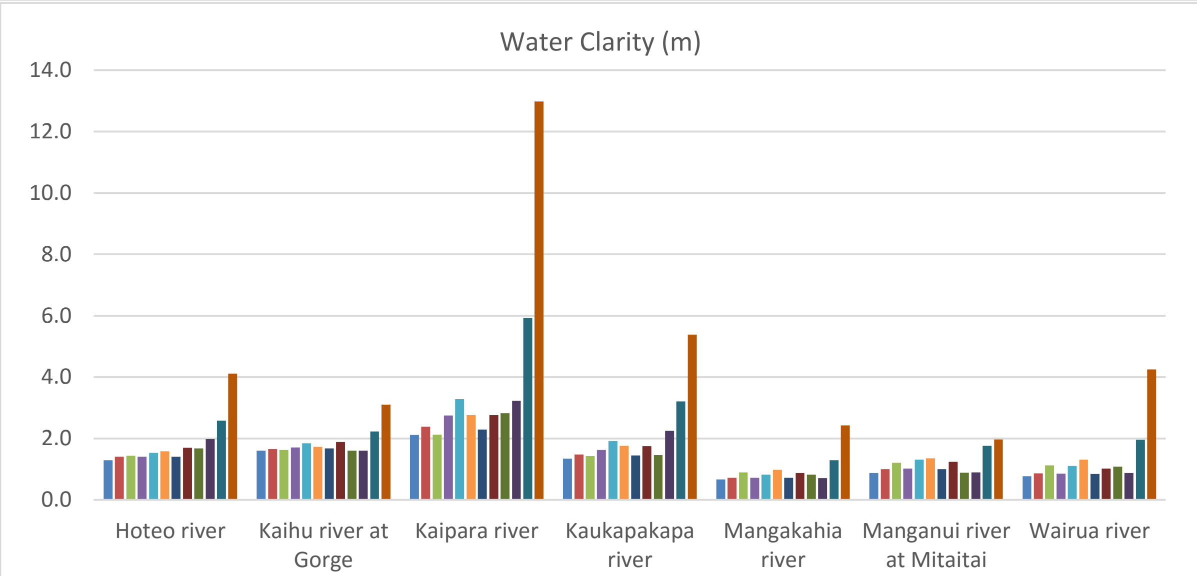



**Figure ES.2:** Marine Annual Average Sedimentation Rate (AASR) by Scenario and Deposition Area. Areas include: Wairoa intertidal flats (WAIF), Arapaoa intertidal flats (ARIF), Otamatea intertidal flats (OTIF), Tinopai subtidal flats (TNSF), Whakaki intertidal flats (WHIF), Oruawharo intertidal flats (ORIF), Kakarai intertidal flats (KAIF), Makarau intertidal flats (MAIF), Kaipara intertidal flats (KPIF).

The freshwater sediment attributes also follow a similar pattern, with large impacts in suspended sediment, water clarity, and euphotic depth occurring often only occurring under conditions with significant afforestation (Fig. ES.3). The combined stock exclusion and riparian planting or combined fencing pole planting on HEL scenarios do have a potentially noticeable effect on some attributes, and could increase water clarity and euphotic depth by at least 0.4 metres in a majority of the catchment nodes. As with many of the other results, these findings suggest that expectations about what could be achieved through policies aimed at managing sediment in the Kaipara Harbour Catchment will be warranted.



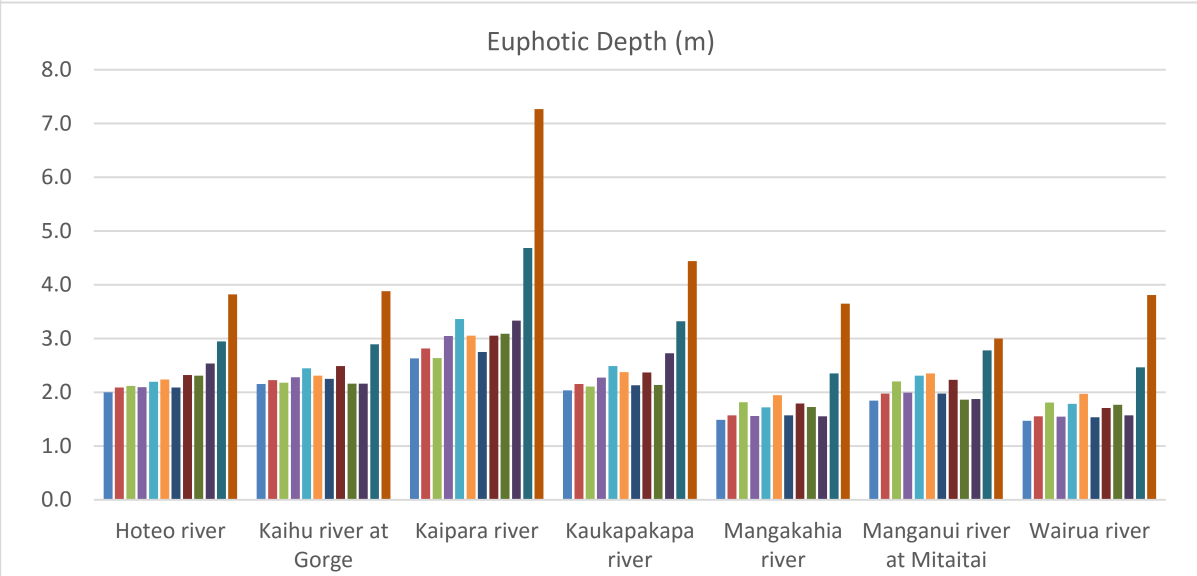




**Figure ES.3:** Freshwater sediment attributes by scenario and catchment node. (N.B., suspended sediment data not available for Manganui River at Mitaitai)

# 1 Introduction

Northland Regional Council (NRC) with support from Auckland Council (AC) and Ministry for the Environment (MfE) have contracted a consortium led by Streamlined Environmental Ltd and consisting of Streamlined Environmental, Landcare Research, NIWA, and the University of Otago, to conduct the Kaipara Harbour Sediment Mitigation Study (KHSMS).

The principle aim of the study is to develop a catchment economic model for use in assessing the economic costs and environmental benefits of a range of scenarios for mitigating sediment losses to rivers and estuaries within the Kaipara Harbour catchment (KHC).

Sediment mitigation applied in the catchment reduces sediment runoff, which translates into changes in “sediment attributes” such as suspended-sediment concentration, water clarity and euphotic depth in freshwater, and sedimentation rate and seabed muddiness in the harbour. Changes in sediment attributes may have an impact on ecosystem health and functioning and other water quality dependent values, for example, kaimoana gathering and swimming.

The catchment economic model will estimate the cost of applying sediment mitigation in the catchment and the reduction in sediment runoff and the associated changes in sediment attributes that will result from the application of the prescribed mitigations. Model predictions will assist NRC and AC with decisions and options to management sediment losses to waters in the Kaipara Harbour and its catchment.

The catchment economic model of the KHC consists of three key components: (1) baseline sediment losses for each hectare of land in the study regions; (2) how these losses are modified with the use of mitigations (primarily on-farm); and (3) how the changes in land and stream bank sediment throughout the freshwater network affect overall loads in the catchment. The model allows for a wide range of individual and combinations of mitigation measures to be applied at farm, sub-catchment and catchment levels to achieve spatially distributed environmental objectives that are expressed as attribute states.

The catchment economic modelling of the Kaipara Harbour catchment (KHC) was completed using a spatially explicit economic land use model, the New Zealand Forest and Agriculture Regional Model (NZFARM). The model incorporated data and estimates from economic and land use databases and biophysical models. Annual sediment loads from various land uses in the KHC were estimated using the SedNet model (Dymond 2016), while the harbour sediment budget was estimated by Streamlined Environmental (Green et al. 2017). Land-based mitigation costs and effectiveness in reducing sediment were obtained from a range of sources and summarized by Basher (2017). The estimates from the catchment economic model are also incorporated into more detailed analyses and narratives about the potential impacts of mitigation on freshwater sediment attributes (Matthaei 2017) and harbour ecosystem health and functioning (Lohrer 2017).

NZFARM includes several options for managing sediment from different land uses that ranging from intensive pasture to native bush. These options include implementing farm-management plans, fencing streams, and constructing wetlands, as well as number of other practices.

Several model scenarios were conducted to assess the possible impacts for a range of management and mitigation approaches to reduce sediment in the KHC. For the analysis, these included practice-based approaches such as fencing all streams to exclude livestock as well as outcome-based approaches such as meeting sediment load reduction targets in specific freshwater nodes or marine sediment basins of the KHC. We also modelled full pine afforestation and full native afforestation with constructed and restored wetlands to establish the minimum feasible loads and best possible attribute states that could be achieved in the KHC. In all scenarios, mitigation costs estimates are reported as annual figures. 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 KHC, the model also estimated changes in marine and freshwater sediment attributes. These included three freshwater sediment attributes: water clarity, euphotic depth, and suspended sediment, and one harbour sediment attribute: the annual average sedimentation rate (AASR).

The economic catchment model was primarily developed to bring various aspects of the KHSES together using an integrated framework to analyse the potential impacts of sediment management in the Kaipara Harbour catchment. While the scenarios were defined with the assistance of NRC and AC, the findings of this report should be interpreted more as an illustration of the range of options and impacts that could occur in the KHC as opposed to a formal regulatory analysis of a specific policy or rule change.

# 2 Methodology

This report presents the assessment of the potential economic and environmental impacts of reducing sediment in the KHC, which spans both Northland and Auckland. The economic analysis is conducted using the NZFARM model. Baseline estimates of sediment were obtained through the SedNet (Dymond 2016). Economic impacts are estimated as the cost to landowners and councils for implementing mitigation options relative to their current management practices. Environmental impacts are measured as changes in sediment loads and related attributes relative to a no mitigation baseline[5]. A more detailed description of the integrated economic catchment model follows.

## 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

[5] N.B., while we do quantify the physical change in catchment-based erosion in the KHC, the benefits associated with reduced sediment and improved water quality attributes are not monetized.

Research (Daigneault & Samarasinghe 2015; Daigneault et al. 2017a). Its primary use is to provide decision-makers with information on the economic impacts of environmental policy. It can be used to assess how changes in technology, commodity supply, 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 model developed for the KHC analysis tracks changes in land use, land management, agricultural production, and sediment 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 period 10 years or more to fully implement.

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 KHC 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 load restrictions in NZFARM are parameterised using estimates from biophysical and farm budgeting models, which are described in more detail below.

The model's objective function maximizes the net revenue[6] of agricultural production across the entire Kaipara Harbour 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:

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

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, $\omega^{live}$, $\omega^{vc}$, $\omega^{fc}$ are the respective livestock, variable (e.g. fertilizer), and fixed (e.g. accounting) input costs, $\tau$ is an environmental tax (if applicable), $\gamma^{env}$ is an environmental output coefficient, $\omega^{land}$ is a land use conversion cost, and *Z* is the area of land use change from the initial (baseline)

[6] 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.

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 ($\alpha^{proc}$) that specifies what can be produced by a given activity in a particular part of the catchment:

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

Landowners are allocated a certain amount of irrigation ($\gamma^{water}$) for their farming activities, provided that there is sufficient water (*W*) available in the catchment:[7]

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

Land cover in the catchment is constrained by the amount of land available (*L*) in a specific sub-catchment 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:

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

[7] N.B. For this analysis, we assume there are no irrigated land uses in the KHC.

The model also includes a constraint on changes to enterprise area (*E*), if desired:[8]

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

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 loads. In the case where farm-based loads ($\gamma^{env}$) are regulated by placing a cap on a given environmental output from land-based activities (*ENV*), landowners could also face an environmental constraint:[9]

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

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:

$$Y, X, L \geq 0 \quad (10)$$

The 'optimal' distribution of land-based activities based on sub-catchment $s_{1 \ldots i}$, 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 sediment reduction target at least cost). Commodity prices, environmental constraints (e.g. sediment load cap), 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).

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[8] N.B. The KHC analysis was primarily focused on the effects of land management on sediment 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.

[9] 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.

At the highest levels of the CET nest, land use is distributed over the zone based on the fixed area of various sub-catchments. 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, pole planting) 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, $\sigma_i$, 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 ($\sigma_S$) is set to be 0, as the area of a particular sub-catchment in a zone is fixed.[10] In addition, the parameter for agricultural production ($\sigma_A$) 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 postitive mathematical programming (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).

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[10] Recall that other NZFARM-based catchment models (e.g. Daigneault et al. 2017a) 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.

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 contracted to undertake an analysis of baseline erosion rates and sediment yields in the KHC using the SedNetNZ model (Dymond 2016). The catchment erosion and sediment model simulates several erosion processes, sediment storages, and transfers. For this analysis, SedNetNZ has been calibrated for the KHC and downscaled to the farm scale. For the economic catchment model, sediment is estimated to come from two sources: land-based[11] 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 18,000 in the KHC (Fig. 1a–b). More details on SedNetNZ are available in Dymond (2016), and larger versions of these maps are included in Appendix 3.

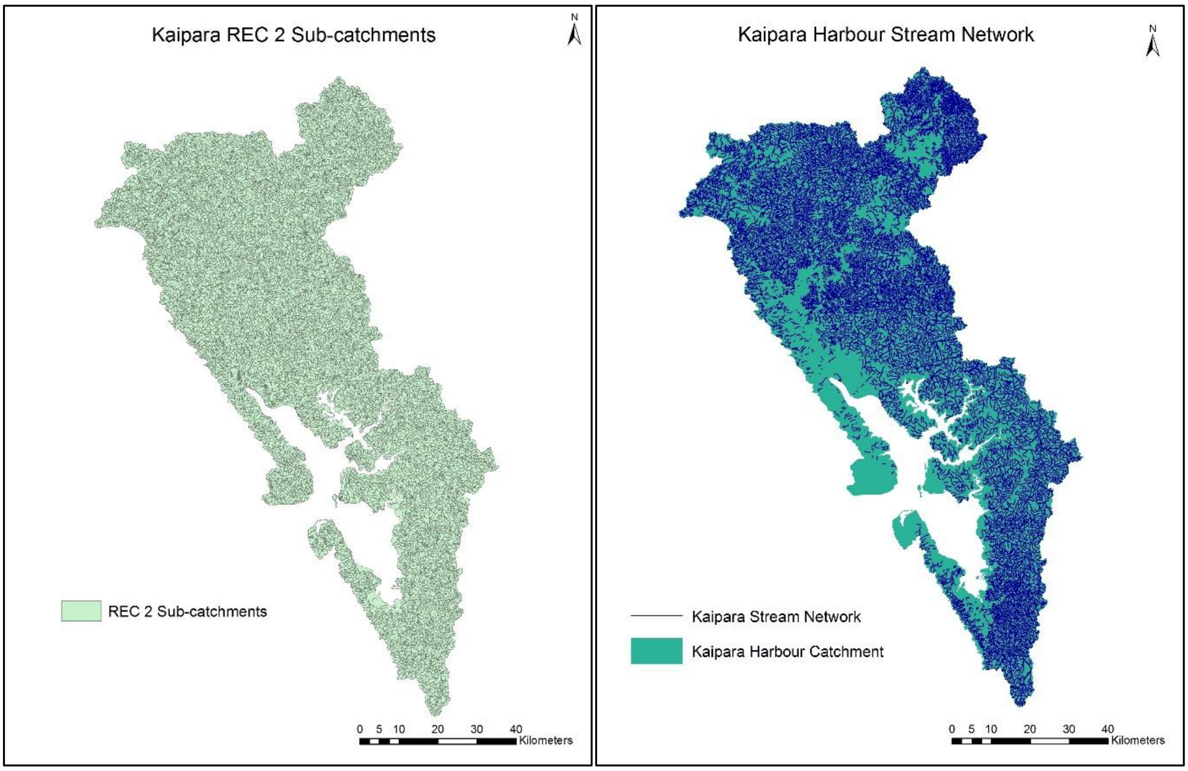


**Figure** 1a-**b**: Kaipara Harbour Catchment river environmental classification level 2 (REC2) sub-catchments and stream network.

[11] N.B. 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 et al. (2017) used estimates from SedNetNZ to estimate the sediment budget for 9 reporting zones within the KHC. 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 et al. (2017) that relate catchment sediment runoff and mass of marine sediments transported by waves and currents to sedimentation rates in nine estuary depositional basins were incorporated into NZFARM. The reporting zones and depositional basins are shown in Figure 2a–b.

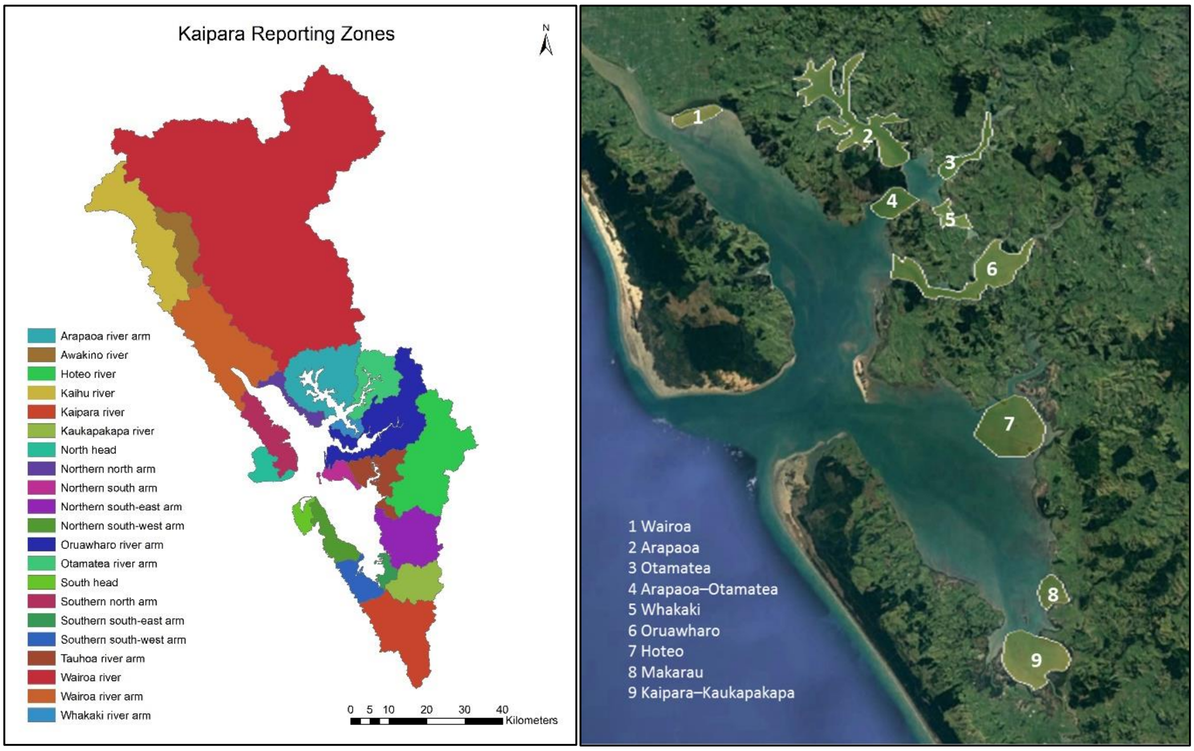


**Figure** 2a-**b**: Kaipara Harbour Catchment reporting zones and depositional basins[12].

## 2.4 Water quality attributes

This report models the impact of land management on a range of freshwater and marine water quality attributes. These include three freshwater sediment attributes: water clarity,

[12] Areas include: 1. Wairoa intertidal flats (WAIF), 2. Arapaoa intertidal flats (ARIF), 3. Otamatea intertidal flats (OTIF), 4. Arapaoa-Otematea and Tinopai subtidal flats (TNSF), 5. Whakaki intertidal flats (WHIF), 6. Oruawharo intertidal flats (ORIF), 7. Kakarai intertidal flats (KAIF), 8. Makarau intertidal flats (MAIF), and 9. Kaipara-Kaukapakapa intertidal flats (KPIF).

euphotic depth, and suspended sediment; and one estuary sediment attribute: average annual sediment rate (AASR).

### 2.4.1 Freshwater sediment attributes

The three attributes agreed upon for freshwater sediment attributes in the KHSMS are water clarity, euphotic depth, and suspended sediment. 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 are perfectly correlated. Dymond (2016) provides more details on how these attributes were estimated for 7 sites in the Kaipara Harbour Catchment (Fig. 3).

Due to a lack of knowledge about what the ‘appropriate’ targets should be, the KHSMS did not specify explicit targets for the freshwater sediment attributes as part of this analysis.[13] 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” (i.e. no scenarios produced more erosion or sediment that the no mitigation baseline at any given site).

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

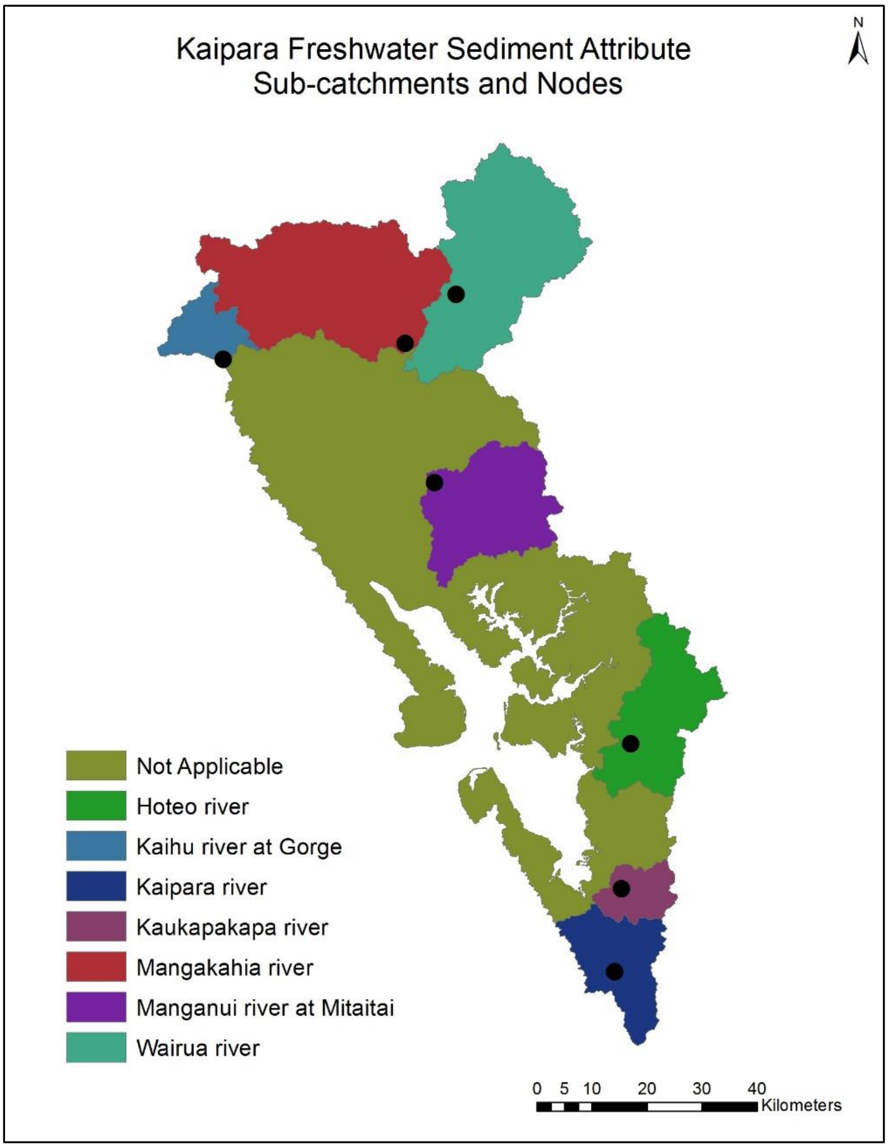


**Figure 3**: Kaipara Harbour catchment freshwater sediment node sub-catchments.

### 2.4.2 Estuary sediment attributes

Green et al. (2017) showed how the Kaipara Harbour catchment estuary sediment budget could be manipulated to calculate catchment sediment load limits that will achieve a target annual-average sedimentation rate (AASR) in a specific harbour basin. Green (2013) 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. The same report also 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 (Green et al, 2017). 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 sediment attribute. Still, they suggest using the AASR as the single estuary sediment attribute in the KHSMS on the basis that it is reasonable to assume AASR is indicative of a wide range of sediment related effects in the region, thus rendering it an appropriate attribute for the Kaipara Harbour.

## 2.5 Mitigation practices

We track several mitigation options for reducing sediment loads from pastoral, arable, and horticultural land in the catchment, which were based on Basher (2017). A description of each option is listed in Table 1. More details on the mitigation options are presented in Appendix 1. Note that although there are several options presented in the table and included in the catchment economic model, many of them are assumed to apply only to arable and horticultural enterprises. Less than 1% of the total area in the Kaipara Harbour catchment is of these land uses, which produce about 0.5% of total baseline annual erosion, and thus implementing many of these practices will have little to no effect on total erosion in the catchment. Finally, we did not include any options to mitigation urban-based sediment in the KHC in the catchment economic model as this was outside the scope of the study. This omission should have minimal impact on the results, as both the area and sediment associated with urban land is less than 0.5% of the catchment baseline.

**Table 1:** Summary of the modelled mitigation options

| Mitigation Type | Description | Land Cover Applicability | | Erosion Process | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Pasture | Arable & Horticulture | Earth flow | Gully erosion | Land slides | Surface erosion | Bank erosion |
| Afforestation | Plant non-native land with pine plantations or native bush | X | X | X | X | X | | X |
| Farm Management Plan (e.g. Space-planting) | Plan largely consisting of poplar or willow planting of various widths and densities. Also may include other farm-specific options such as bunds | X | | X | X | X | | |
| Riparian fencing | Construct fences along permanently flowing waterways (rivers and streams) | X | | | | | | X |
| Riparian fencing + planting | Construct fences along permanently flowing waterways (rivers and streams) and plant 5m strips of grass or other vegetation | X | X | | | | X | X |
| Riparian grass buffer strip | Plant 5m strips of grass or other vegetation without fencing | X | X | | | | X | |
| Wetland Construction | Construct or restore wetlands of various sizes | X | X | X | | X | X | |
| Cover crops | Applied to arable or horticultural land | | X | | | | X | |
| Debris dams | Construct in gully, often along with tree planting | X | | | X | | | |
| Sediment retention pond | Construct pond to trap sediment at bottom of sub-catchment | X | X | | | | X | |
| Silt fence | Erected to catch urban sediment flow | | X | | | | X | |
| Wheel track diking | Applied to arable or horticultural land | | X | | | | X | |
| Wheel track ripping | Applied to arable or horticultural land | | X | | | | X | |
| Combination | Includes a combination of the practices listed above. Often more effective, albeit at a higher cost | X | X | X | X | X | X | X |

## 2.6 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, etc.).

Table 2 lists the key variables and data requirements used to parameterise the KHC version of NZFARM, while Table 3 provides specific elements of the model. More details on the data and parameter assumptions used to populate the KHC version of the model are provided below, while further information can be found in Section 3 of Daigneault et al. (2017a). All the figures in the NZFARM are converted to per hectare values and 2012 NZD so that they are consistent across sources and scenarios and previous studies conducted in the region (e.g., Daigneault and Samarasinghe 2015).

**Table 2**: Data sources for NZFARM's modelling of Kaipara Harbour Catchment

| Variable | Data requirement | Source | Comments |
|---|---|---|---|
| Geographic area | GIS data identifying the catchment area | Catchment and sub-catchments based on REC 2 | Provided by NRC |
| Land cover and enterprise mix | GIS data file(s) of current land use with the catchment<br>Key enterprises (e.g. dairy). | Estimated using national land use map based on AgriBase (v2014) and LCDBv4 | Land use map verified by project partners. |
| Management practices | Distribution of feasible management practices (e.g. stream fencing, farm, management plan, etc.) | List developed by Basher (2017) | Data and assumptions verified by project partners |
| Climate | Temperature and precipitation | Historical data<br>Future climate projections being developed in alternative project | Analysis assumes constant climate and production |
| 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 and Auckland Region, but nothing specific to KHC | 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 | Streambank Erosion/Sediment<br>Land-based sediment (Earth flow + gully erosion + landslides + surface erosion) | Sediment based on SedNet model | Data supplied by project partners |

**Table 3**: List of key components of NZFARM Kaipara Harbour Catchment

| Enterprise (E) | Mitigation Practice (M) | Sub-catchment (S) | Reporting Zone (R) | Environmental Indicators (ENV) |
|---|---|---|---|---|
| Dairy<br>Sheep & Beef<br>Deer<br>Lifestyle<br>Forestry<br>Horticultural crops<br>Arable crops<br>Scrub<br>Native bush<br>Other | Afforestation<br>Cover crops<br>Debris dams<br>Riparian fencing<br>Riparian fencing+planting<br>Riparian grass buffer strip<br>Wetland Construction<br>Sediment retention pond<br>Silt fence<br>Space-planting<br>Wheel track diking<br>Wheel track ripping<br>Combination | 18,700 REC 2 sub-catchments | 21 Kaipara harbour catchment reporting zones | Streambank sediment<br>land-based sediment<br>Total sediment<br>Suspended sediment<br>Water clarity<br>Euphotic depth<br>Annual-average sedimentation rate |

### 2.6.1 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 2014 GIS-based land use map created by Landcare Research using the latest information from Agribase and the NZ Land Cover Database version 4 (LCDBv4) (Fig. 4). The catchment is approximately 602,000 ha in size, and key land uses include sheep & beef (47%), dairy (23%), plantation forestry (14%), and native bush (14%). Approximately 74% of the catchment has a landcover of pasture, and thus many of the farm-based mitigation options explored in this study should have a noticeable effect on erosion loads in the catchment.[14]

[14] N.B. This is different than the Whangarei Harbour Catchment study (Daigneault & Samarasinghe 2015), where only 46% of the catchment was covered in pasture, and thus significant erosion load came from other sources.

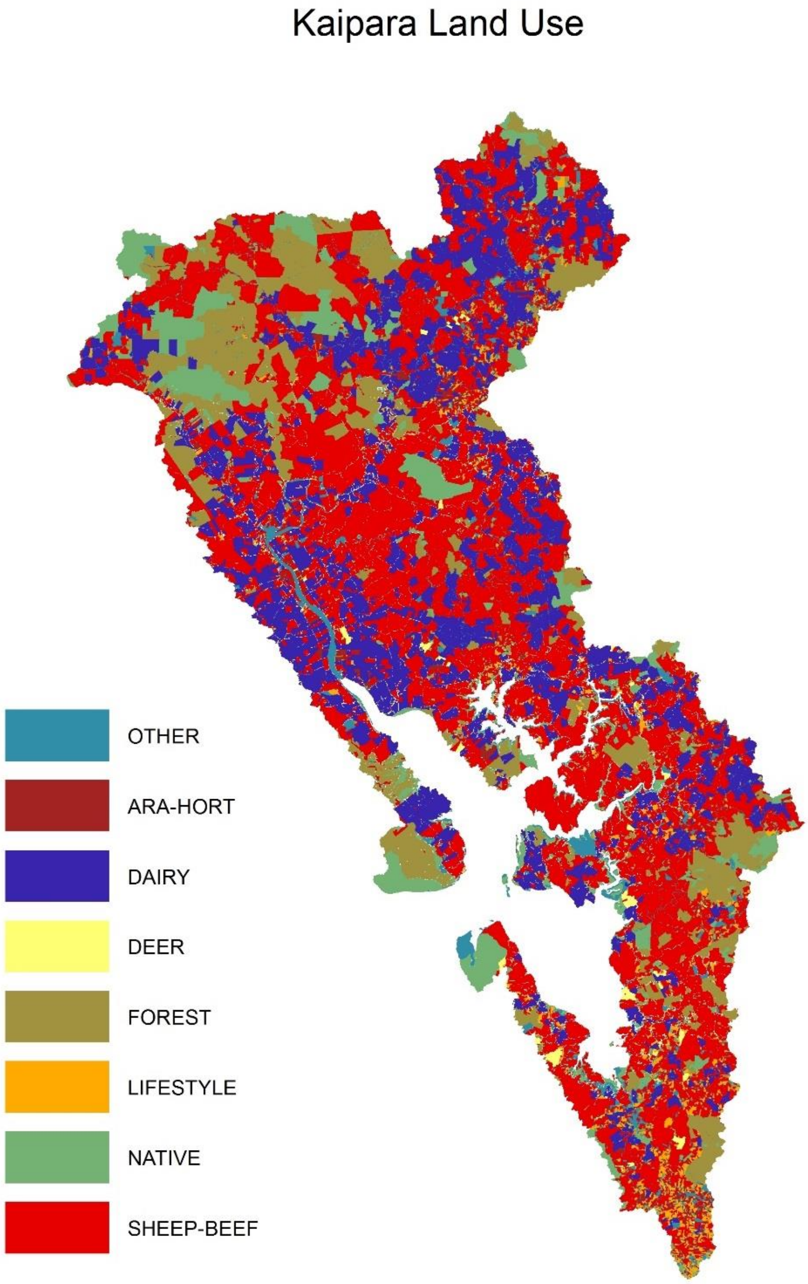


**Figure 4**: Kaipara Harbour Catchment land use.

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. (2017a). In addition, the KHC-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 5. Although dairy only makes up 23% of total land use in the catchment, it produces about 78% of the total farm net revenue, followed by forestry (14%), horticulture and arable (6%). Sheep and beef farming largely occurs on steep and low productivity land, and thus only produces 3% of total net farm revenue in the Kaipara Harbour catchment.

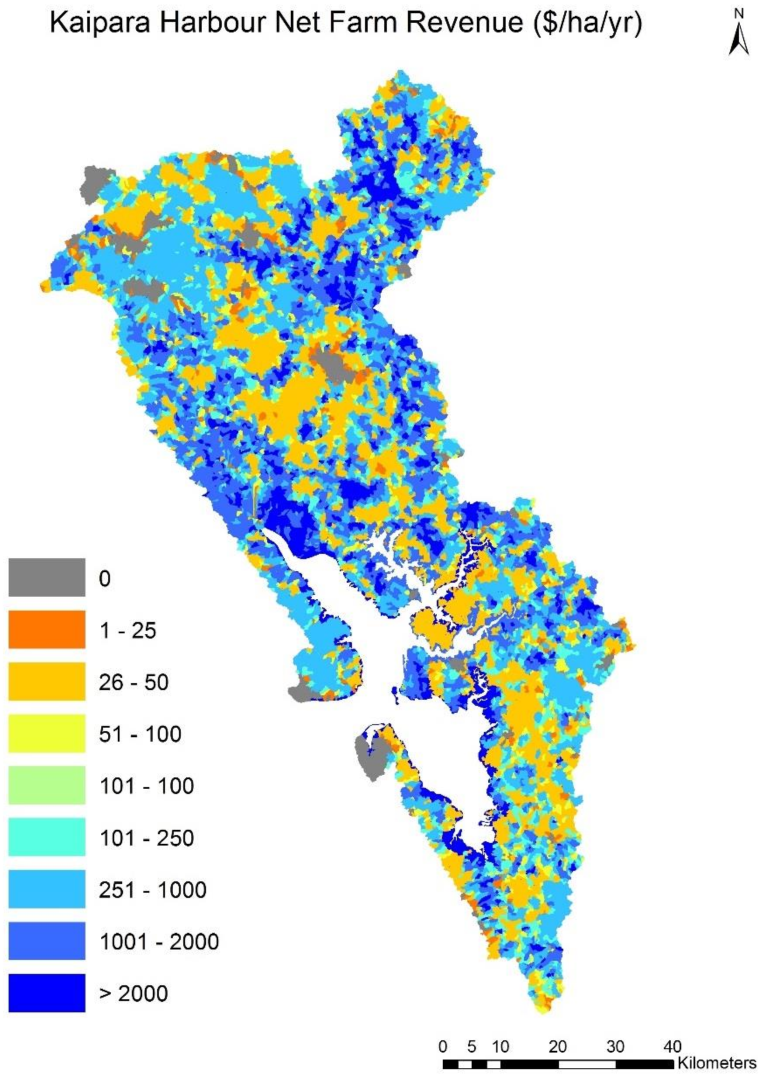


**Figure 5**: Baseline net farm revenue ($/ha/yr).

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 and retention bunds. 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.[15] 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[16] (e.g. nutrients reduction targets in Daigneault et al. 2013).

### 2.6.2 Nodes of Importance

The project group consisting of AC, NRC, Streamlined Environmental and Landcare Research established that there are seven sites that could be defined or classified as freshwater nodes of importance. These sites were primarily chosen because they are located near environmental monitoring stations (Dymond 2016), where sediment rating curves could be developed so that quantitative relationships between sediment loads and attributes could be established. The locations of the sites are shown above in Figure 3. Table 4 presents the land use distribution, in hectares, at the seven nodes. It is important to note that the total size and land use distribution for each node varies widely, which has an impact on the total effectiveness of implementing particular mitigation options to meet attributes for each of these nodes. For example, 46% of the land that feeds into the Mangakahia river node is classified as forestry or native bush and thus does not benefit from implementing the erosion control practices identified for this study near that site as much as, say, the Manganui river at the Mitaitai node, which is only 10% forest cover.

**Table 4**: Land use area (ha) of Kaipara Harbour Catchment sites classified as nodes of importance

| Land Use | Hoteo river | Kaihu river at Gorge | Kaipara river | Kaukapakapa river | Mangakahia river | Manganui river at Mitaitai | Wairua river | Node Total |
|---|---|---|---|---|---|---|---|---|
| Dairy | 7,177 | 4,029 | 2,031 | 1,957 | 10,823 | 17,018 | 28,119 | 71,155 |
| Sheep & Beef | 18,914 | 4,055 | 10,670 | 5,042 | 30,257 | 23,216 | 21,870 | 114,025 |
| Deer | 121 | 0 | 340 | 205 | 2 | 235 | 224 | 1,125 |
| Lifestyle | 1,642 | 184 | 4,974 | 1,441 | 331 | 302 | 2,837 | 11,711 |
| Arable & Hort | 62 | 0 | 1,124 | 84 | 388 | 131 | 1,175 | 2,964 |
| Forestry | 9,135 | 2,696 | 3,417 | 706 | 25,691 | 3,154 | 6,676 | 51,474 |
| Native Bush | 3,867 | 3,498 | 1,601 | 783 | 13,060 | 1,949 | 4,400 | 29,159 |
| Other | 3,965 | 1,146 | 4,311 | 2,147 | 3,359 | 3,414 | 9,470 | 27,814 |
| **Total** | **44,885** | **15,608** | **28,468** | **12,365** | **83,912** | **49,418** | **74,771** | **309,426** |

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

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

### 2.6.3 Sediment Loads

Sediment load estimates are taken directly from the SedNetNZ model (Dymond 2015), which quantifies annual land-based 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 reported figures from SedNetNZ.

SedNetNZ estimates that the total load in the catchment is about 692,000 tonnes of sediment per year. About 52% of this is estimated to arise from land-based erosion, while the remainder is from streambank erosion (Figures 6–8).

A bulk of the sediment is estimated to come from land used for sheep and beef farming (36%), native land (26%), and pine plantations (13%), due to both the proportion of total area of these land uses in the catchment as well as physical characteristics of the land on which these enterprises are located. 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 was converted to pasture, the level of erosion could increase by a factor of 10 (Dymond et al. 2010).

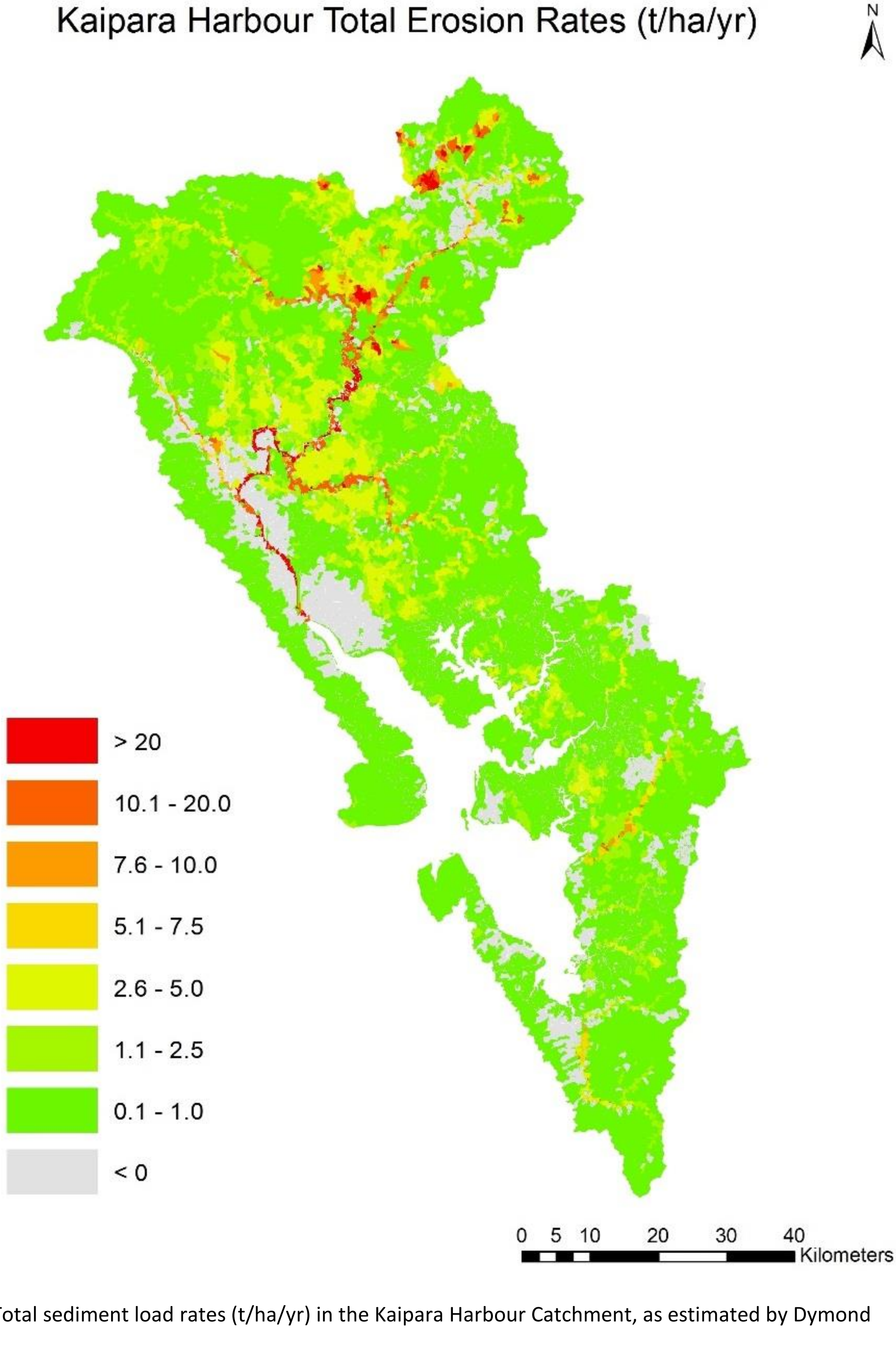


**Figure 6**: Total sediment load rates (t/ha/yr) in the Kaipara Harbour Catchment, as estimated by Dymond (2016).

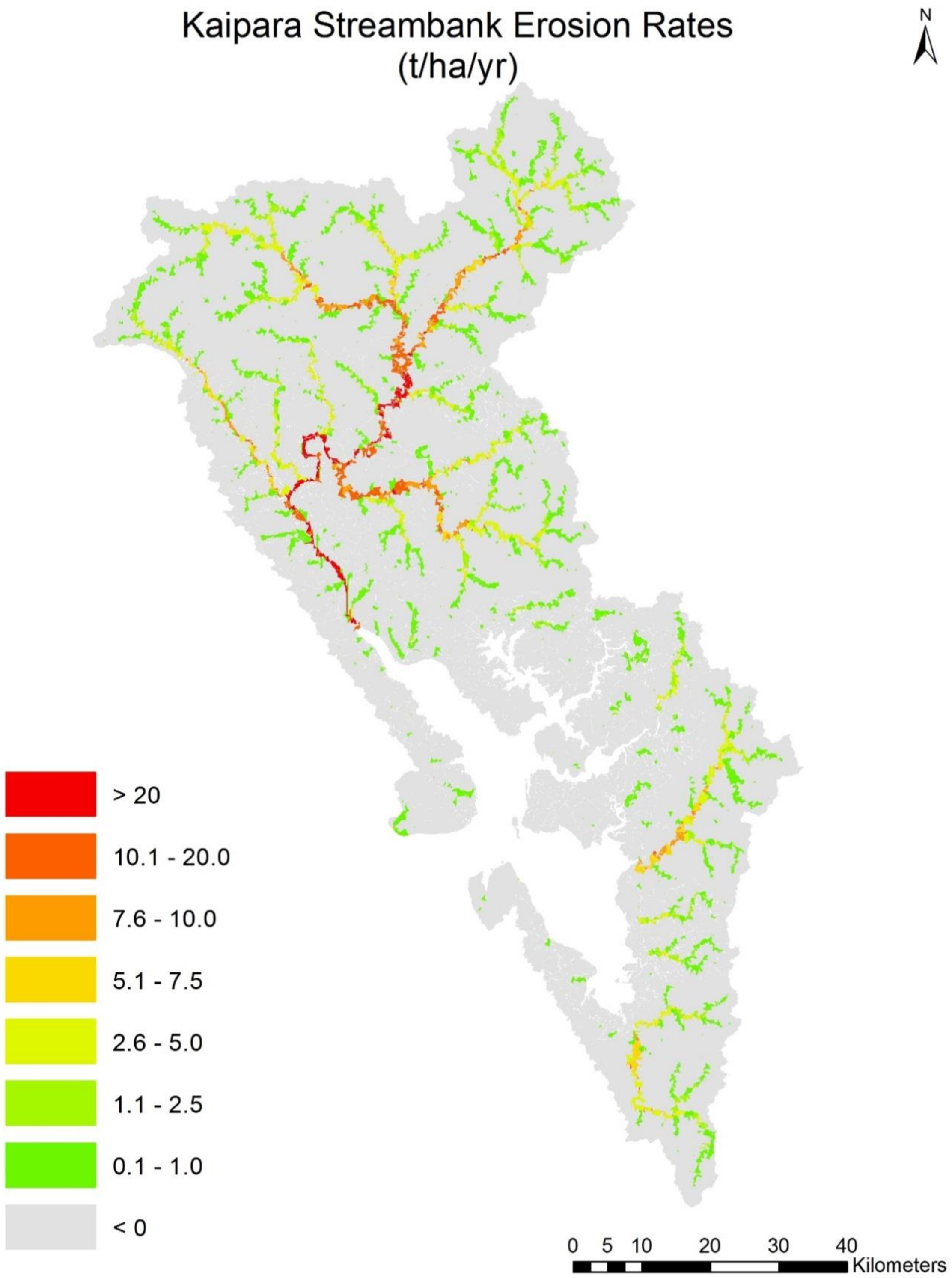


**Figure 7:** Total streambank sediment load (t/ha/yr) by REC2 stream reach in the Kaipara Harbour Catchment, as estimated by Dymond (2016).

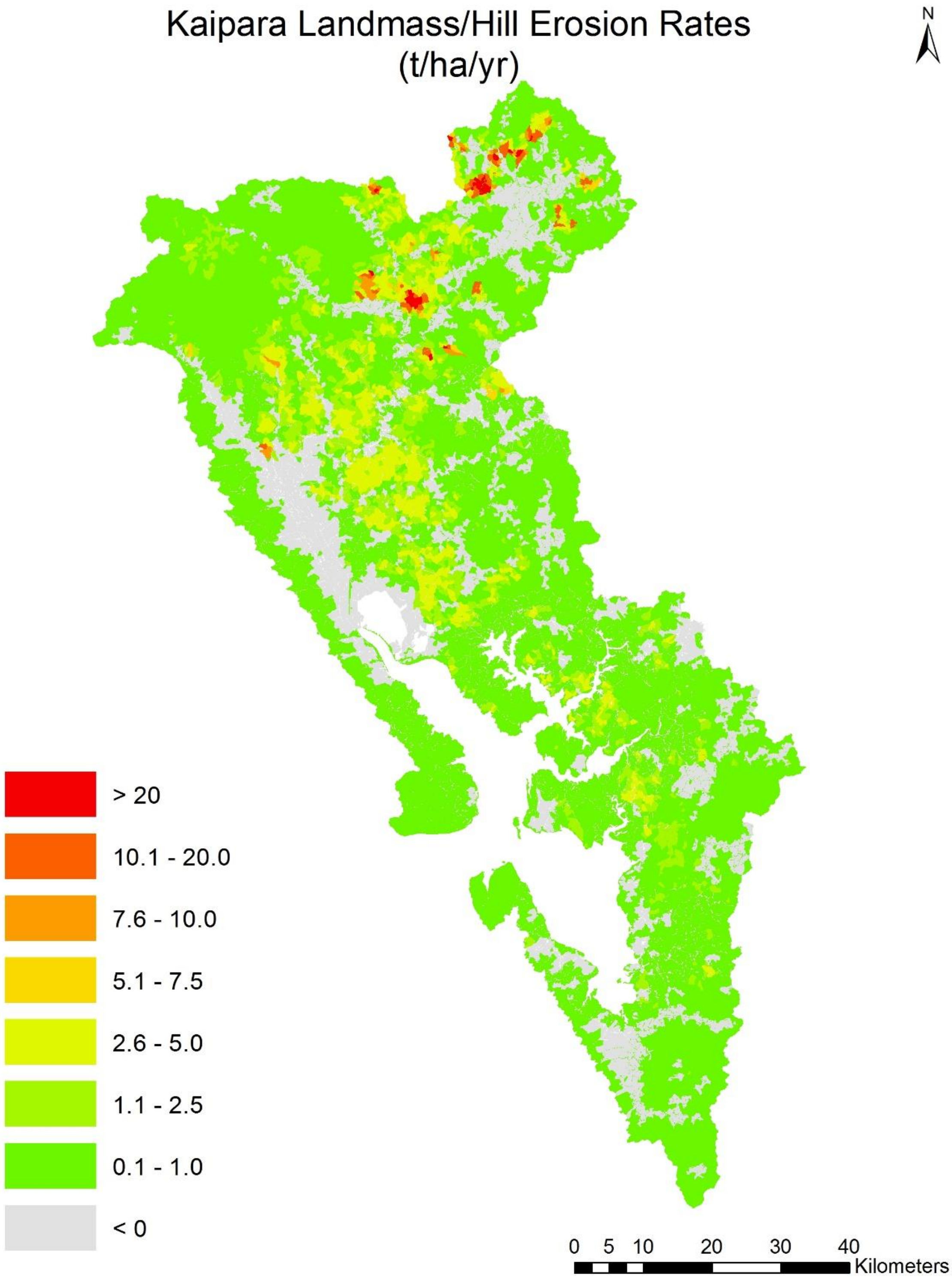


**Figure 8:** Total land-based sediment (t/ha/yr) by REC2 stream reach in the Kaipara Harbour Catchment, as estimated by Dymond (2016).

### 2.6.4 Freshwater Sediment Attributes

Dymond (2016) estimated relationships between the reduction in sediment loads and resulting freshwater attribute state for seven nodes (sites) in the KHC where monitoring and flow data was available (Table 5). Modelled attributes include water clarity, euphotic depth, and suspended sediment. NZFARM has been programmed with all of the equations from Dymond (2016) 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 (i.e. 10, 80, and 95) as well[17].

**Table 5**: Baseline freshwater sediment attribute estimates for seven nodes (sites) in Kaipara Harbour catchment, defined by the median flow percentile for each node

| Freshwater Sediment Node | suspended sediment (gm/m3) | water clarity (m) | euphotic depth (m) |
|---|---|---|---|
| Hoteo at Gubbs | 3.5 | 1.3 | 2.0 |
| Kaihu at Gorge | 2.6 | 1.6 | 2.2 |
| Kaipara | 1.83 | 2.11 | 2.63 |
| Kaukapakapa at Taylors | 3.36 | 1.34 | 2.04 |
| Mangakahia at Titoki | 11.1 | 0.7 | 1.5 |
| Manganui at Mitaitai | 2.63 | 0.87 | 1.84 |
| Wairua at Purua | 7.3 | 0.8 | 1.5 |

### 2.6.5 Harbour/Estuary Sediment Attributes

The harbour sediment attribute of AASR is estimated using methods reported by Green et al. (2017), who develop 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.

The baseline values for the AASR in the nine harbour deposition basins, as estimated by Green et al. (2017), are shown in Figure 9. The total ASSR is broken out by a combination of land and marine sourced sediment.

These equations specified by Green et al. (2017) 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 and-based and streambank erosion in the catchment. Thus, we only model the impact of land management in the KHC on the blue portion of the bars in Figure 9. This suggests land

[17] N.B., the catchment economic model has been programmed to quantify impacts for all four percentiles, but results for this study were only quantified for the median flow.

management will have a larger influence on the AASR rate in the Kaipara-Kaukapakapa and Makarau basins than in the Arapaoa-Otamatea and Hoteo basins.

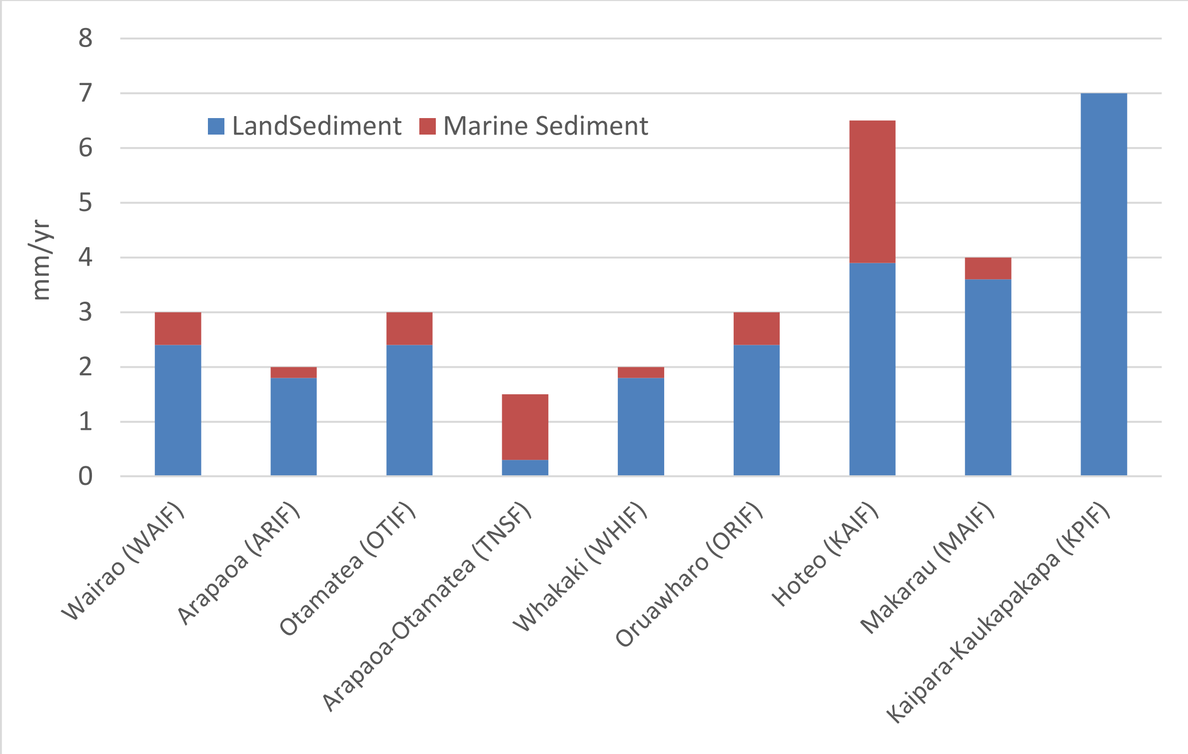


**Figure 9**: Contribution to baseline AASR for nine Kaipara Harbour deposition basins of land and marine sources of sediment.

### 2.6.6 Mitigation Costs

Assumptions about mitigation costs and effectiveness in reducing sediment loads were created by Les Basher of Landcare Research, with input from experts and regional land managers (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, an expert on this topic, who also visited the Wairua sub-catchment as part of another project and conferred with other members of the project team (see Appendix 2, Daigneault et al. 2017b, and Daigneault & Samarasinge 2015). The costs are broken out by initial capital, ongoing and periodic maintenance, and opportunity costs from taking land out of production. A summary of many of these costs are outlined in Table 6.

**Table 6**: Detailed mitigation cost and effectiveness assumptions for key mitigation practices used in KHSMS^

| Mitigation Option | | Eligible Land Uses | Max coverage | Cost Component | | | Mitigation Effectiveness (% from baseline) | |
|---|---|---|---|---|---|---|---|---|
| | | | | **Initial Capital (year 0)** | **Maintenance** | **Annual Opportunity** | **Land-based Erosion*** | **Bank Erosion** |
| 1 | Farm Management Plan (e.g. Space-planting) for land-based erosion control | Pasture | all farms | Plan: $5000/farm up to 100 ha + $10/ha for each additional ha<br>Implementation: $250/ha | None | None, as plan assumed to identify options where benefits offset production losses | 70% | 0% |
| 2 | Riparian Fencing | Pasture | all REC2+ permanently flowing rivers and streams | S&B: $35/m, including materials, construction, and reticulation<br>Dairy: $7.50/m | None | None | 0% | 50% |
| 3 | Constructed wetland | Pasture, arable | 1 per 400 ha | $100,000/system, including planting and fencing | $300/system/yr | 40% of farm income in occupied area | 70% | 0% |
| 4 | Farm Plan + Fencing | Pasture | See 1 & 2 | Sum of #1 and 2 | None | None | 70% | 50% |
| 5 | Farm Plan + Fencing + Wetland | Pasture | See 1– 3 | Sum of #1, 2 and 3 | Sum of #1, 2 and 3 | 40% of farm income in area occupied by wetland | 70% | 50% |
| 6 | Riparian Fencing + Planting | Pasture | all REC2+ permanently flowing rivers and streams | Sum of #2 and $4/m2 for planting costs | Periodic | 50% of farm income in area occupied by riparian planting | 50% | 70% |
| 7 | Afforestation - Harvest | All non-forestland | all farms | $1000/ha | None | 100% of lost farm income in planted area, less new income from forestry | 80% | 80% |
| 8 | Afforestation - No Harvest | All non-forestland | all farms | $1000/ha | None | 100% of lost farm income in planted area | 90% | 90% |

^N.B., model also included arable and horticultural mitigation practices, which were never estimated to be implemented. See Appendix 1 for detailed costs.

*Includes landslide, gully, earthflow, and surficial erosion

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%, which are typical assumptions for this type of analysis (e.g. Daigneault & Samarasinghe 2015; Grintner & White 2016).[18] 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.

Each mitigation option has the potential to have different impacts based on the size, location, and net revenue of the farm. For example, a large sheep and beef farm next to a large stream will likely face higher absolute costs for the fencing option than for the farm management plan. This is because the farm management plan consists of a large initial fixed cost ($5,000+) that does not vary by farm size. In contrast, 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 and thus incur an opportunity cost.

# 3 Scenarios

NRC and AC specified a range of mitigation scenarios to be analysed. For the analysis, these included five practice-based approaches, such as fencing all streams for stock exclusion, as well as four outcome-based approaches, such as meeting sediment-load reduction targets in specific freshwater nodes or marine sediment basins of the KHC. We also modelled two large afforestation scenarios to establish the minimum feasible loads and best possible attribute states that could be achieved in the KHC. In all scenarios, mitigation costs estimates are annualised and assumed to be accrued for 25 years.

In addition to assessing the cost and effectiveness of practices and policies that could reduce loads in the KHC, the model also estimated changes in marine and freshwater sediment attributes. These included three freshwater sediment attributes: water clarity, euphotic depth, and suspended sediment, and one harbour sediment attribute: the annual average sedimentation rate (AASR).

[18] This approach is common for farm financial modelling as well as in estimating returns for the forest sector, where yearly costs and returns are estimated using an equal annual equivalent (EAE), calculated as:

$EAE_{mitigation} = \frac{r * NPV_{mitigation}}{1-(1+r)^{-n}}$, where $NPV_{mitigation}$ is the total net present value of all costs (i.e. initial, maintenance, and opportunity) for a given mitigation option (e.g. farm management plan), *r* is annual interest rate, *n* is the number of years the costs are annualized. For this study, we annualize the costs over 25 years using a discount rate of 8%. This equates to multiplying the NPV of the mitigation option by a factor of 0.09368.

**Table 7:** NZFARM scenarios for the Kaipara Harbour catchment

| Scenario # | Scenario Name | Scenario Description |
|---|---|---|
| 0 | Baseline | Current land use with no mitigation practices to match same assumption as SedNetNZ erosion model. |
| | | Practice-based Scenarios |
| 1 | Current Mitigation | Current land use with likely proportion of mitigation practices implemented today. Assumes 80% of streams and rivers on dairy farms and 30% of streams and rivers on other pastoral land are fenced to exclude livestock (dairy cattle, dairy support cattle, beef cattle and deer) and 10% of pastoral land area with 1.0 t/ha/yr or higher erosion rates (i.e., highly erodible land, HEL) has soil conservation measures. |
| 2 | Farm Management Plan on all Highly Erodible Pastoral Land | Current land use with farm management plans (predominately promoting soil conservation by planting poplar or willow poles) implemented on all HEL. |
| 3 | Stock Exclusion Rules | Current land use with riparian fencing of River Environment Classification 2 (REC2) or larger permanent streams for stock exclusion on all pastoral land meeting the NZ Government's proposed stock exclusion regulations (2017). |
| 4 | Stock Exclusion with Riparian Planting | Current land use with riparian fencing for stock exclusion on all pastoral land meeting the NZ Government's (2017) proposed stock exclusion regulations on REC2 or larger permanent streams, but also with 5m stream buffer with planted vegetation. |
| 5 | Stock Exclusion + All HEL Plans | Combination of scenarios 2 and 3. |
| | | Outcome-based Scenarios |
| 6 | Freshwater Node 10% | Total annual sediment load reduced in all seven freshwater zones reduced by 10%. |
| 7 | Freshwater Node 30% | Total annual sediment load reduced in all seven freshwater zones reduced by 30%. |
| 8 | Marine Deposition 15% | Total annual sediment load reduced in all nine marine sediment deposition basins reduced by 15%. |
| 9 | Marine AASR 2mm above 'natural' state | Average annual sedimentation rate (AASR) from catchment-based erosion is no more than 2mm greater than AASR under 'natural' land conditions (Scenario 11). |
| | | Afforestation Scenarios |
| 10 | Full Afforestation (Pine) | All non-forest land (e.g., pasture, arable, lifestyle blocks) is planted with radiata pine. Used to estimate maximum attainable mitigation while maintaining a 'productive' land use. |
| 11 | Full Afforestation (Native) & Wetland Restoration | All non-forest land is planted with native bush and likely extent of pre-human wetlands are restored. Used to estimate 'natural' erosion loads in the catchment and thus maximum attainable mitigation. |

Three scenarios require further explanation. First, the scenarios that targeted farm management plans (i.e. 2 and 5) define highly erodible land (HEL) as pasture land with mean land-based erosion of at least 1.0 t/ha/yr, which was defined in consultation with NRC. Soil management or conservation plans primarily involves planting poplar or willow polies, but exclude stock exclusion (unless practice is combined with riparian fencing). As a result, the area to target is a maximum of 61,800 ha, or 10% of the entire catchment area (Fig. 10a).

The second scenario that requires additional detail is the one that models the NZ government's proposed stock exclusion regulations, which are based on the 'Clean Water' consultation document recently released by the New Zealand Government (MfE 2017). The proposal is that dairy cattle on milking platforms and farmed pigs must be excluded from all permanently flowing waterways at least 1m wide at any one point by the end of 2017. Dairy support cattle (including third-party dairy grazing), plus beef cattle and farmed deer, must be excluded from permanently flowing waterways on land that has a slope of between 0 and 15 degrees (Table 8). For the scenarios that 'followed' these rules, we assumed that all eligible farms had fully implemented their riparian fencing requirements by the end of the model simulation period (i.e., 2030). The area of the catchment in each slope classification is displayed in Figure 10b[19].

**Table 8:** NZ government stock exclusion rules from permanent waterways, as defined by MfE (2017).

| Farm/stock type | Plains (0–3 deg) | Undulating/rolling land (>3–15 deg) | Steep land (>15 deg) |
|---|---|---|---|
| Dairy cattle | X | X | X |
| Dairy support^ | X | X | X |
| Beef cattle and deer | X | X | |

^ land use map did not differentiate between dairy platform and support, so just assumed to be 'Dairy'

* land use map did not differentiate between beef and sheep and beef, so just assumed all sheep and beef land 15 degrees was only beef and had to comply with the proposed regulations.

[19] N.B., the study also evaluated the potential impact of fencing both permanent and intermittent streams in the Auckland Council part of the KHC. Details on this sensitivity case are included in Appendix 7.

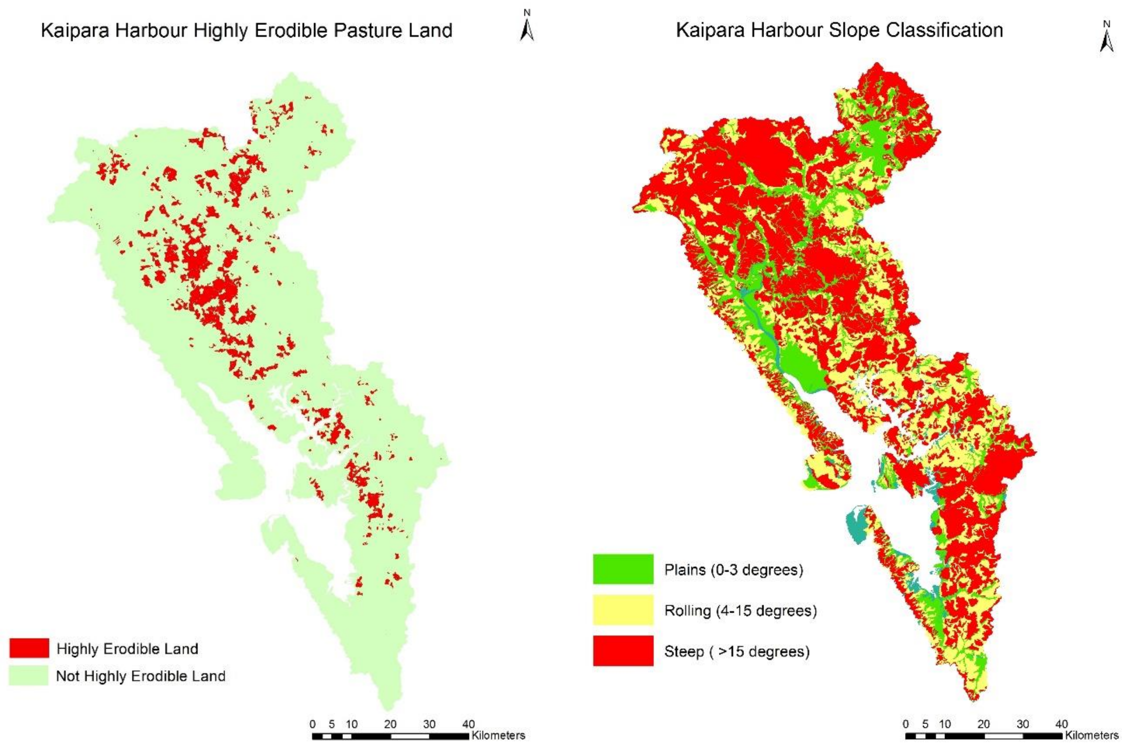


**Figure 10a–b:** Highly erodible pastoral land and slope classification for Kaipara Harbour Catchment (provided by NRC).

The other scenario that requires further explanation is Scenario 8, which constrains the AASR that is produced from catchment-based erosion to 2 mm above 'natural' state. The natural state is based on estimates from Scenario 11, in which all non-forest land is planted with native bush and pre-settlement wetlands are restored. As a result, the blue bars in Figure 9 will have to be 2 mm high or less (as depicted in Figure 11Figure 9). This means that reductions will primarily have to occur in three of the nine harbour deposition basins: Hoteo (KAIF), Makarau (MAIF), and Kaipara-Kaukapakapa (KPIF), in which the land sediment component of the AARS will have to be reduced by 28%, 31%, and 55%, respectively, relative to the baseline (see Figure 9). Note that the contribution of marine-based sediment to the AASR in each basin will remain the same as the baseline as we do not model the effect of mitigation on this source.

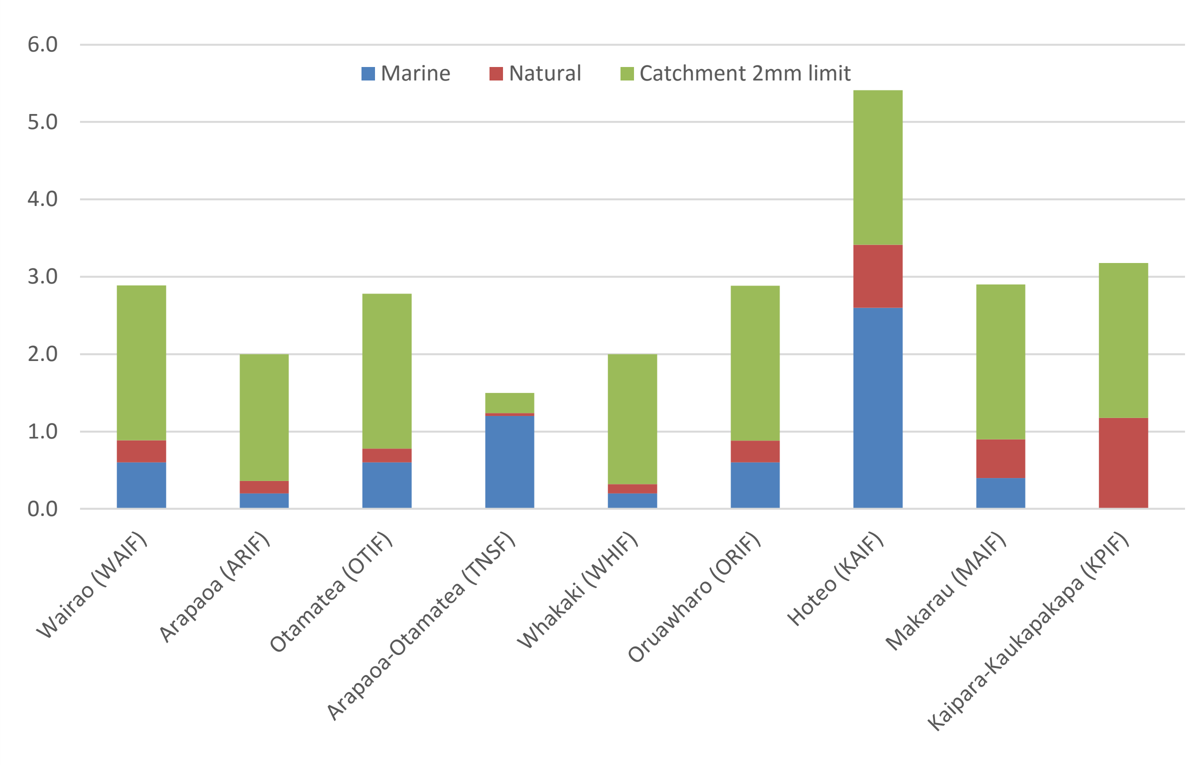


**Figure 11**: Contribution to 'natural' + 2-mm AASR scenario for 9 Kaipara Harbour deposition basins of land and marine sources of sediment

# 4 Baseline

NZFARM must establish a baseline for the KHC before conducting any scenario analysis. Here we specify that the distribution of enterprise area in each of the model's 18,000-plus sub-catchments match the land use map. The baseline also assumes no sediment mitigation practices or policies have been implemented (including existing farm plans or stream fencing).[20] The 'no mitigation' baseline is the same assumption that was used for sediment modelling in SedNetNZ. This approach was taken to define the 'baseline' as there was no spatially explicit information on which farms in the catchment are currently fenced or how effective that fencing is.[21] That is, while NRC could provide a general estimate that about 10% of land classified as HEL is likely to have implemented a farm management plan, they could not provide details on where exactly in the catchment these plans have been carried out. Thus, the NZFARM sediment mitigation figures – and costs associated to achieve

[20] 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. Alternative estimates comparing scenario outputs relative to the 'current' scenario are presented in Appendix 6 (Table A.6.3).

[21] We model current fencing and farm management plans (e.g. pole planting) in one of the scenarios, which presents a possible sensitivity of our no mitigation assumption.

specific reduction targets – 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 9. Total net farm income from land-based operations with the current land use mix is estimated at $16.6 million/yr or $618/ha for all land and $697/ha for land that is currently earning revenue from farming and forestry. Total sediment load is about 691,000 tonnes, of which more than 52% comes from land-based erosion. Nearly all the catchment-based sediment deposited into the Kaipara Harbour (Green et al. 2017).

These baseline estimates represent the figures against which the scenario analysis impacts are measured, including changes in sediment load, net farm revenue, and freshwater and marine sediment attributes.

**Table 9**: Baseline area, annual farm earnings, and annual erosion outputs by land use

| Land Use | Area (ha) | Net Farm Revenue ($/yr) | Land-based Erosion (t/yr)* | Streambank Erosion (t/yr) | Total Erosion (t/yr) |
|---|---|---|---|---|---|
| Dairy | 140,584 | 289,470,359 | 70,463 | 96,999 | 167,462 |
| Sheep & Beef | 283,999 | 12,543,034 | 216,599 | 146,994 | 363,592 |
| Deer | 3,032 | 3,016,544 | 769 | 766 | 1,535 |
| Lifestyle | 17,021 | 1,203,422 | 4,165 | 7,428 | 11,593 |
| Arable & Hort | 5,488 | 22,202,055 | 155 | 3,261 | 3,416 |
| Forestry | 83,596 | 43,397,500 | 41,675 | 24,173 | 65,848 |
| Native Bush | 53,446 | 0 | 23,161 | 15,103 | 38,263 |
| Other | 14,865 | 274,853 | 1,523 | 38,260 | 39,783 |
| **Total** | **602,031** | **372,107,767** | **358,510** | **332,982** | **691,492** |

# 5 Scenario Analysis

This section reports the economic and environmental impacts of the sediment mitigation scenarios described in Section 3 of this report. The key results reported for each policy scenario include net farm revenue, total annual cost, land-based and streambank sediment loads, average annual harbour sediment deposition rates (AASR), and the freshwater attributes of suspended sediment, water clarity, euphotic depth. The estimates in this section compare the scenario estimates with the 'no mitigation' baseline after they have been fully implemented.[22] All values are listed as mean annual figures, unless specified otherwise.

A series of maps showing the spatial distribution of the key findings for each policy scenario are presented in Appendix 4, while more detailed outputs from the catchment economic

[22] 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.

model are listed in Appendix 5. 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 6.

## 5.1 Catchment-wide Results

The total estimated impacts for the entire KHC are listed in Table 10. The table indicates that the impacts vary widely across scenarios. More insight on each scenario is provided in the next section.

**Table 10**: Key model scenario estimates, Kaipara Harbour catchment

| Scenario | Net Revenue (mil $) | Total Mitigation Cost (mil $/yr) | Average Mitigation Cost ($/t/yr) | Land-based Erosion (t/yr) | Stream bank Erosion (t/yr) | Total Erosion (t/yr) |
|---|---|---|---|---|---|---|
| No Mitigation Baseline | $372.1 | $0 | $0 | 358,510 | 332,982 | 691,492 |
| Change from No Mitigation Baseline | | | | | | |
| Current Mitigation | –2.0% | $6.6 | $81 | –5% | –19% | –12% |
| Farm Management Plan - All HEL | –1.0% | $2.6 | $13 | –54% | 0% | –28% |
| Stock Exclusion Rules | –3.0% | $10.5 | $118 | 0% | –27% | -13% |
| Stock Exclusion Rules + Planting | –11.0% | $41.3 | $194 | –25% | -37% | –31% |
| Stock Exclusion + All HEL Plans | –3.0% | $13.0 | $46 | –54% | –27% | –41% |
| Freshwater Node 10% | –0.1% | $0.2 | $5 | –8% | -3% | –6% |
| Freshwater Node 30% | –0.3% | $1.2 | $10 | –24% | 9% | –17% |
| Marine Deposition 15% | –0.2% | $0.6 | $6 | –17% | -13% | –15% |
| Marine 2mm above 'natural' AASR | –2.3% | $8.7 | $84 | –11% | -5% | –8% |
| Full Afforestation (Pine) | –69% | $255.3 | $543 | –66% | -71% | -68% |
| Full Afforestation (Native) & Wetlands | –89% | $330.8 | $546 | –90% | –85% | –88% |

The pine afforestation and native afforestation with constructed wetlands 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 88%. 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 (Fig. 12). For the practice-based scenarios, the mitigation is prescribed. For the outcome based scenarios, the catchment economic model selects the most cost-effective option to meet the catchment policy objectives. As a result, landowners would implement a mix of mitigation practices, namely farm plans, fencing, and wetlands, depending on their collective cost and effectiveness. In addition, practices are often imposed only in areas with high erosion rates (i.e., landmass erosion with significantly higher sediment rates than 1.0 t/ha/yr and highly erodible stream banks), and as a result can achieve significant reductions in sediment at relatively low cost. This is apparent when you compare average mitigation costs across the different scenarios. For three of the four outcome-based scenarios, the average cost of mitigation is between $5 and $10 per tonne of sediment mitigated. Most of the practice-based scenarios require mitigation to be implemented on a much greater area of the catchment and hence yield average mitigation costs of $46/tonne or more. The key exception is the scenario that only focuses on implementing farm management plans on highly erodible land, as by definition it is targeting areas with relatively high erosion rates.

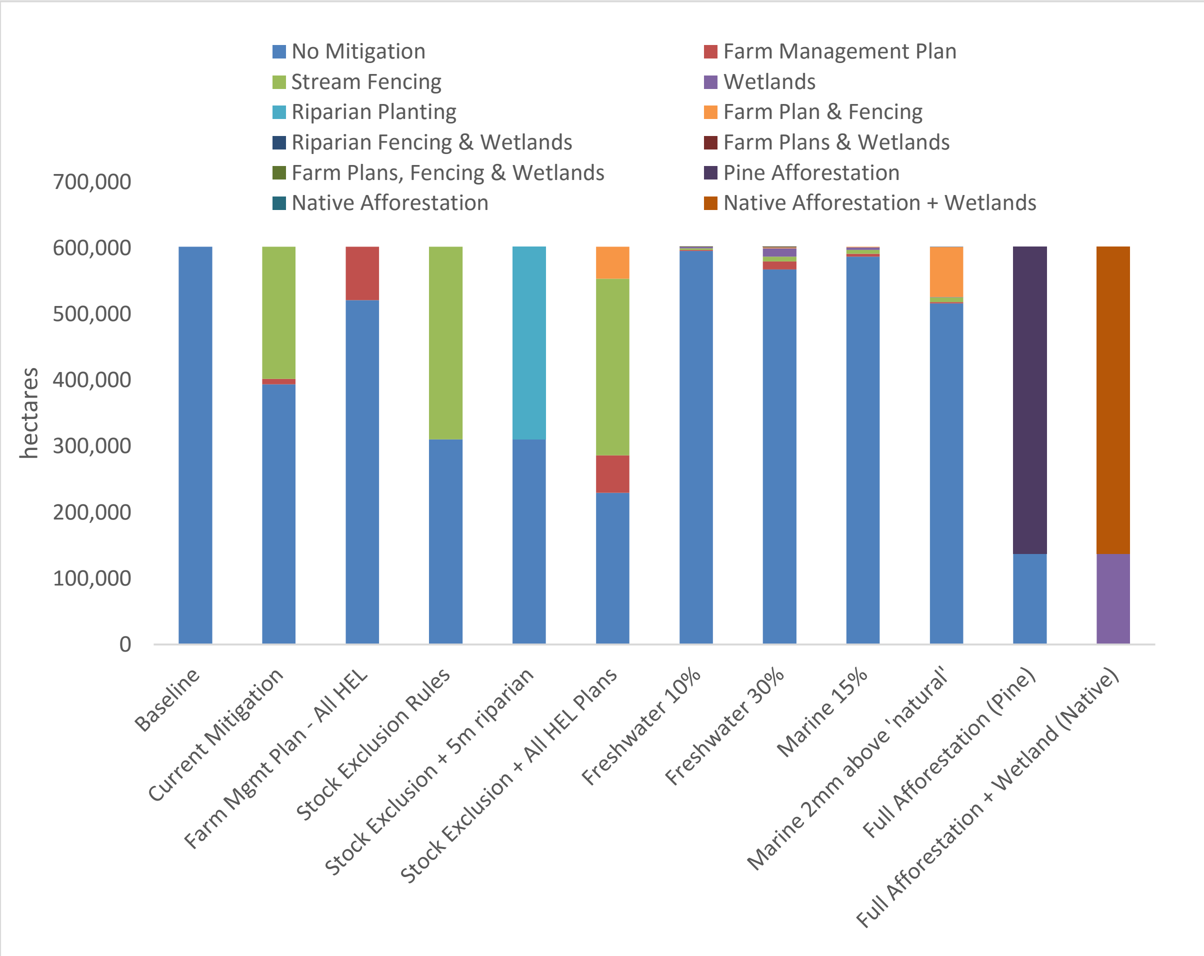


**Figure 12**: Area (ha) of implemented mitigation option by scenario.

The total costs for the non-afforestation scenarios range from $2.6 million/yr for implementing farm management plans on all pasture designated as highly erodible land (HEL) (1.0 t/ha/yr) to about $41.3 million/yr for implementing the NZ government's proposed stock exclusion regulations and planting a 5 metre buffer zone of riparian vegetation on all eligible land in the catchment (Fig. 13). Sheep & beef farms face the largest total and per hectare costs for nearly all scenarios. This is to be expected, as this enterprise consists of the largest area of productive land and pasture in the catchment, often located on land with high erosion rates, with the greatest length of streams running through them. Note that the total costs for scenarios that include fencing and farm management plans as a mitigation option may be overstated by as much as $6.6 million/yr (based on estimates from Scenario 1, current mitigation) as some dairy and sheep & beef farmers have already fenced some or all of their streams.

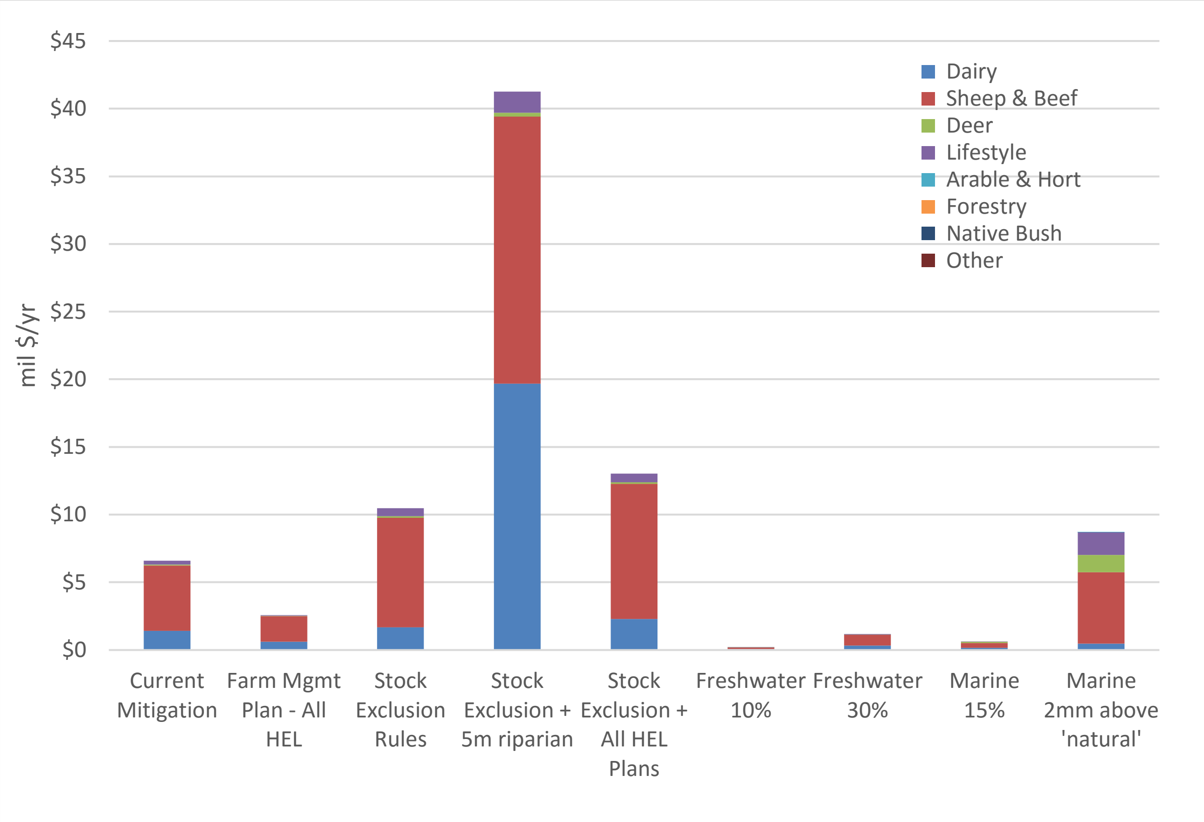


**Figure 13**: Total annual cost (mil $/yr), by land uses for non-afforestation scenarios.

The mean annual mitigation costs figures for each scenario are broken out into per hectare values in Table 11. It is apparent from these figures that there is a wide distribution of impacts across both land use and scenario. Higher per hectare costs are generally for the scenarios that account for opportunity costs from taking some land out of production. Many of the estimates appear relatively cheaper than one may anticipate, because mitigation is not necessarily implemented on every parcel of land in the catchment. For example, both the stock exclusion and HEL farm management plan scenarios assume that mitigation is only implemented on pastoral farms that meet certain criteria, which are defined by land use, slope, and annual erosion rate.

**Table 11:** Mean annual mitigation cost by land use ($/ha/yr)*

| Scenario | Dairy | Sheep & Beef | Deer | Lifestyle Blocks | Arable & Hort | Forestry | Native Bush | Other | Total Area | Mitigation Area Only^ |
|---|---|---|---|---|---|---|---|---|---|---|
| Baseline | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 |
| Current Mitigation | $10 | $17 | $18 | $17 | $0 | $0 | $0 | $0 | $11 | $32 |
| Farm Mgmt Plan - All HEL | $4 | $7 | $7 | $2 | $0 | $0 | $0 | $0 | $4 | $32 |
| Stock Exclusion Rules | $12 | $29 | $34 | $35 | $0 | $0 | $0 | $0 | $17 | $36 |
| Stock Exclusion + 5m riparian | $140 | $69 | $96 | $92 | $0 | $0 | $0 | $0 | $69 | $141 |
| Stock Exclusion + All HEL Plans | $16 | $35 | $41 | $37 | $0 | $0 | $0 | $0 | $22 | $35 |
| Freshwater 10% | $0.5 | $0.4 | $0.0 | $0.4 | $0 | $0 | $0 | $0 | $0.3 | $31 |
| Freshwater 30% | $2.3 | $2.8 | $1.4 | $2.8 | $0 | $0 | $0 | $0 | $1.9 | $34 |
| Marine 15% | $1.2 | $1.2 | $28.2 | $1.9 | $0 | $0 | $0 | $0 | $1.1 | $42 |
| Marine 2mm above 'natural' | $3 | $19 | $419 | $99 | $5 | $0 | $0 | $0 | $14 | $101 |
| Full Afforestation (Pine) | $1,659 | $1 | $595 | $1 | $3,645 | $0 | $0 | $10 | $424 | $549 |
| Full Afforest (Native) + Wetland | $2,054 | $39 | $990 | $66 | $4,040 | $37 | $25 | $14 | $550 | $550 |

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

^ Only includes areas in the catchment where mitigation practices were implemented in model

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, land-based sediment (e.g. landslide and gully erosion) is reduced more than sediment from streambanks (Fig. 14). The two exceptions are the current mitigation and stock exclusion rules scenarios. This is because fencing streams without any other mitigation practices does not have an impact on land-based sediment.

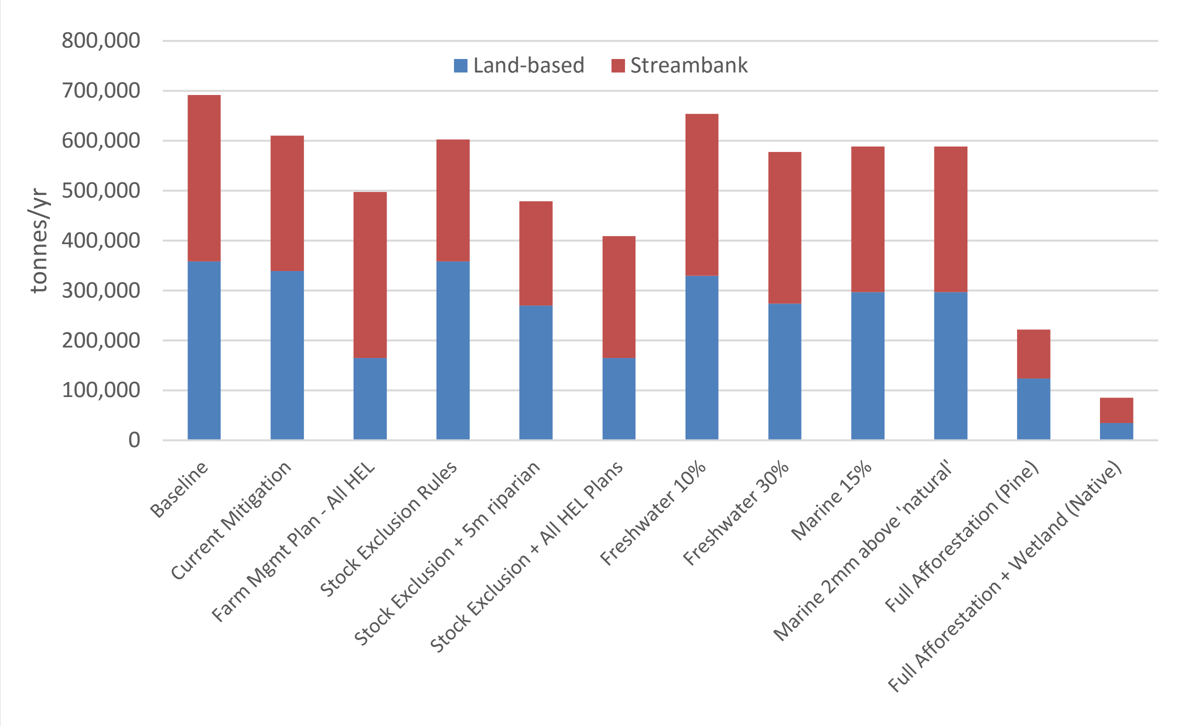


**Figure 14**: Catchment sources of total sediment (t/yr) by scenario.

The spatial impacts of total erosion by scenario are illustrated in Figures 15 and 16.[23] Apparent in the figures is the large variation in the location and magnitude of sediment reductions across the different scenarios. For example, the largest impacts of HEL farm management plans are primarily located along a northwest to southeast ridge across the middle of the catchment, while fencing and riparian planting are spread across the entire catchment.

For the outcome-based scenarios, the areas where mitigation practices are applied and sediment loads reduced is highly concentrated in small but specific areas of the catchment. Interestingly, although the freshwater node and marine sediment reduction scenarios have distinctly different objectives, the areas where sediment is reduced are relatively similar. The most obvious difference between the two outcomes is that more of the marine deposition reductions appear to be concentrated along major streams in the catchment. This makes sense because for the freshwater node case, most of the areas that fed into the nodes were located in the 'upland' portion of the catchment.

The two afforestation scenarios indicate there is potential for significant reductions throughout the catchment. The afforestation with native bush and wetland restoration scenario map (Fig. 16) illustrates the additional reductions that can be had not only when planting trees on land that is currently pasture, but also when restoring wetlands throughout the catchment, including in areas that are still forested today.

[23] Larger versions of maps of the scenarios are presented in Appendix 4.

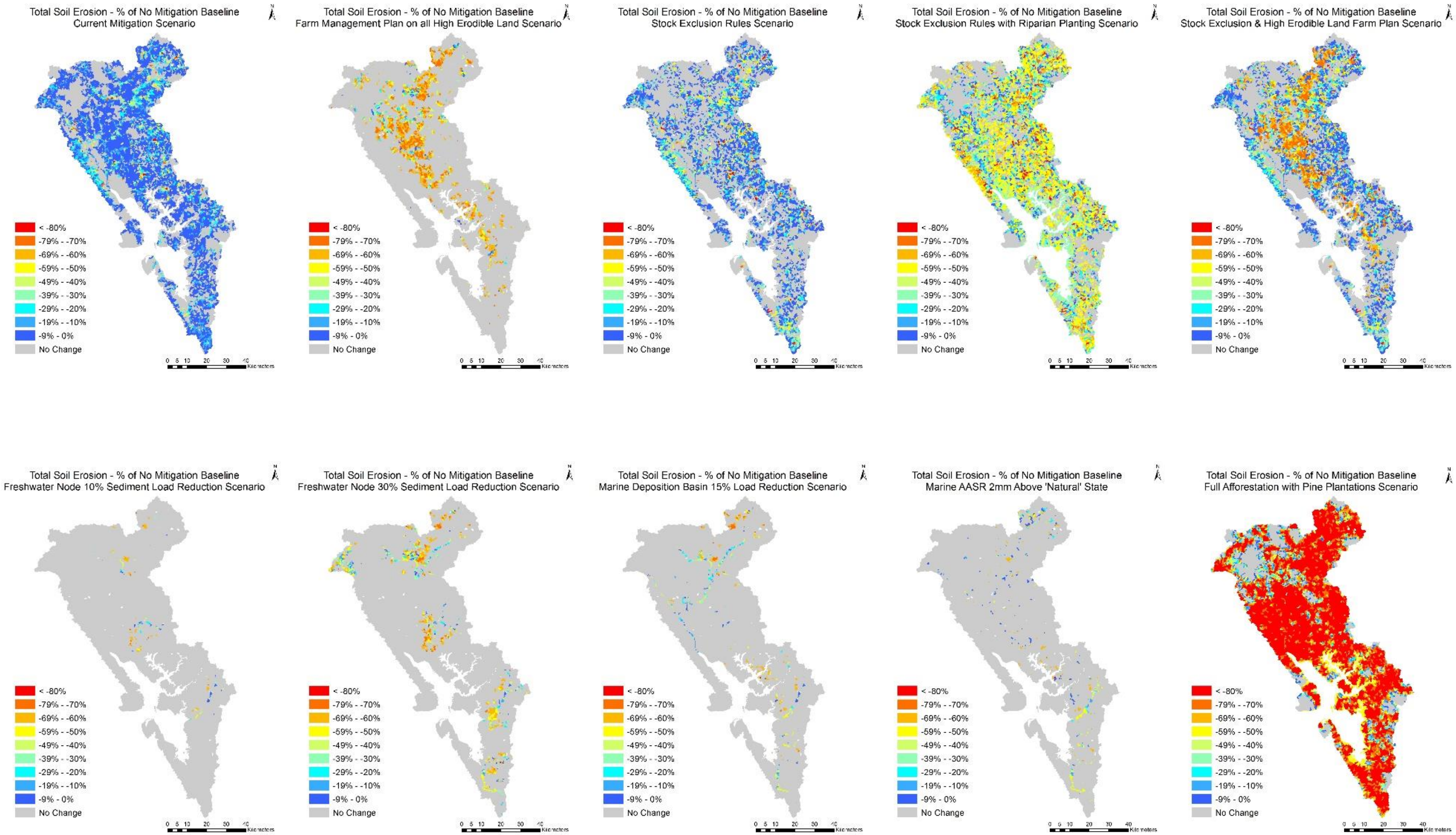


**Figure 15:** Percent change from baseline in total erosion by REC2 sub-catchment by scenario.

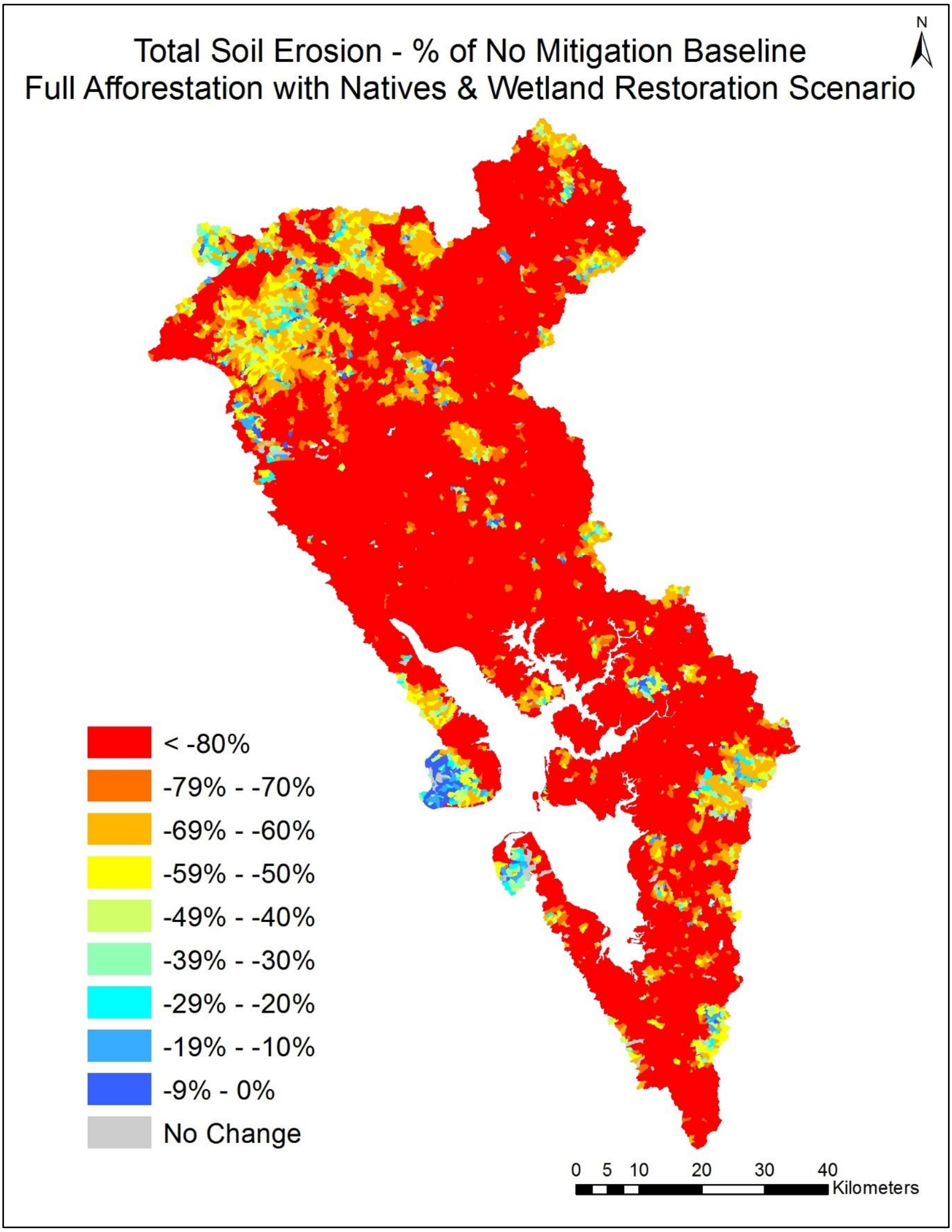


**Figure 16:** Percent change in total erosion by REC2 sub-catchment – native bush afforestation on all pasture land & wetland restoration scenario.

## 5.2 Attribute Estimates

### 5.2.1 Harbour/Estuary sediment

The modelled scenarios are also estimated to have a range of impacts on freshwater and marine sediment attributes as well. In the case of the marine sediment attribute (AASR), most of the nine modelled deposition areas in the harbour are not estimated to see declines in sedimentation rates of more than 1 mm/yr unless there large areas of the catchment are afforested (Fig. 17). This is because (a) the total reductions in sediment in key areas of the catchment that have the largest effect on AASR are relatively small, and (b) the AASR is a result of both land- and sea-based sediment, for which catchment mitigation has an impact only on the former process. More details on the potential impact of these estimates on the marine ecology of the Kaipara Harbour are presented in another component of the KSHMS. A more detailed analyses and narrative about the potential impacts of mitigation on harbour ecosystem health and functioning is available in a separate KHSMS report (Lohrer 2017).

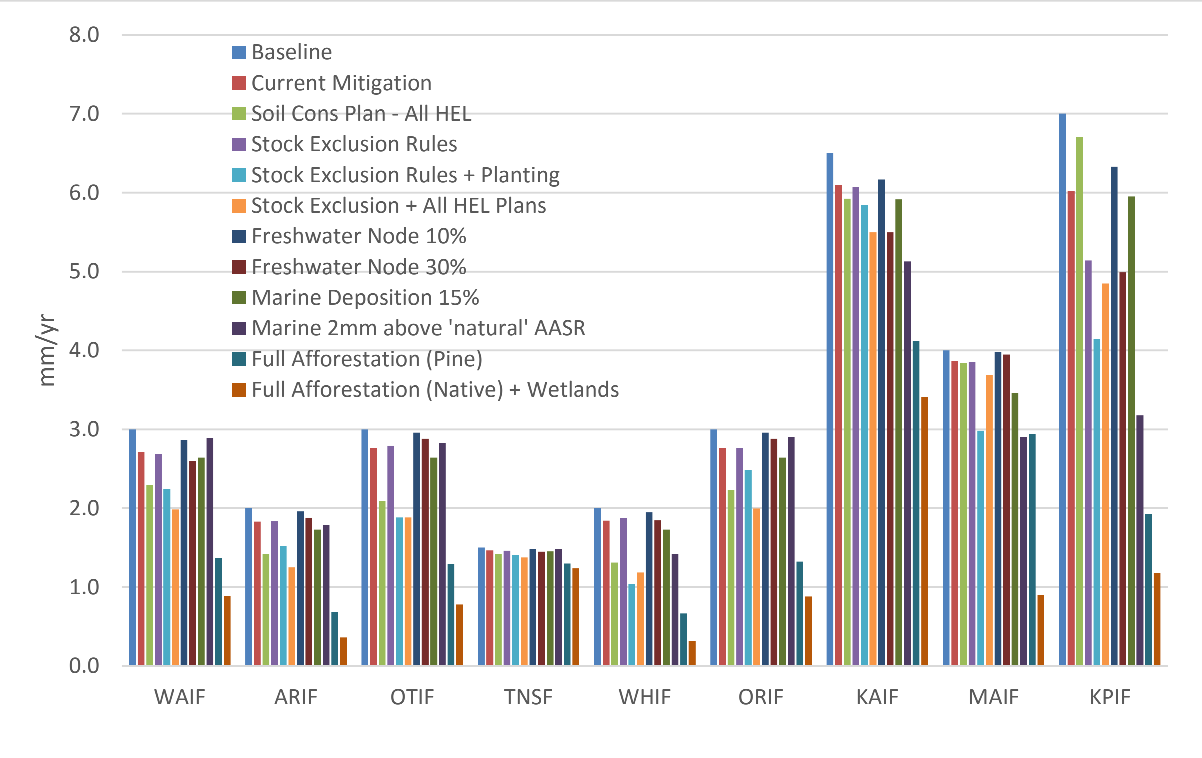


**Figure 17:** Marine Annual Average Sedimentation Rate (AASR) by Scenario and Deposition Area. Areas include: Wairoa intertidal flats (WAIF), Arapaoa intertidal flats (ARIF), Otamatea intertidal flats (OTIF), Tinopai subtidal flats (TNSF), Whakaki intertidal flats (WHIF), Oruawharo intertidal flats (ORIF), Kakarai intertidal flats (KAIF), Makarau intertidal flats (MAIF), Kaipara intertidal flats (KPIF)

### 5.2.2 Freshwater sediment

The freshwater sediment attributes also follow a similar pattern, with large impacts in suspended sediment, water clarity, and euphotic depth occurring often only occurring under conditions with significant afforestation (Fig. 18 a–c). The combined stock exclusion and HEL scenario does have a noticeable effect on some attributes, and could increase water clarity and euphotic depth by about 0.5 metres in a majority of the catchment nodes. As with many of the other results, these findings suggest that expectations about what could be achieved through policies aimed at managing sediment in the Kaipara Harbour Catchment will be warranted. More details on the potential impact of these estimates on the freshwater ecology of the seven freshwater nodes tracked in the catchment economic model are presented in another KSHMS report (Matthaei 2017).

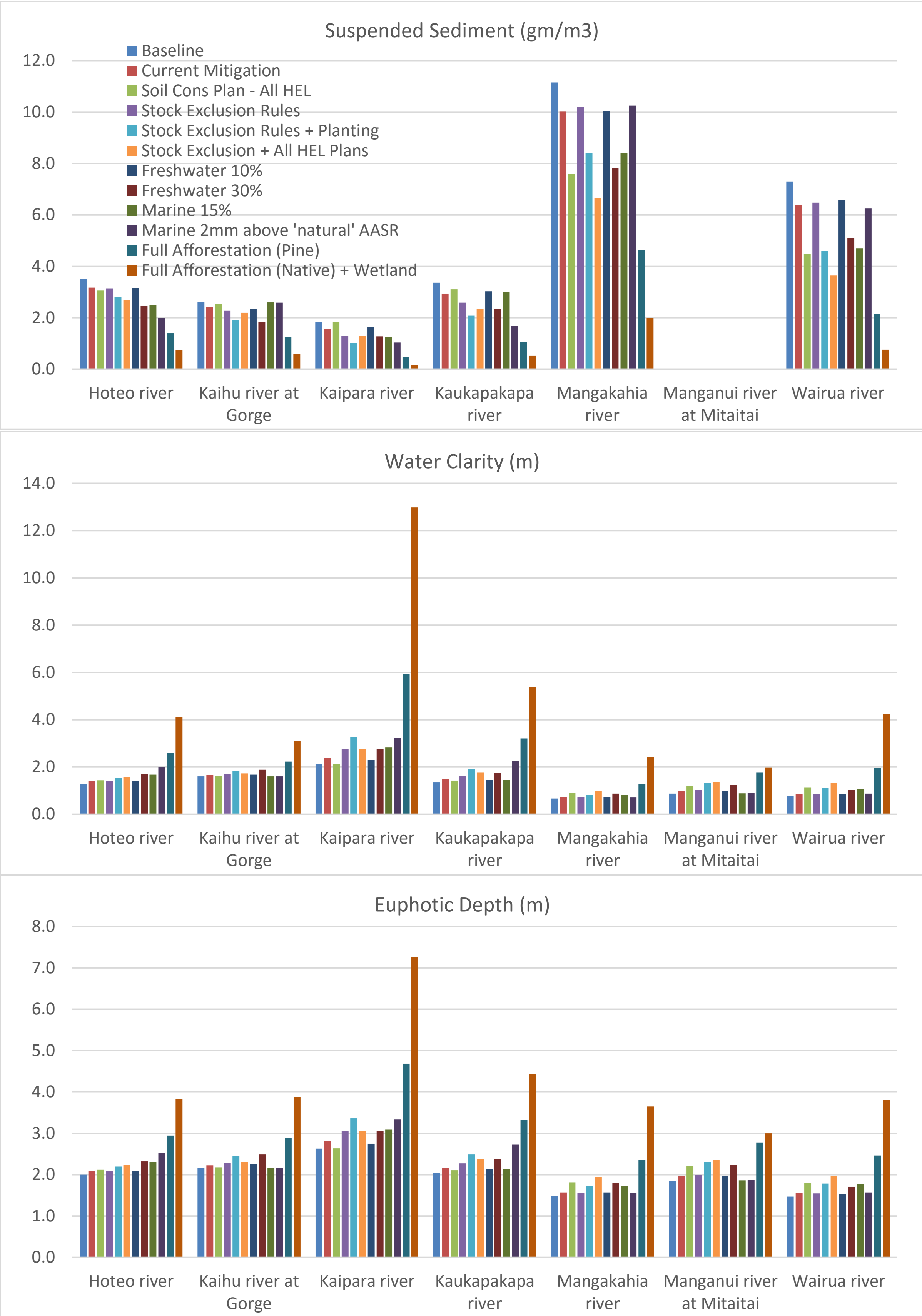


**Figure** 18a–c: Freshwater sediment attributes by scenario and catchment node. (N.B., suspended sediment data not available for Manganui River at Mitaitai)

# 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 vs 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 in the KHC. Some of the modelling limitations from the KHSMS include:

1. **Input data** – The quality and depth of the economic analysis depends on the datasets and estimates provided by biophysical models like SedNetNZ, 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 KHC 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 2014 land use map, (2) net farm revenue was based on a 5-year average of input costs and output prices (2010-2014), and (3) no landowners were implementing management practices intended to reduce sediment in the catchment. Assumption three is likely to have the greatest impact on model estimates, as NRC and AC have 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.

4. **Management practices** – The model only includes some management practices deemed feasible and likely to be implemented in a catchment as a result of sediment reduction policies and practices, 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 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 loads (e.g. 50% of baseline streambank sediment loads for riparian fencing). In reality, the actual impact of a given practice is likely to vary depending on where, when, and how well the practice is implemented. A sensitivity analysis that quantifies the potential effect of adjusting the effectiveness rates for farm management plans, fencing streams, and riparian planting is included in Appendix 6.

6. **Optimisation routine** – For this analysis, NZFARM has been programmed so that all landowners are assumed to collectively select the 'optimal' combination of management practices required to achieve specific outcomes related to managing sediment in the KHC. 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. **Economic benefits of mitigation** – The catchment economic model does quantify the physical change in erosion from a range of sources and mitigation practices, where the sediment is likely to be deposited, and the change in distinct water quality attributes as a result. It does not, however, attempt to monetize the benefits that improving water quality can provide to a wide range of ecosystem services. Thus, while it is implicit that there are valuable benefits from reducing sediment in the Kaipara Harbour catchment, the estimates produced solely from this model cannot be used for a formal benefit-cost analysis.

8. **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 at catchment level.

# 7 Summary and Conclusions

Northland Regional Council and Auckland Council have identified that sediment poses key water quality challenges in the Kaipara Harbour and its catchment. As a result, the councils engaged in a joint project to undertake a sediment study in the catchment, in collaboration with the Ministry for the Environment.

The objective of this component of the Kaipara Harbour Sediment Mitigation Study was to develop a catchment economic model that could be used to identify cost-effective ways to manage sediment loads in streams and rivers in the Kaipara Harbour catchment, as well as in the harbour itself. The study had a particular focus on the impact of mitigation on various freshwater and marine sediment 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 loads from land uses ranging from intensive pasture to native bush.

A range of mitigation scenarios were analysed to test and illustrate the utility of the catchment economic model. For this analysis, these focused on practice-based approaches such as fencing, and farm plans as well as environmental outcome-based scenarios like reducing sediment loads in specific freshwater nodes of the catchment.

A large pine afforestation scenario and a full native afforestation and constructed wetland scenario were also modelled to establish the minimum feasible or 'natural' loads that could be achieved in the Kaipara Harbour catchment. This provided a benchmark from which to assess the other scenarios. Afforesting all land with native bush and reconstructing the likely extent of pre-human wetlands could reduce total sediment by as much as 88%, but at a cost of several hundreds of million dollars per year relative to the baseline net farm earnings.

The most cost-effective mitigations in the draft analysis are those that focus on implementing farm management plans (i.e., predominantly spaced pole plantings) on highly erodible pasture land. This mitigation enables a focus on the particular hot spots of land-based sediment, i.e. rates greater than 1.0 t/ha/yr. This mitigation cost of $2.6 million/year reduced net revenue in the catchment by around 1%, but total sediment loads are estimated to fall by around 28%.

Fencing all streams that flow through pasture land meeting the specifics of the New Zealand Government's 2017 proposed stock exclusion regulations has an effect on streambank erosion from pasture, but no impact on land-based erosion (52% of sediment in the catchment results from land-based erosion). As a result, streambank erosion is estimated to be reduced by 27% relative to the baseline, while total erosion is reduced by just 13%. Thus, it is likely more will have to be done to achieve noticeable improvements in sediment loads and related attributes in the catchment.

Nearly all scenarios estimated some reduction in the harbour sediment attribute included in this study, the average-annual sedimentation rate (AASR). Estimates varied widely across the nine deposition basins as they are all affected differently in terms of the amount of sediment they receive annually from both land and marine sources. It was also found that in order to reduce the AASR by at least a millimetre per annum, all eligible farms needed to jointly implement the stock exclusion rules and farm management plans.

In all the non-afforestation scenarios, water clarity and euphotic depth were estimated to increase by no more than 0.6 metres at all nodes for nearly all of the modelled scenarios. There was also wide variation in impacts on the freshwater sediment attributes estimated at the seven reporting nodes in the catchment. Changes in sediment loads were estimated to have a greater impact on the Kaipara and Kaukapkapa river sites, which include a variety of pastoral land uses with relatively high erosion rates that could benefit from implementing a range of mitigation practices. However, other sites in areas of the catchment that had a relatively high proportion of forest plantations or native bush produced minimal erosion and/or had limited mitigation potential, and thus did not see the same increases in water clarity and euphotic depth.

The estimates from this analysis illustrate the range of costs and benefits that could occur from implementing a wide range of mitigation options in the catchment. The broad findings are that targeting both land-based and streambank erosion by mandating practices on specific farms located on about 60% of the total area of the KHC could reduce sediment by up to 41% relative to a no-mitigation baseline. However, they also indicated that sediment attributes measured in different areas of the catchment are likely to vary, and some may not be improved as much as initially expected. Thus, landowners may have to undertake additional sediment mitigation practices and/or change land use by afforestation of highly erodible land.

## 8 Acknowledgements

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## Appendix 1 – Erosion mitigation type, effectiveness, and cost based on Basher (2017)

| Erosion process | Mitigation alternative | Effectiveness (% reduced) | Land use | Comment | Total Cost of mitigation (i.e., not annualized) | Source (cost) |
|---|---|---|---|---|---|---|
| Surface erosion (sheet, rill) | Wetlands (natural or constructed) and sediment traps | 60-80 | Pasture | Based on estimates in McKergow et al. (2007) and Tanner et al. (2013). Effectiveness depends mostly on size of wetland (as % of catchment area) - 60% for 1% wetland and 80% for 2.5% wetland | Depends on type of wetland. Lowest cost estimated for natural wetland $200/ha for dairy and $600/ha for sheep and beef and constructed wetlands (1%, $565/ha) | Whangarei Harbour catchment study derived from McKergow et al. (2007) |
| Surface erosion (sheet, rill) | Sediment retention ponds without chemical treatment | 30 | Urban | Typically a combination of erosion and sediment control practices are used for urban earthworks. A conservative overall efficiency could be used based on average efficiency aimed for in using sediment retention ponds with chemical treatment of 70% | | |
| Surface erosion (sheet, rill) | Sediment retention pond with chemical treatment | 70 | Urban | | | |
| Surface erosion (sheet, rill) | Silt fence | 99 | Urban | | | |
| Surface erosion (sheet, rill) | Sediment retention pond | 50 | Horticulture | Conservative estimate based on Pukekohe study and limited overseas literature | $750-1300/ha treated | Estimates from Chris Keenan presentation in 2013 – http://files.ecan.govt.nz/public/lwrp/hearing-evidence/doc/doc1831479.PDF |
| Surface erosion (sheet, rill) | Riparian grass buffer strip | 40 | Horticulture and pasture | Conservative estimate based on McKergow et al. (2007) – can be >80%. Will probably be highly slope-dependent | $255/ha | Estimates from Chris Keenan presentation in 2013 – http://files.ecan.govt.nz/public/lwrp/hearing-evidence/doc/doc1831479.PDF |

| Erosion process | Mitigation alternative | Effectiveness (% reduced) | Land use | Comment | Total Cost of mitigation (i.e., not annualized) | Source (cost) |
|---|---|---|---|---|---|---|
| Surface erosion (sheet, rill) | Wheel track ripping | 90 | Horticulture | Based on Pukekohe study on clay-rich soils | $33/ha | Estimates from Chris Keenan presentation in 2013 – http://files.ecan.govt.nz/public/lwrp/hearing-evidence/doc/doc1831479.PDF |
| Surface erosion (sheet, rill) | Wheel track diking | 60 | Horticulture | Effectiveness has not been characterised in NZ. Likely to be significantly less than ripping | $33/ha | Estimates from Chris Keenan presentation in 2013 – http://files.ecan.govt.nz/public/lwrp/hearing-evidence/doc/doc1831479.PDF |
| Surface erosion (sheet, rill) | Cover crops | 40 | Horticulture | Limited NZ studies show seasonal reduction in soil loss of c.30%; international studies show reductions in erosion rate compared to bare ground of 40–>90% | $82/ha | Estimates from Chris Keenan presentation in 2013 – http://files.ecan.govt.nz/public/lwrp/hearing-evidence/doc/doc1831479.PDF |
| Landslides | Space-planting | 70 | Pasture | Assumes all area is planted, and all plants survive. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated | $1650/ha | Whangarei Harbour catchment study – $20/stem at 11m spacing (82 stems/ha); would reduce to $1200 at 13 m spacing (59 stems/ha) and $900 (44 stems/ha) at 15 m spacing |
| Landslides | Afforestation | 90 | Pasture | Assumes all area is planted. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated. Also assumes trees not harvested - if harvested reduce effectiveness to 80% | $1000/ha | Mike Marden, pers. comm. Does not include fencing cost |

| Erosion process | Mitigation alternative | Effectiveness (% reduced) | Land use | Comment | Total Cost of mitigation (i.e., not annualized) | Source (cost) |
|---|---|---|---|---|---|---|
| Gully erosion | Space-planting | 70 | Pasture | Assumes all area is planted, and all plants survive. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated | $1650/ha | Whangarei Harbour catchment study – $20/stem at 11-m spacing (82 stems/ha); would reduce to $1200 at 13-m spacing (59 stems/ha) and $900 (44 stems/ha) at 15-m spacing |
| Gully erosion | Afforestation | 90 | Pasture | Assumes all area is planted. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated. Also assumes trees not harvested – if harvested reduce effectiveness to 80% | $1000/ha | Mike Marden pers. comm. Does not include fencing cost |
| Gully erosion | Debris dams | 80 | Pasture | No data available but considered to be highly effective in trapping sediment within gullies so long as gully walls are stabilised with trees. Typically used in combination with vegetation, fencing and control of runoff into gullies to trap sediment within gully systems | | |
| Earthflow | Space-planting | 70 | Pasture | Assumes all area is planted, and all plants survive. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated | $1650/ha | Whangarei Harbour catchment study – $20/stem at 11-m spacing (82 stems/ha); would reduce to $1200 at 13-m spacing (59 stems/ha) and $900 (44 stems/ha) at 15-m spacing |
| Earthflow | Afforestation | 90 | Pasture | Assumes all area is planted. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated. Also assumes trees not harvested - if harvested reduce effectiveness to 80% | $1000/ha | Mike Marden, pers. comm. Does not include fencing cost |

| Erosion process | Mitigation alternative | Effectiveness (% reduced) | Land use | Comment | Total Cost of mitigation (i.e., not annualized) | Source (cost) |
|---|---|---|---|---|---|---|
| Bank erosion | Riparian fencing | 50 | Pasture | The 80% previously used is based on a "conservative" adjustment of the Australian SedNet model parameter (Dymond et al. 2016). The available NZ data suggests the effectiveness is likely to be significantly lower; there is insufficient data to determine whether riparian planting significantly increases effectiveness above simply fencing (to restrict stock access) or to determine effect of width of fencing set back | Fencing estimated at $7.10/m to fence out cattle (and provide water supply), and $11.10 with poplar planting added. Fencing out all stock estimated at $34.60/m | Whangarei Harbour catchment study. Other options are costed in the workshop report including planting natives |
| Bank erosion | Riparian fencing + planting | 50 | Pasture | | | |

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## Appendix 2 – Wetland mitigation assumptions

**Table A.2.1:** Assumptions about wetland applicability and effectiveness

| Mitigation | Applicability<br>1 Hydrological flow path | Applicability<br>2 Catchment Slope | Proportional areal applicability (% of area) | Proportion of load intercepted (% of load) | Efficacy Sediment (% 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 | 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 | 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 | 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<br>$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<br>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 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 $m^2$) /20 ha catchment)

## Appendix 2 References


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## Appendix 3 – Key baseline maps and estimates by sub-catchment

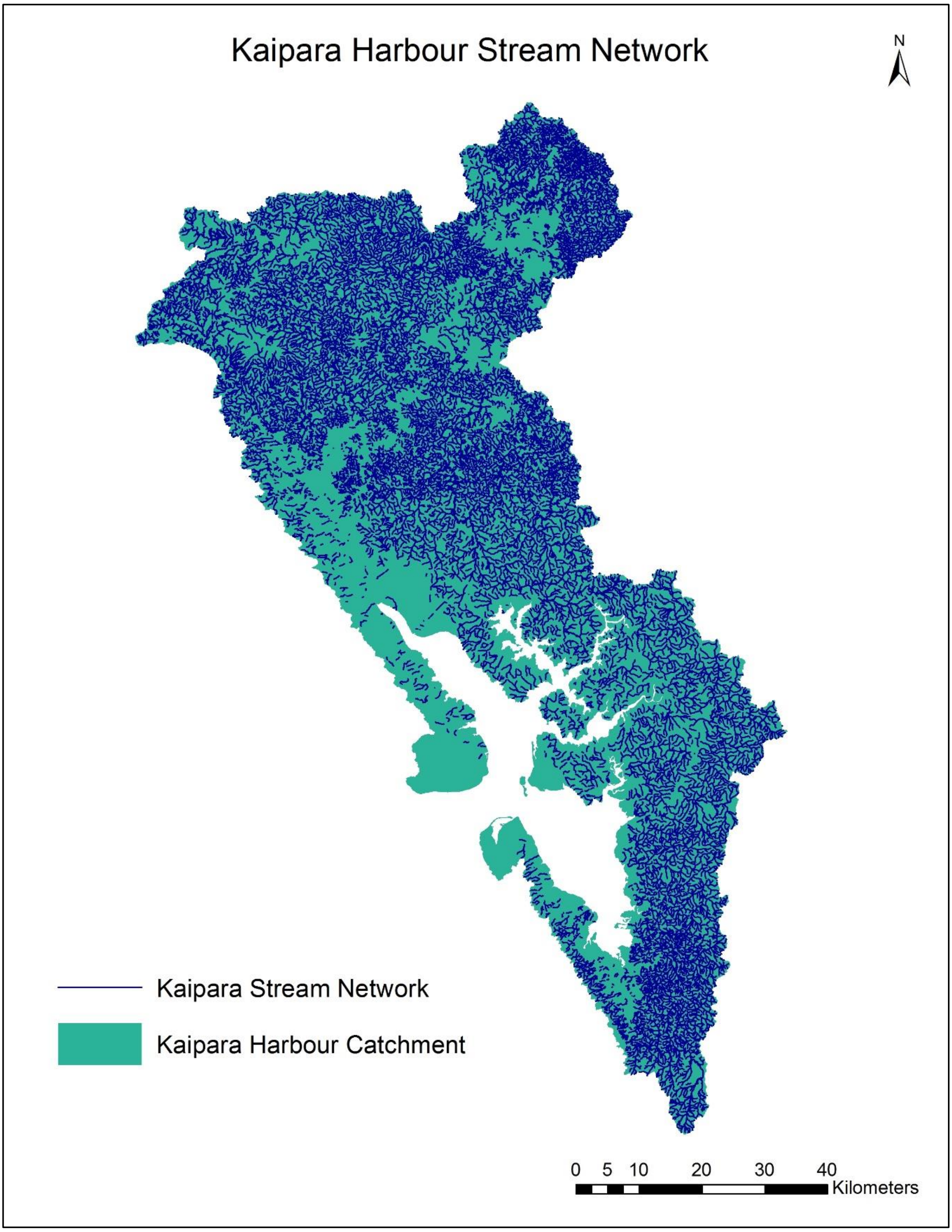


**Figure A.3.1:** Kaipara Harbour catchment stream network.

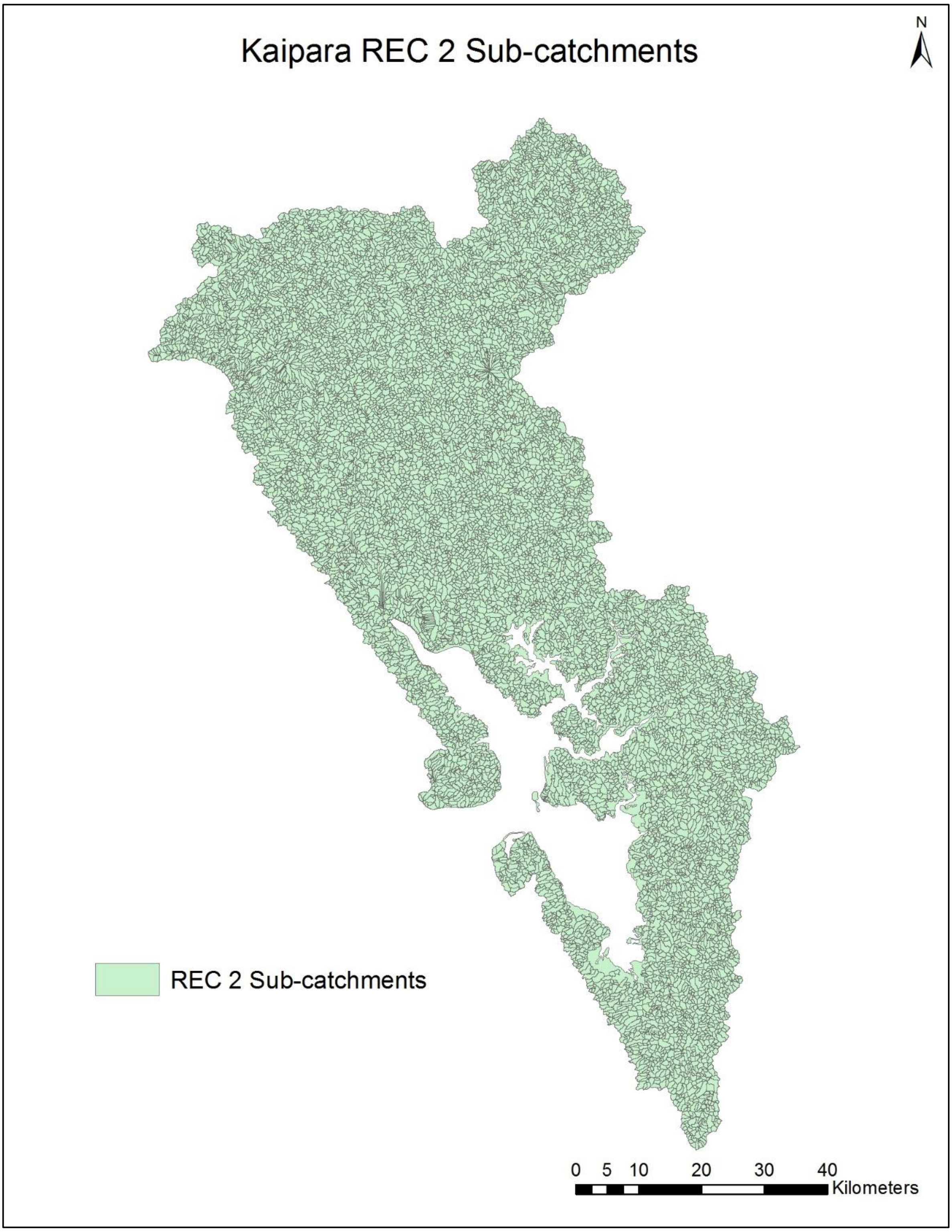


**Figure A.3.2:** Kaipara Harbour catchment river environment classification 2 (REC2) sub-catchments.

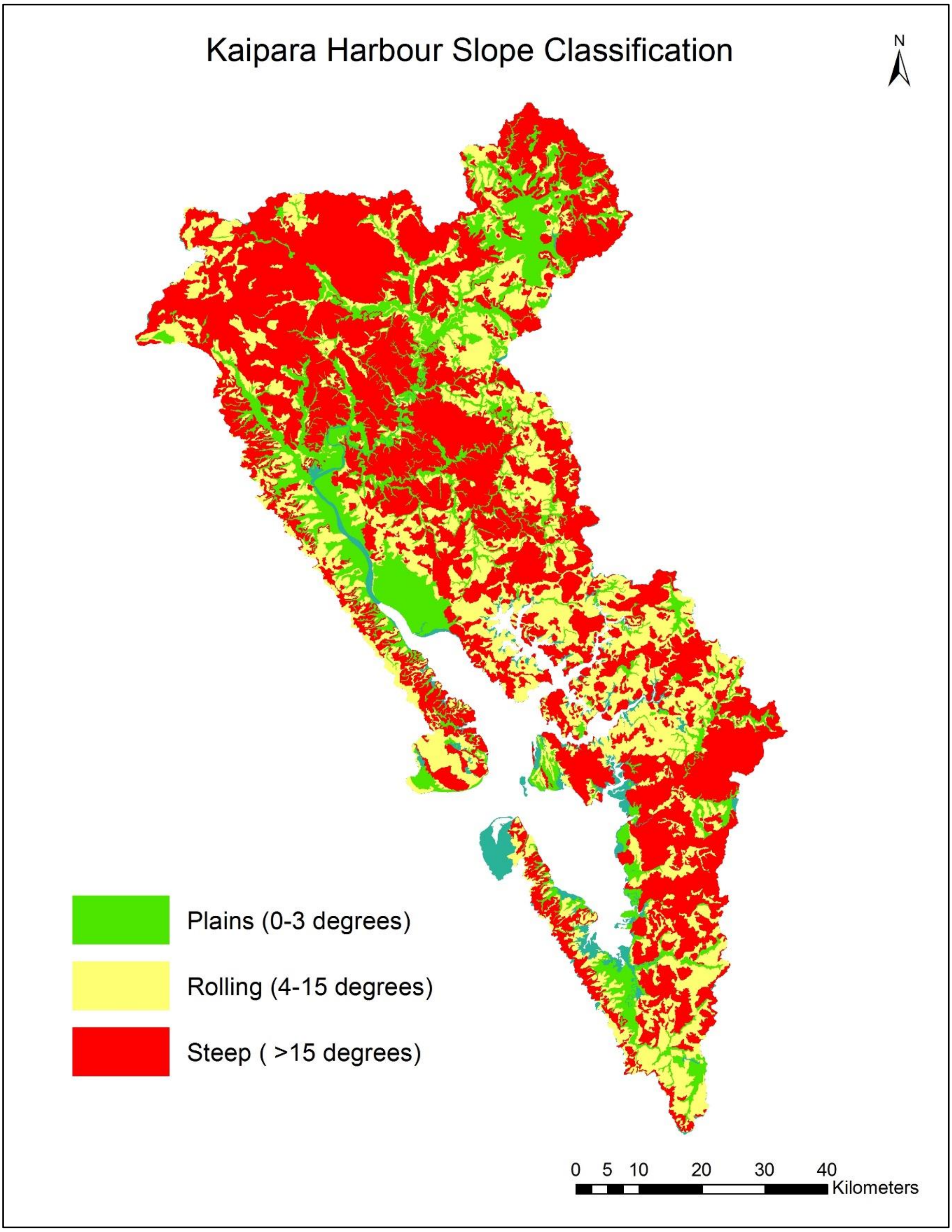


**Figure A.3.3:** Kaipara Harbour catchment slope classification.

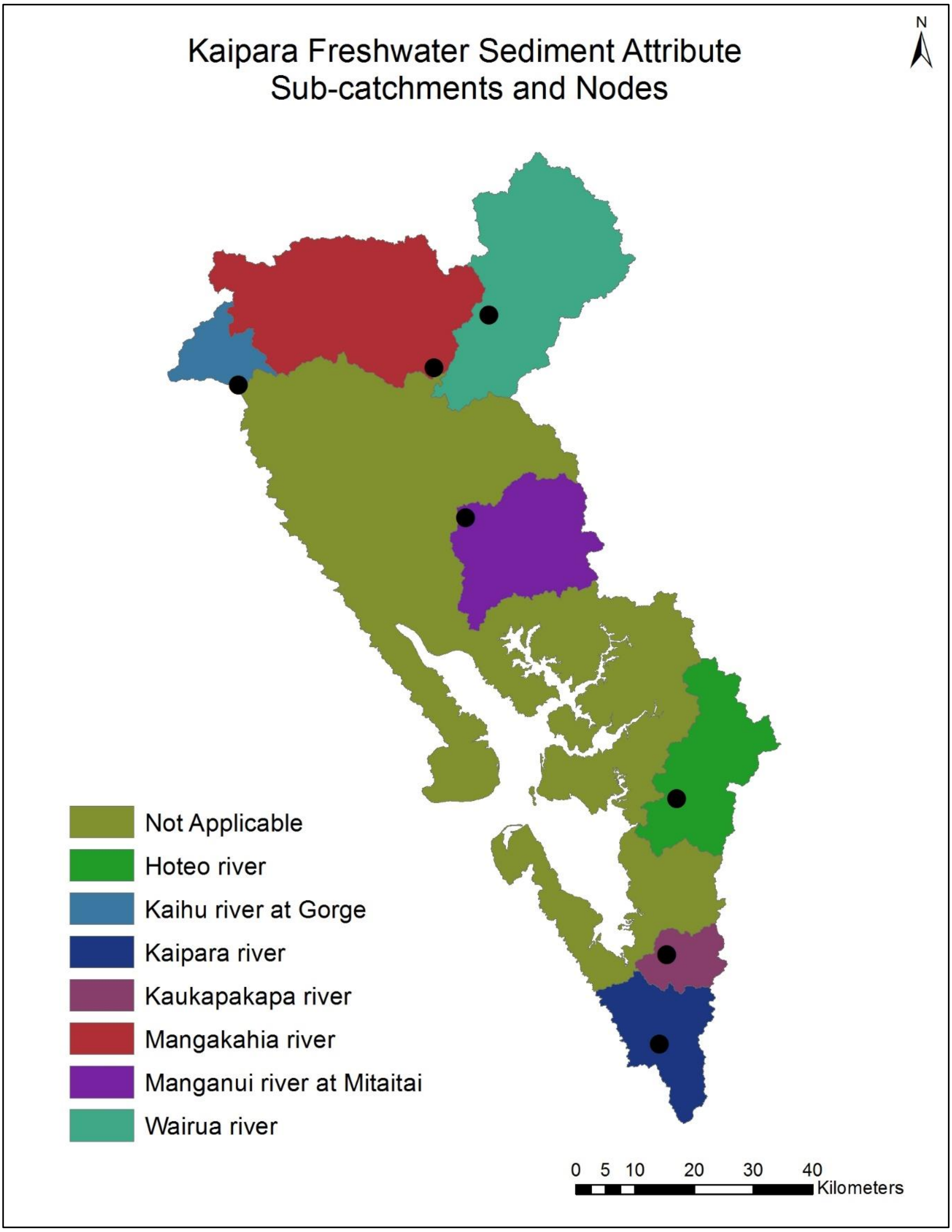


**Figure A.3.4:** Kaipara Harbour catchment freshwater node locations.

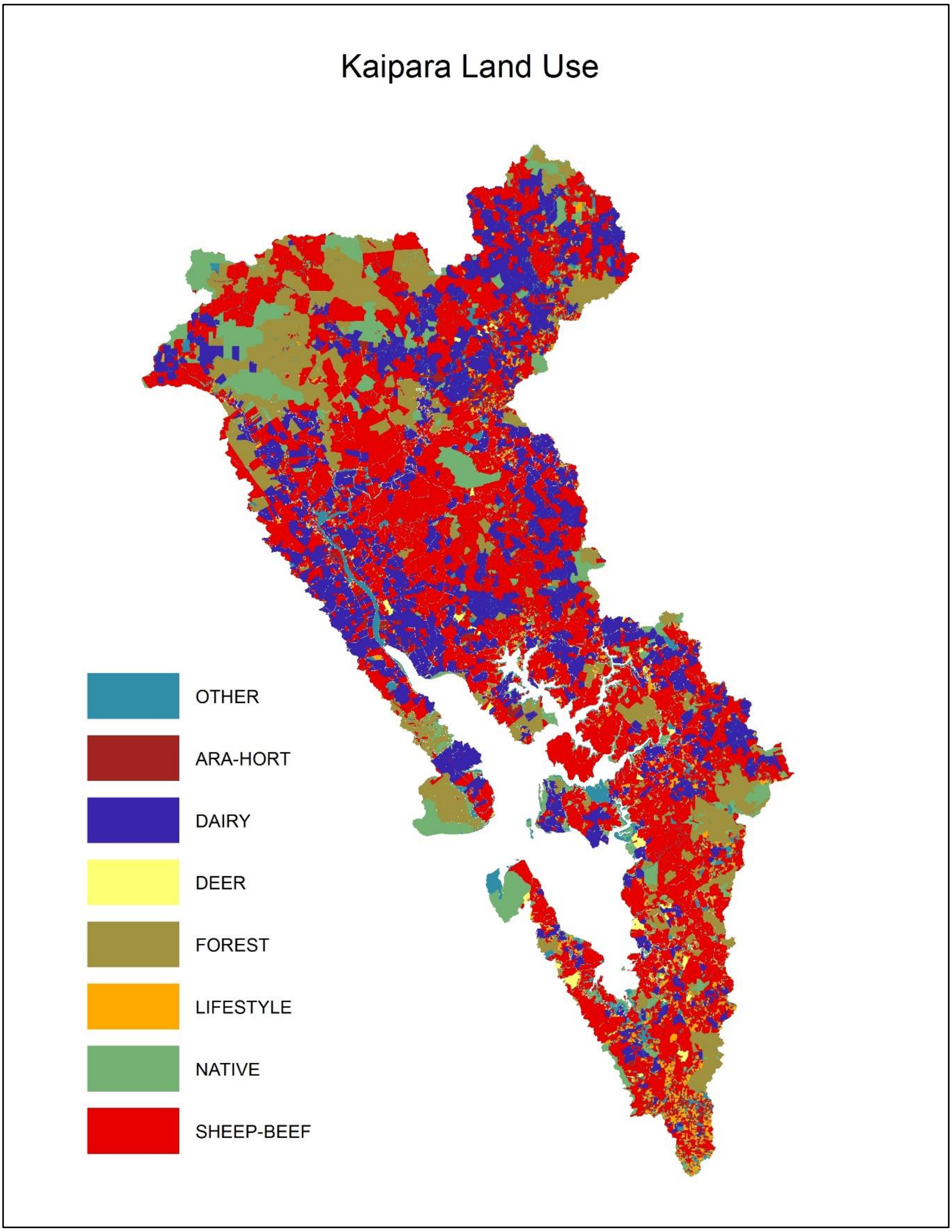


**Figure A.3.5:** Kaipara Harbour land use.

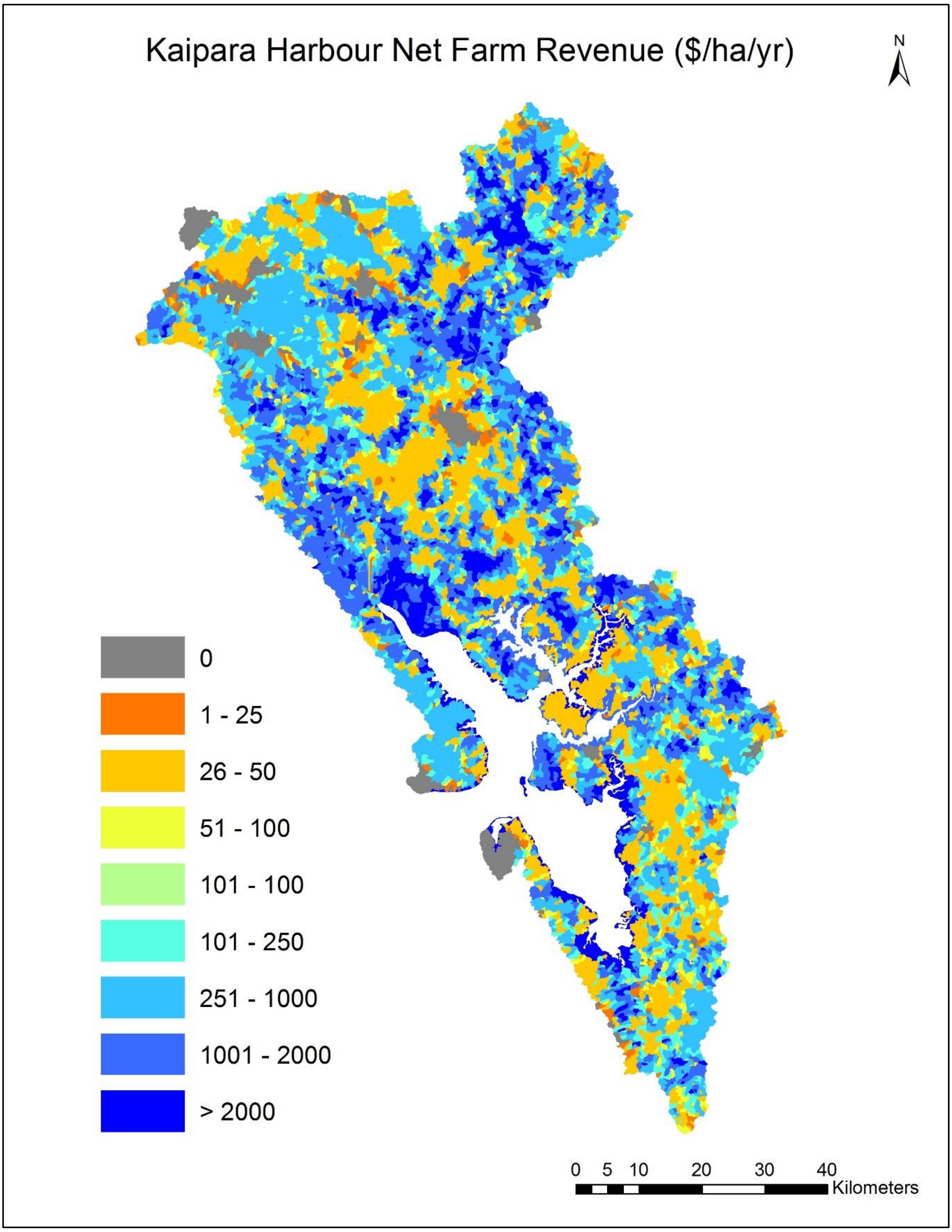


**Figure A.3.6:** Kaipara Harbour net farm revenue.

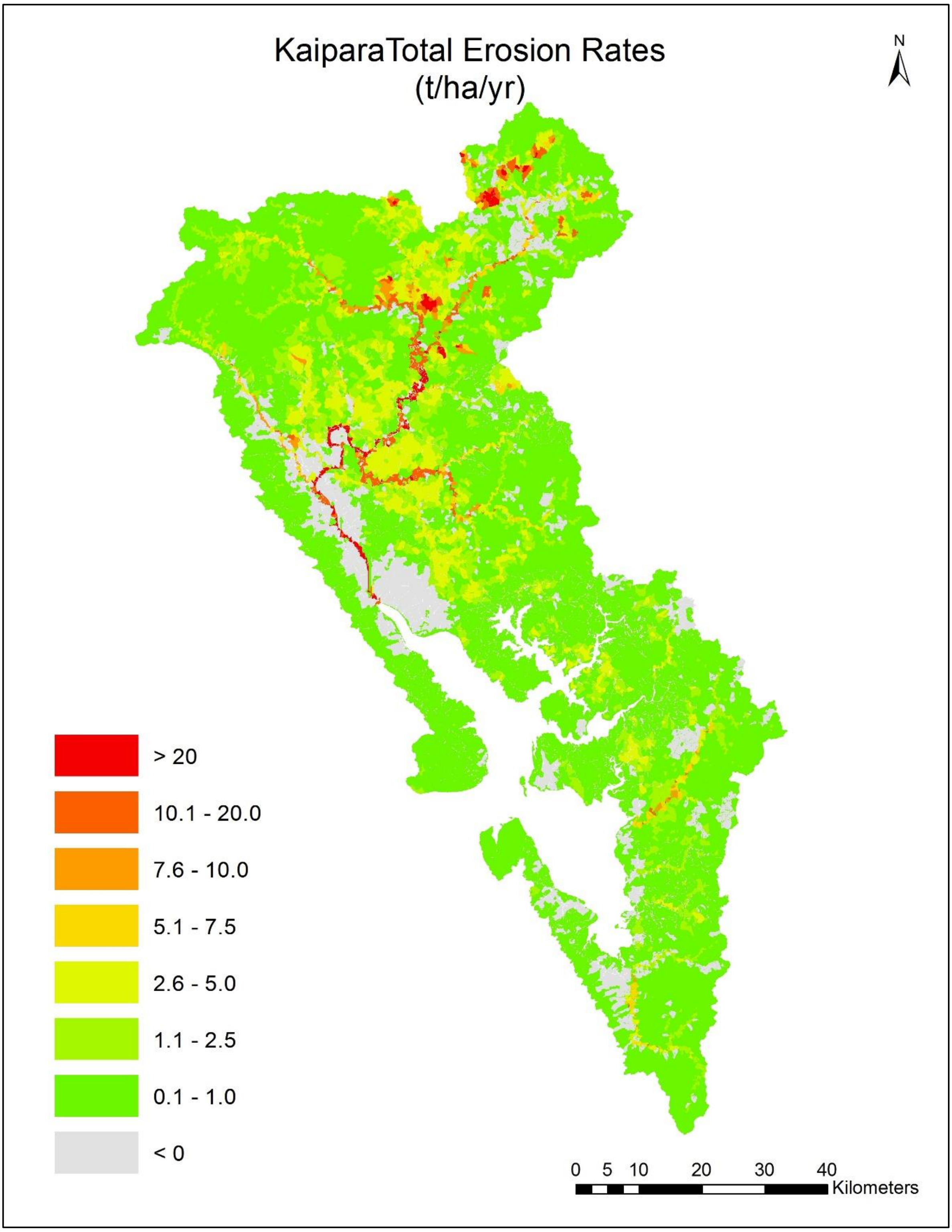


**Figure A.3.7:** Kaipara Harbour catchment total erosion rates (t/ha/yr).

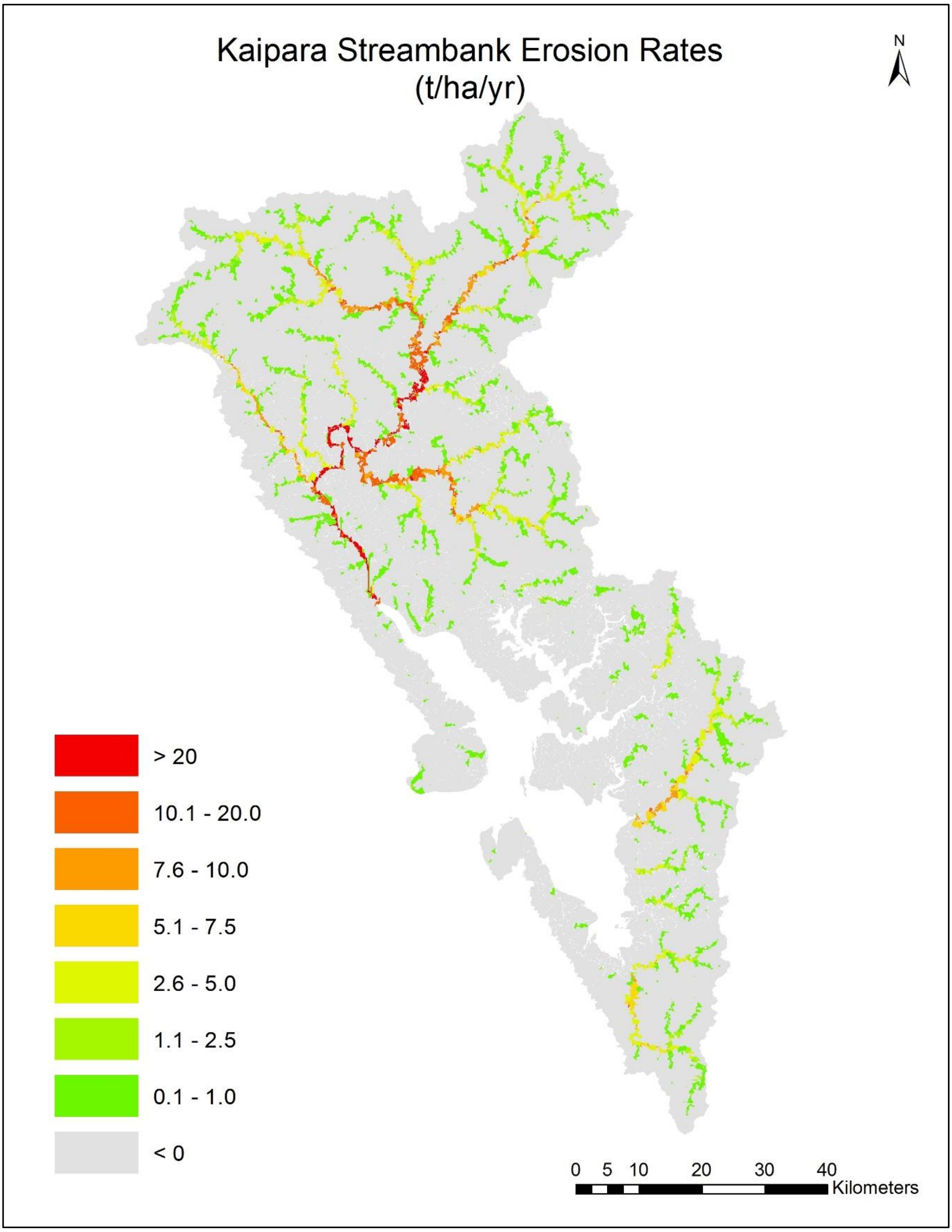


**Figure A.3.8:** Kaipara Harbour catchment streambank erosion rates (t/ha/yr).

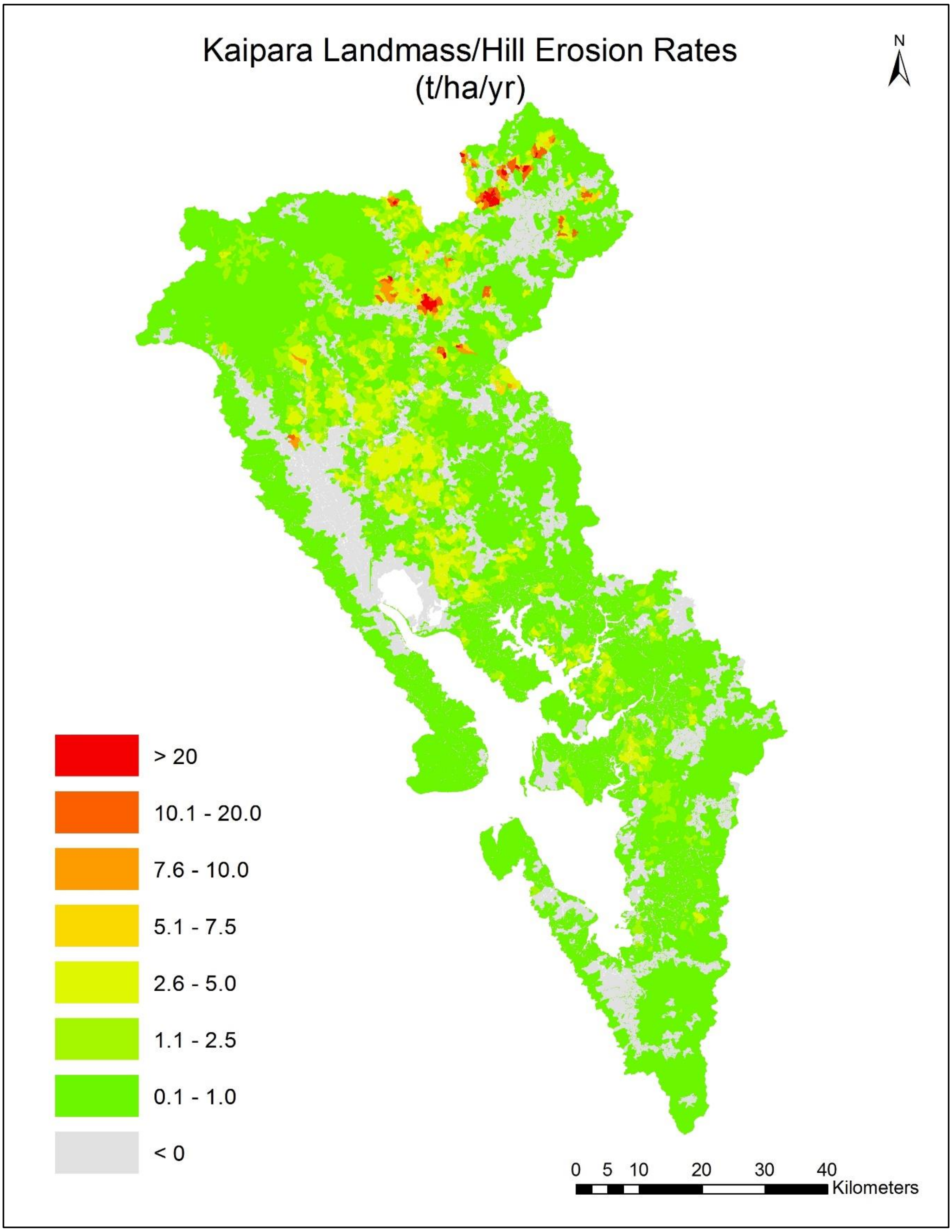


**Figure A.3.9:** Kaipara Harbour catchment land-based (landslide, gully, earthflow, and surficial erosion) erosion rates (t/ha/yr).

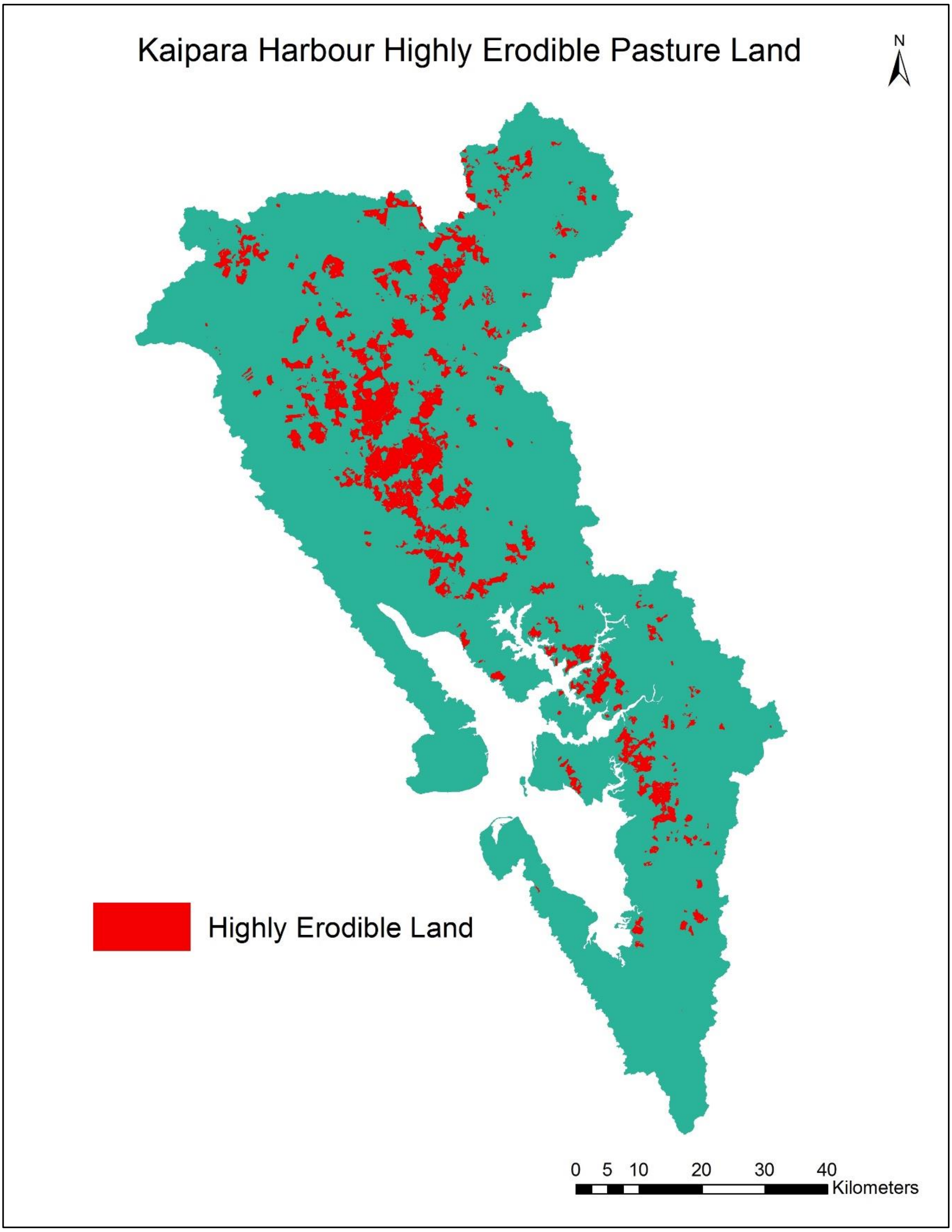


**Figure A.3.10:** Kaipara Harbour highly erodible pasture land (erosion rate > 1.0 t/ha/yr).

## Appendix 4 – Total Erosion estimates by sub-catchment

We have created spatially explicit maps for each of the policy scenarios for total sediment loads. Estimates of these key outputs depict percentage changes for each modelled scenario compared to the no mitigation baseline. This was done by taking the mean estimates for each of the more than 18,000 REC2 sub-catchments from NZFARM and overlaying them onto the baseline land use map.

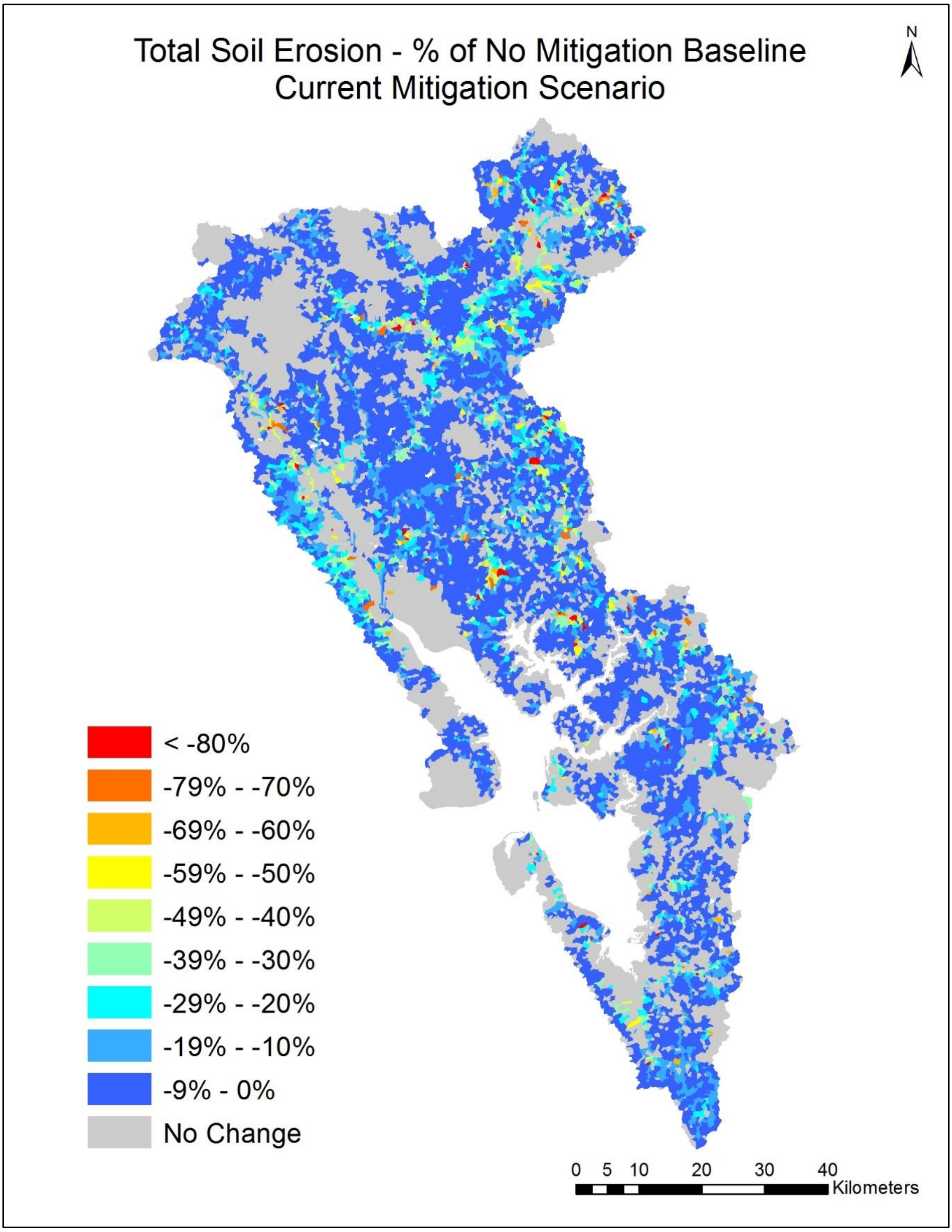


**Figure A.4.1:** Percent change in total erosion by REC2 sub-catchment – current mitigation scenario.

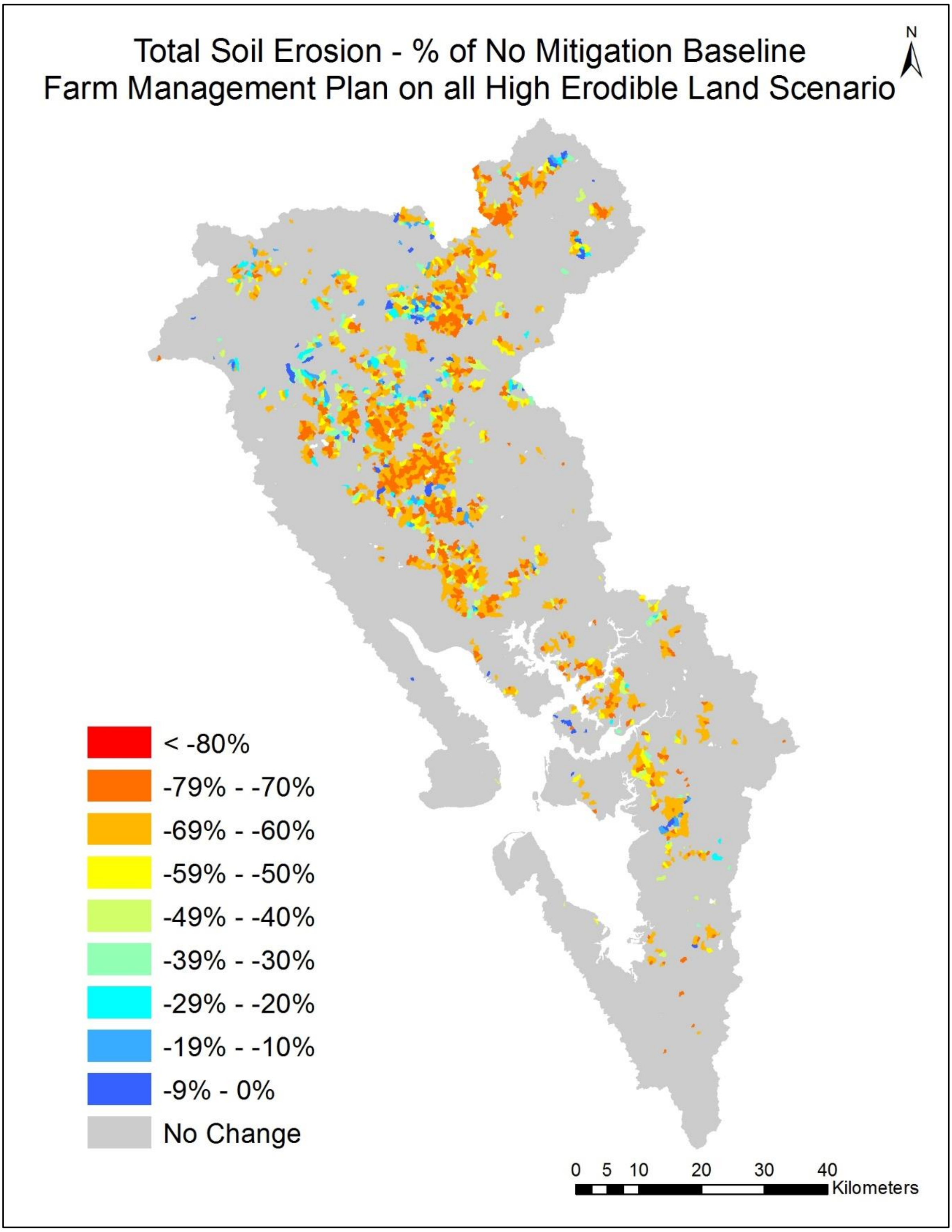


**Figure A.4.2:** Percent change in total erosion by REC2 sub-catchment – farm management plans on highly erodible land scenario.

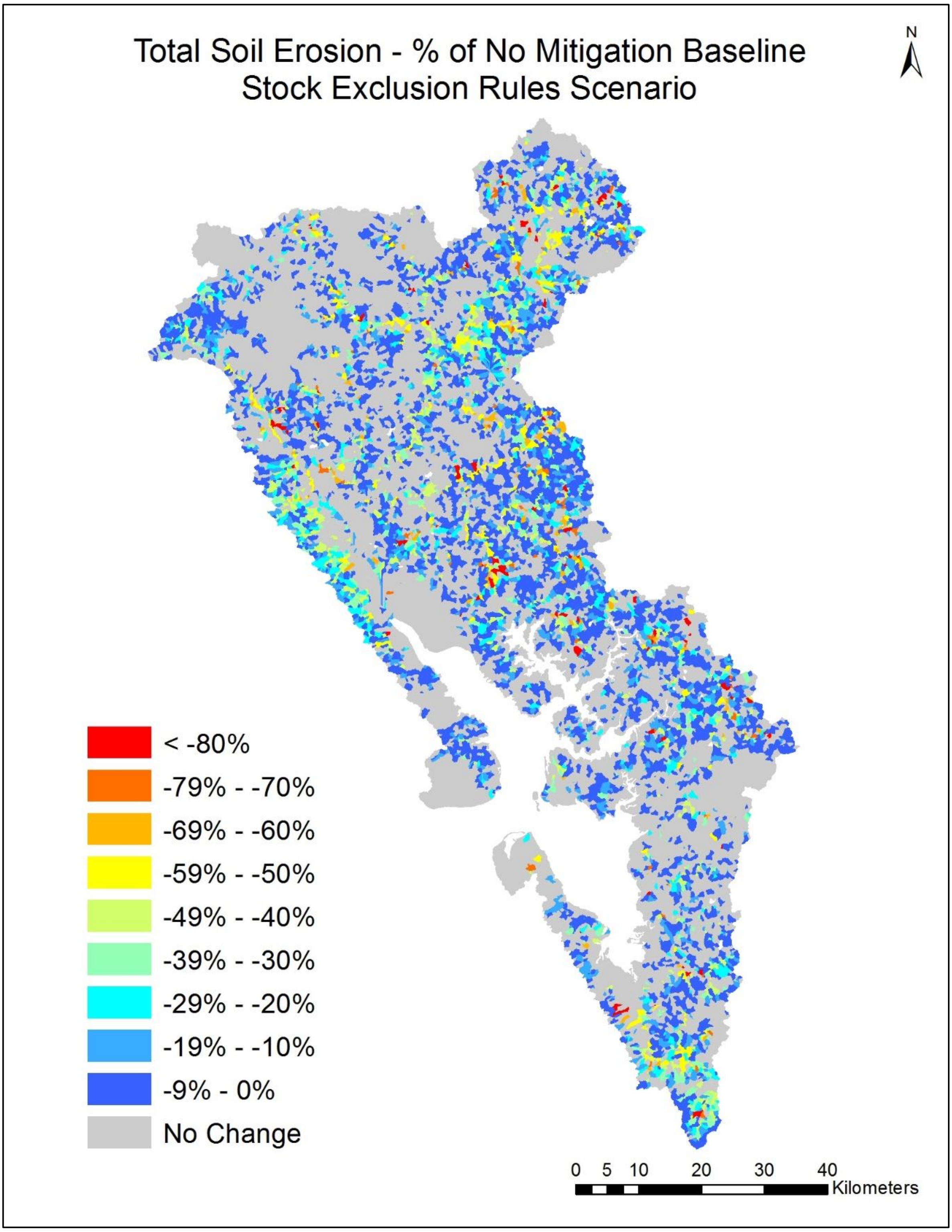


**Figure A.4.3:** Percent change in total erosion by REC2 sub-catchment – stock exclusion rules scenario.

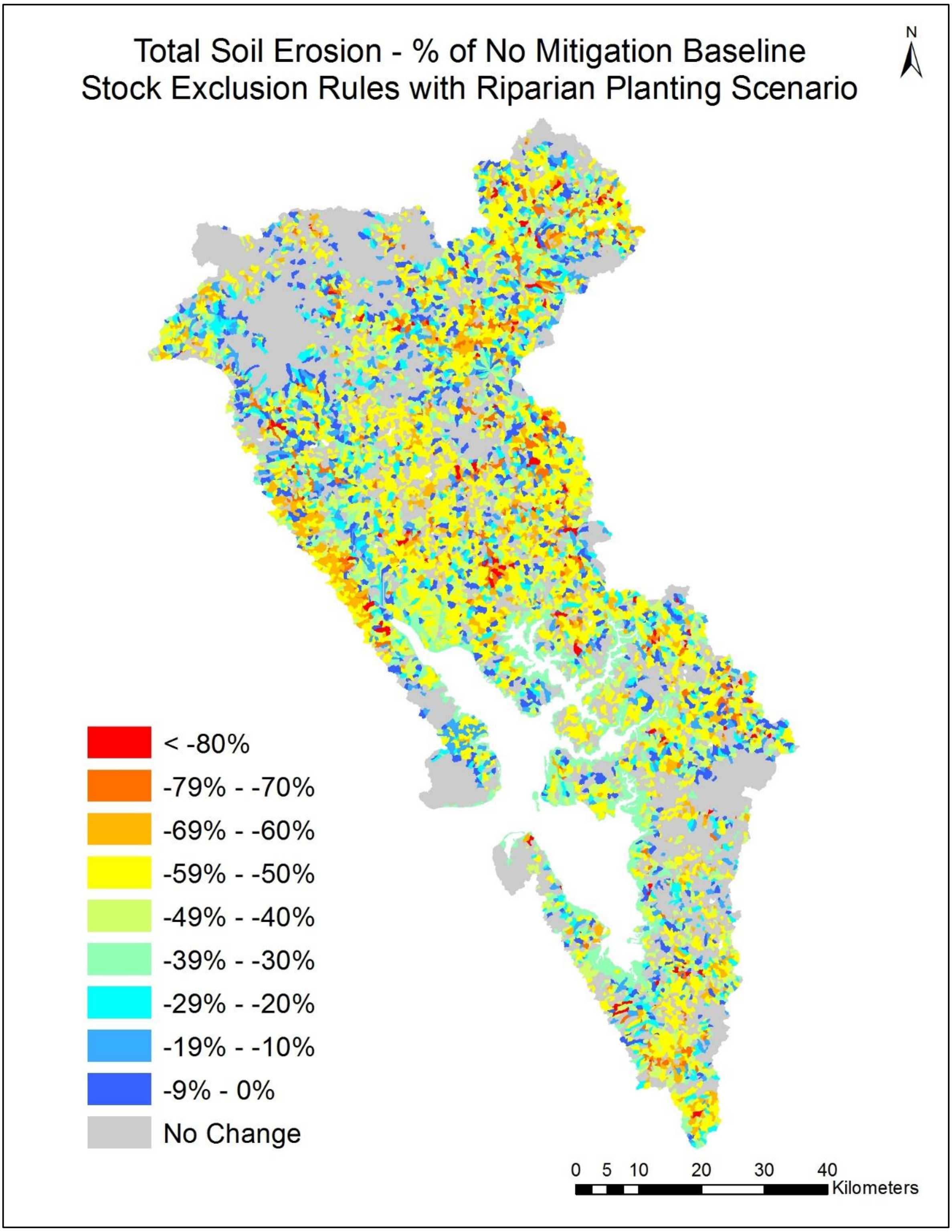


**Figure A.4.4:** Percent change in total erosion by REC2 sub-catchment – stock exclusion with riparian planting scenario.

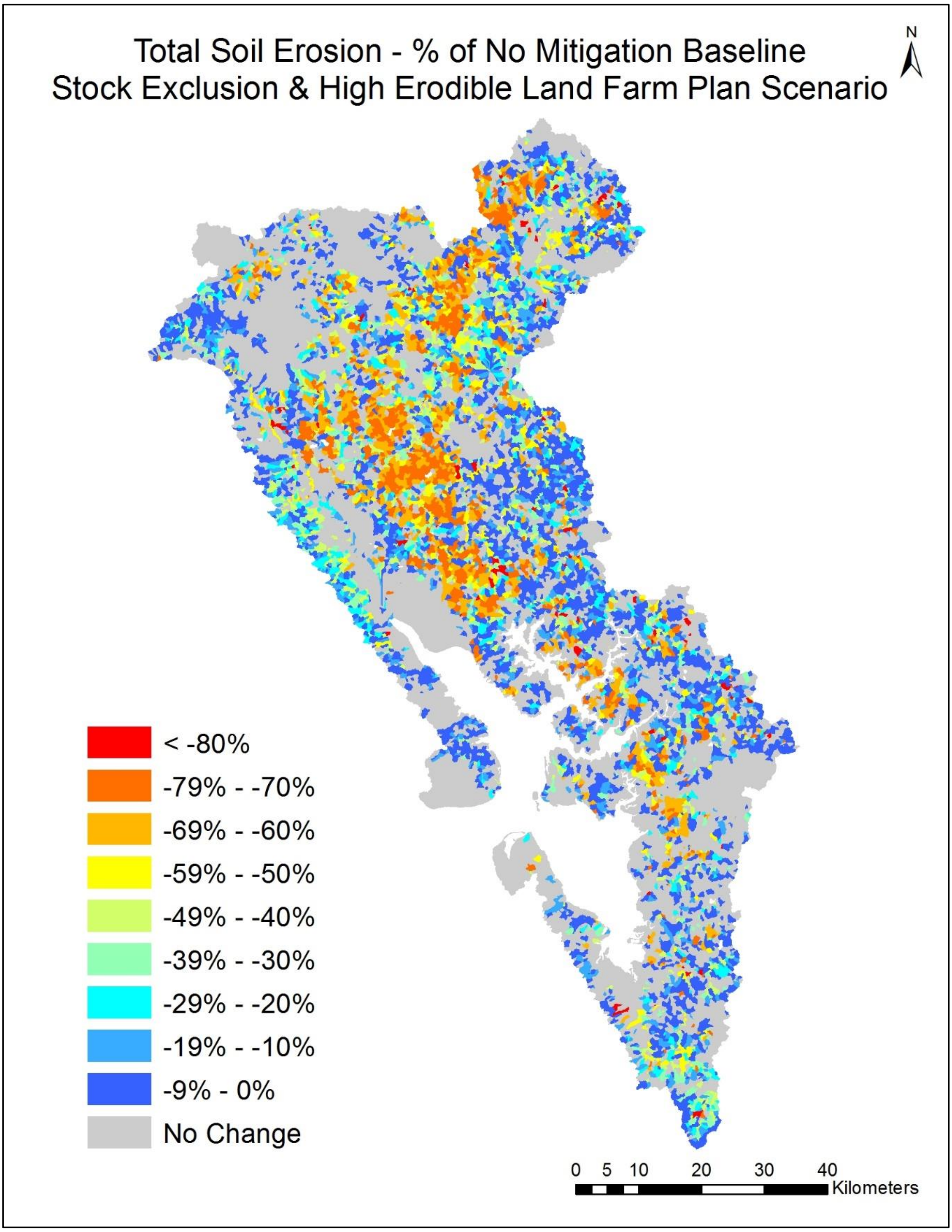


**Figure A.4.5:** Percent change in total erosion by REC2 sub-catchment – stock exclusion rules and farm management plans on highly erodible land scenario.

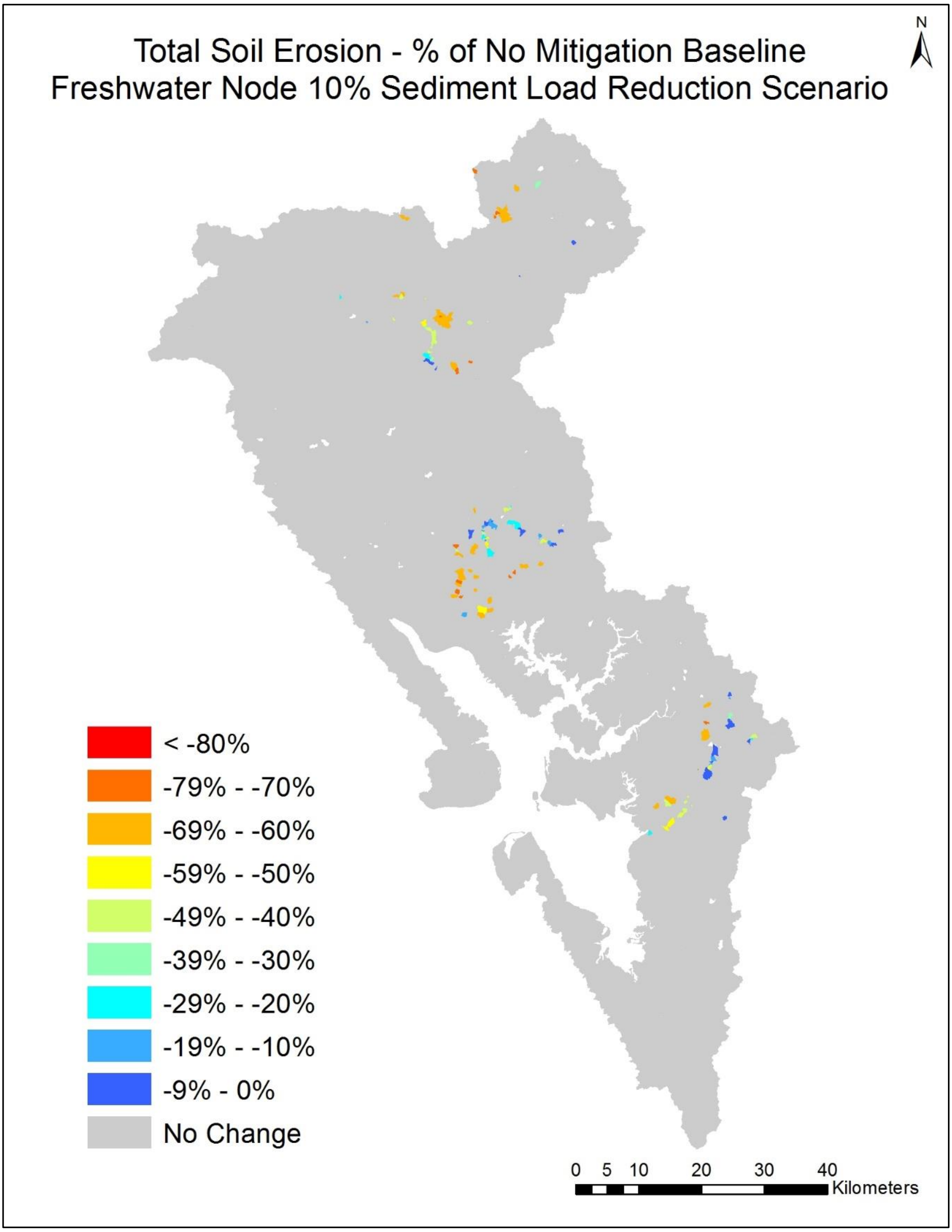


**Figure A.4.6:** Percent change in total erosion by REC2 sub-catchment – 10% sediment load reduction for every freshwater node scenario.

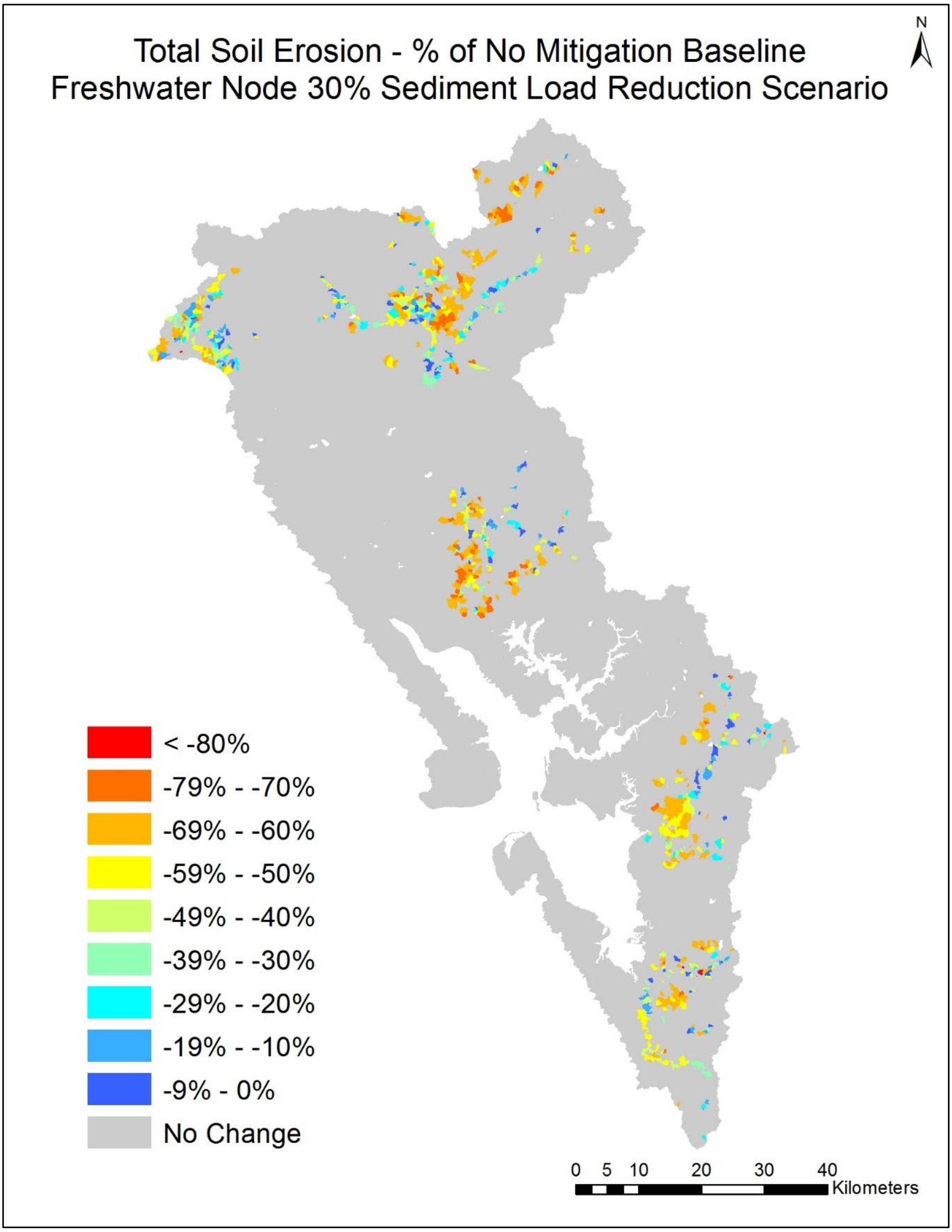


**Figure A.4.7:** Percent change in total erosion by REC2 sub-catchment – 30% sediment load reduction for every freshwater node scenario.

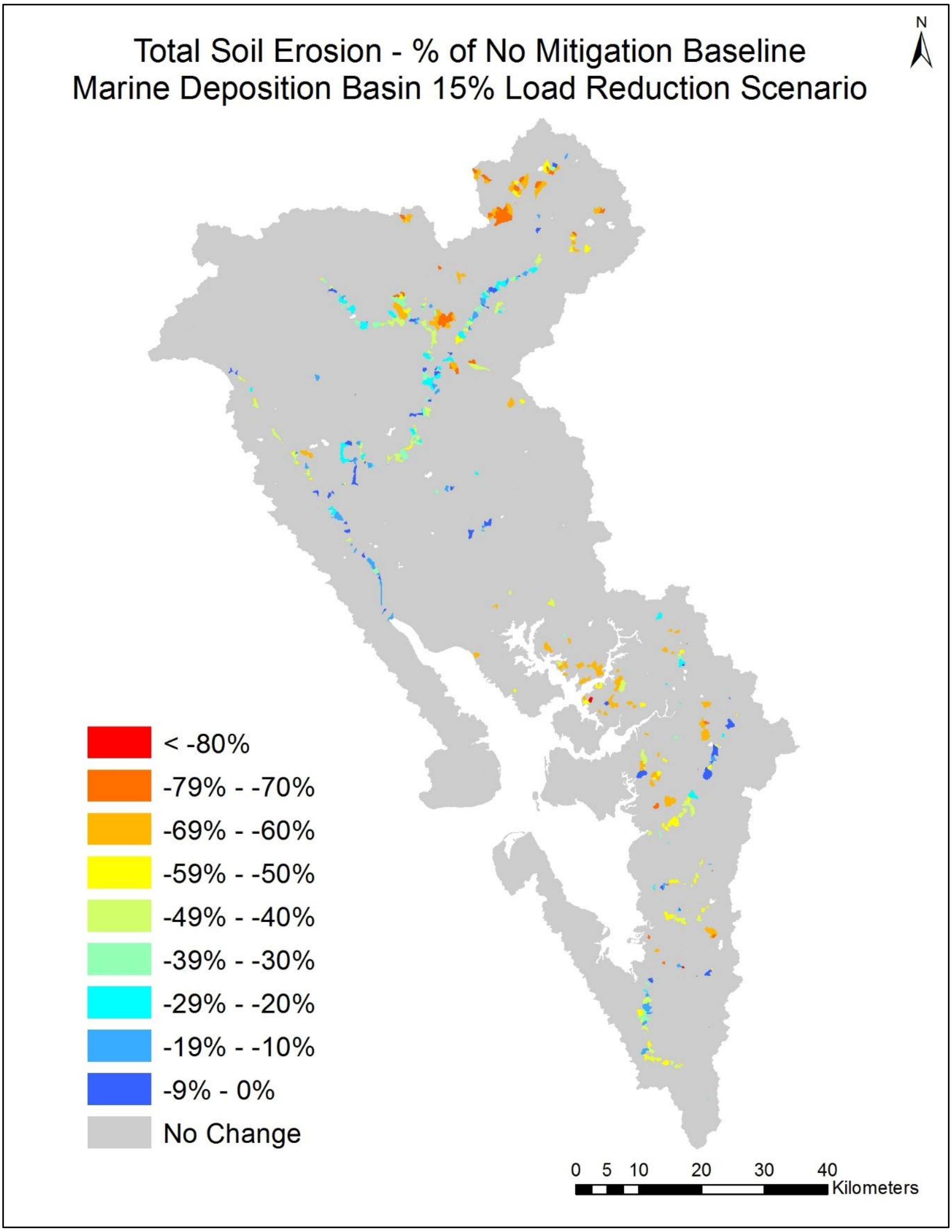


**Figure A.4.8:** Percent change in total erosion by REC2 sub-catchment – 15% sediment load reduction for every marine deposition basin scenario.

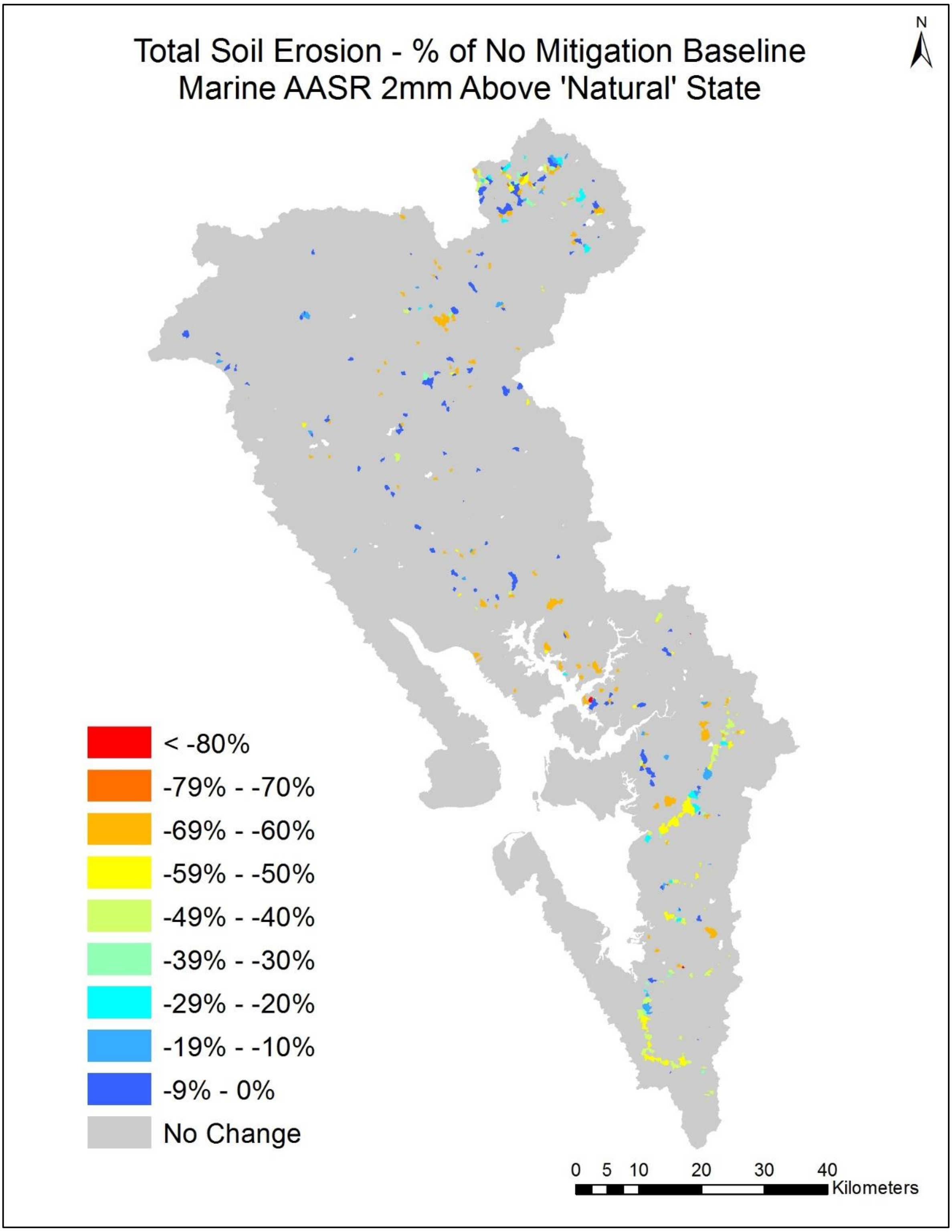


**Figure A.4.9:** Percent change in total erosion by REC2 sub-catchment – Every marine deposition basin required to meet AASR of 2mm above 'natural' state scenario.

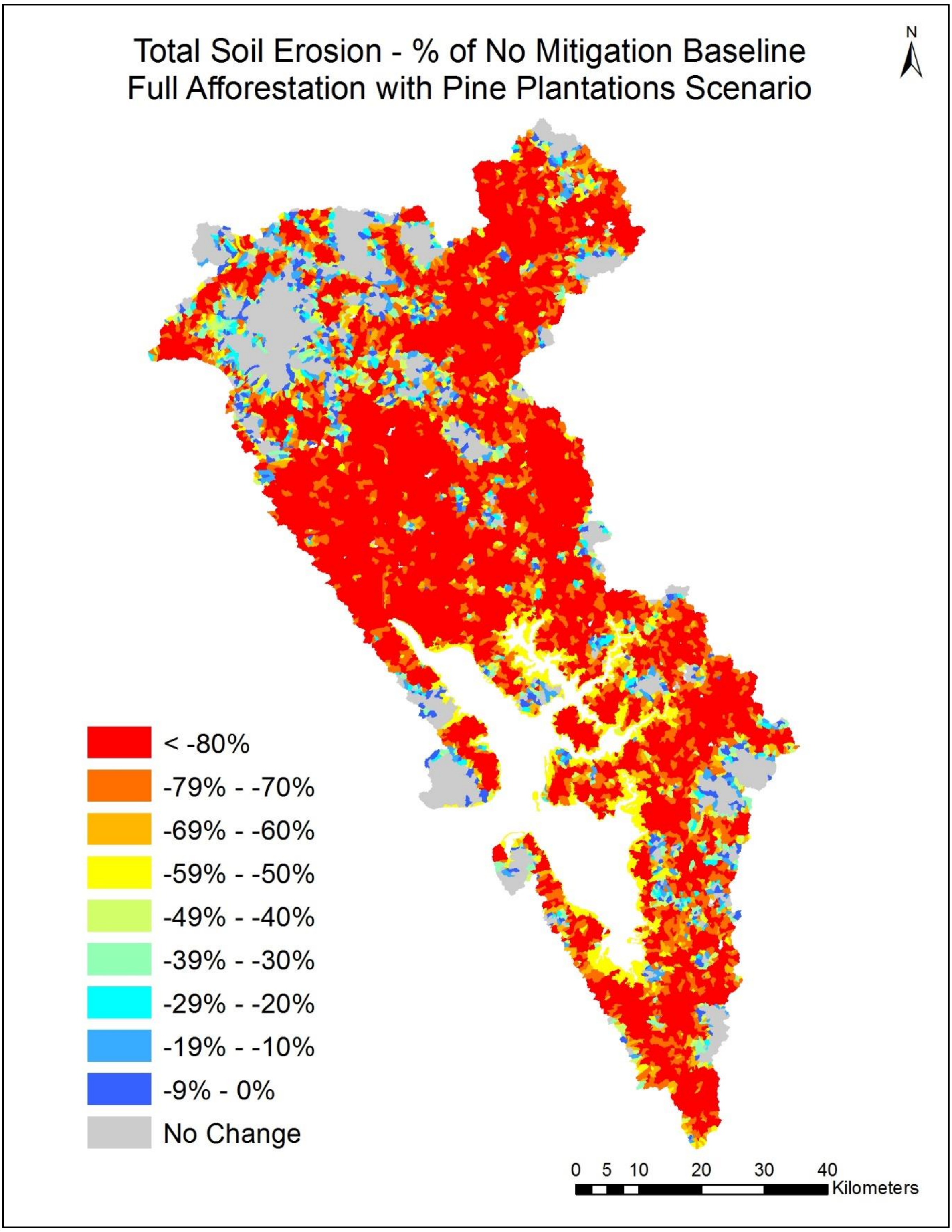


**Figure A.4.10:** Percent change in total erosion by REC2 sub-catchment – pine plantation afforestation on all pasture land scenario.

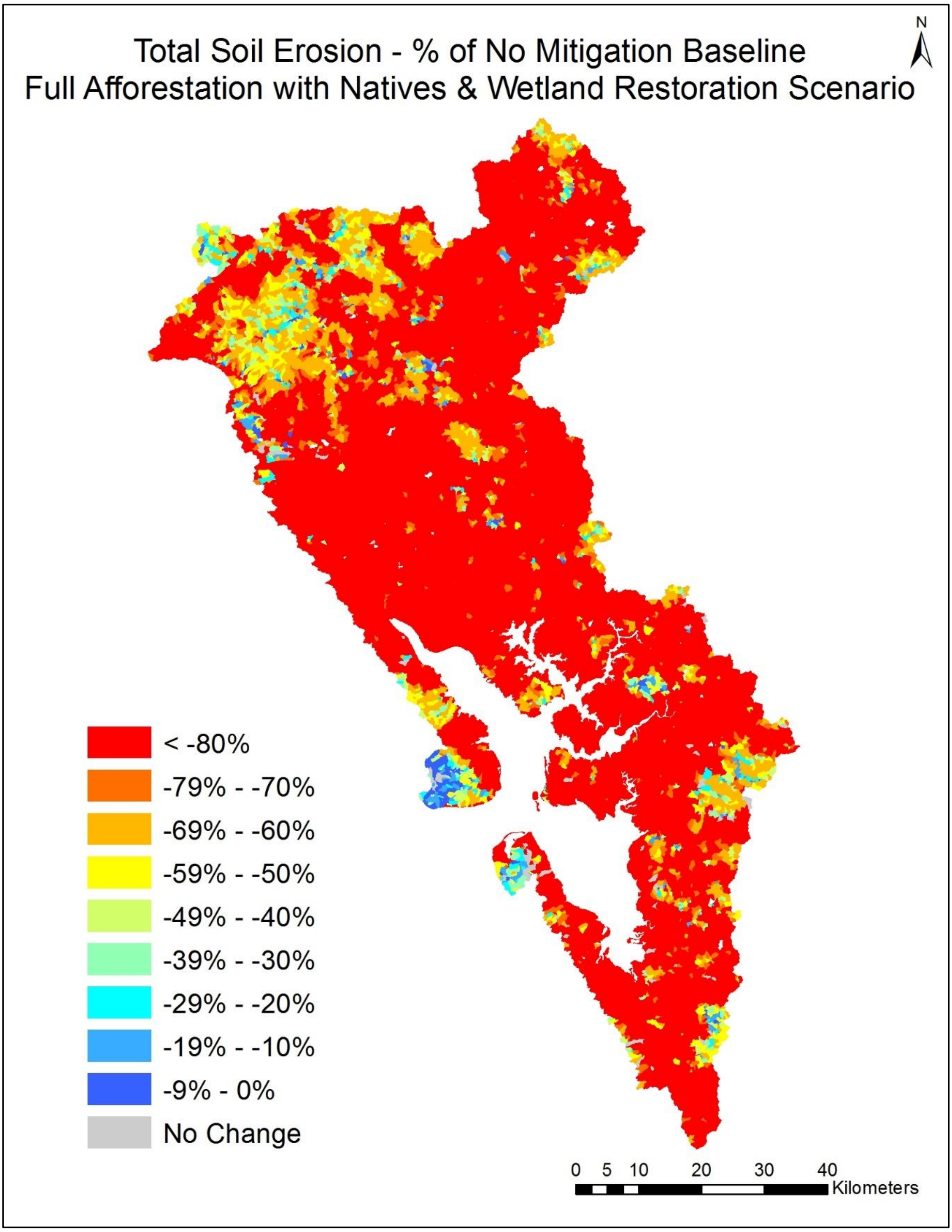


**Figure A.4.11:** Percent change in total erosion by REC2 sub-catchment – native bush afforestation on all pasture land & wetland restoration scenario.

 

## Appendix 5 – Detailed Scenario Results

**Table A.5.1:** Marine Average Annual Sedimentation Rates (mm/yr)

| Deposition Basin | Baseline | Current Mitigation | Soil Cons Plan - All HEL | Stock Exclusion Rules | Stock Exclusion Rules + Planting | Stock Exclusion + All HEL Plans | Freshwater Node 10% | Freshwater Node 30% | Marine Deposition 15% | Marine 2mm above 'natural' AASR | Full Afforestation (Pine) | Full Afforestation (Native) + Wetlands |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WAIF | 3.0 | 2.7 | 2.3 | 2.7 | 2.2 | 2.0 | 2.9 | 2.6 | 2.6 | 2.9 | 1.4 | 0.9 |
| ARIF | 2.0 | 1.8 | 1.4 | 1.8 | 1.5 | 1.3 | 2.0 | 1.9 | 1.7 | 1.8 | 0.7 | 0.4 |
| OTIF | 3.0 | 2.8 | 2.1 | 2.8 | 1.9 | 1.9 | 3.0 | 2.9 | 2.6 | 2.8 | 1.3 | 0.8 |
| TNSF | 1.5 | 1.5 | 1.4 | 1.5 | 1.4 | 1.4 | 1.5 | 1.4 | 1.5 | 1.5 | 1.3 | 1.2 |
| WHIF | 2.0 | 1.8 | 1.3 | 1.9 | 1.0 | 1.2 | 1.9 | 1.8 | 1.7 | 1.4 | 0.7 | 0.3 |
| ORIF | 3.0 | 2.8 | 2.2 | 2.8 | 2.5 | 2.0 | 3.0 | 2.9 | 2.6 | 2.9 | 1.3 | 0.9 |
| KAIF | 6.5 | 6.1 | 5.9 | 6.1 | 5.8 | 5.5 | 6.2 | 5.5 | 5.9 | 5.1 | 4.1 | 3.4 |
| MAIF | 4.0 | 3.9 | 3.8 | 3.9 | 3.0 | 3.7 | 4.0 | 3.9 | 3.5 | 2.9 | 2.9 | 0.9 |
| KPIF | 7.0 | 6.0 | 6.7 | 5.1 | 4.1 | 4.8 | 6.3 | 5.0 | 6.0 | 3.2 | 1.9 | 1.2 |

**Table A.5.2:** Suspended Sediment (gm/m3)

| Freshwater Sediment Node | Baseline | Current Mitigation | Soil Cons Plan - All HEL | Stock Exclusion Rules | Stock Exclusion Rules + Planting | Stock Exclusion + All HEL Plans | Freshwater 10% | Freshwater 30% | Marine 15% | Marine 2mm above 'natural' AASR | Full Afforestation (Pine) | Full Afforestation (Native) + Wetland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hoteo river | 3.5 | 3.2 | 3.1 | 3.1 | 2.8 | 2.7 | 3.2 | 2.5 | 2.5 | 2.0 | 1.4 | 0.8 |
| Kaihu river at Gorge | 2.6 | 2.4 | 2.5 | 2.3 | 1.9 | 2.2 | 2.4 | 1.8 | 2.6 | 2.6 | 1.2 | 0.6 |
| Kaipara river | 1.8 | 1.6 | 1.8 | 1.3 | 1.0 | 1.3 | 1.6 | 1.3 | 1.2 | 1.0 | 0.5 | 0.2 |
| Kaukapakapa river | 3.4 | 2.9 | 3.1 | 2.6 | 2.1 | 2.3 | 2.9 | 2.4 | 3.0 | 1.7 | 1.0 | 0.5 |
| Mangakahia river | 11.1 | 10.0 | 7.6 | 10.2 | 8.4 | 6.6 | 10.0 | 7.8 | 8.4 | 10.2 | 4.6 | 2.0 |
| Manganui river at Mitaitai | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Wairua river | 7.3 | 6.4 | 4.5 | 6.5 | 4.6 | 3.6 | 6.4 | 5.1 | 4.7 | 6.2 | 2.1 | 0.8 |

**Table A.5.3:** Water Clarity (m)

| Freshwater Sediment Node | Baseline | Current Mitigation | Soil Cons Plan - All HEL | Stock Exclusion Rules | Stock Exclusion Rules + Planting | Stock Exclusion + All HEL Plans | Freshwater 10% | Freshwater 30% | Marine 15% | Marine 2mm above 'natural' AASR | Full Afforestation (Pine) | Full Afforestation (Native) + Wetland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hoteo river | 1.3 | 1.4 | 1.4 | 1.4 | 1.5 | 1.6 | 1.4 | 1.7 | 1.7 | 2.0 | 2.6 | 4.1 |
| Kaihu river at Gorge | 1.6 | 1.7 | 1.6 | 1.7 | 1.8 | 1.7 | 1.7 | 1.9 | 1.6 | 1.6 | 2.2 | 3.1 |
| Kaipara river | 2.1 | 2.4 | 2.1 | 2.7 | 3.3 | 2.8 | 2.4 | 2.8 | 2.8 | 3.2 | 5.9 | 13.0 |
| Kaukapakapa river | 1.3 | 1.5 | 1.4 | 1.6 | 1.9 | 1.8 | 1.5 | 1.7 | 1.5 | 2.2 | 3.2 | 5.4 |
| Mangakahia river | 0.7 | 0.7 | 0.9 | 0.7 | 0.8 | 1.0 | 0.7 | 0.9 | 0.8 | 0.7 | 1.3 | 2.4 |
| Manganui river at Mitaitai | 0.9 | 1.0 | 1.2 | 1.0 | 1.3 | 1.4 | 1.0 | 1.2 | 0.9 | 0.9 | 1.8 | 2.0 |
| Wairua river | 0.8 | 0.9 | 1.1 | 0.8 | 1.1 | 1.3 | 0.9 | 1.0 | 1.1 | 0.9 | 2.0 | 4.2 |

**Table A.5.4:** Euphotic Depth (m)

| Freshwater Sediment Node | Baseline | Current Mitigation | Soil Cons Plan - All HEL | Stock Exclusion Rules | Stock Exclusion Rules + Planting | Stock Exclusion + All HEL Plans | Freshwater 10% | Freshwater 30% | Marine 15% | Marine 2mm above 'natural' AASR | Full Afforestation (Pine) | Full Afforestation (Native) + Wetland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hoteo river | 2.0 | 2.1 | 2.1 | 2.1 | 2.2 | 2.2 | 2.1 | 2.3 | 2.3 | 2.5 | 2.9 | 3.8 |
| Kaihu river at Gorge | 2.2 | 2.2 | 2.2 | 2.3 | 2.4 | 2.3 | 2.2 | 2.5 | 2.2 | 2.2 | 2.9 | 3.9 |
| Kaipara river | 2.6 | 2.8 | 2.6 | 3.0 | 3.4 | 3.1 | 2.8 | 3.1 | 3.1 | 3.3 | 4.7 | 7.3 |
| Kaukapakapa river | 2.0 | 2.2 | 2.1 | 2.3 | 2.5 | 2.4 | 2.2 | 2.4 | 2.1 | 2.7 | 3.3 | 4.4 |
| Mangakahia river | 1.5 | 1.6 | 1.8 | 1.6 | 1.7 | 1.9 | 1.6 | 1.8 | 1.7 | 1.6 | 2.4 | 3.6 |
| Manganui river at Mitaitai | 1.8 | 2.0 | 2.2 | 2.0 | 2.3 | 2.4 | 2.0 | 2.2 | 1.9 | 1.9 | 2.8 | 3.0 |
| Wairua river | 1.5 | 1.6 | 1.8 | 1.5 | 1.8 | 2.0 | 1.6 | 1.7 | 1.8 | 1.6 | 2.5 | 3.8 |

**Table A.5.5:** Area by Mitigation Practice (ha)

| Mitigation Practice | Baseline | Current Mitigation | Soil Cons Plan - All HEL | Stock Exclusion Rules | Stock Exclusion Rules + Planting | Stock Exclusion + All HEL Plans | Freshwater 10% | Freshwater 30% | Marine 15% | Marine 2mm above 'natural' AASR | Full Afforestation (Pine) | Full Afforestation (Native) + Wetland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No Mitigation | 602,031 | 393,866 | 521,121 | 310,416 | 310,378 | 229,506 | 595,812 | 567,662 | 586,996 | 516,094 | 137,042 | 0 |
| Farm Management Plan | 0 | 8,092 | 80,910 | 0 | 0 | 56,584 | 1,443 | 12,045 | 4,556 | 2,027 | 0 | 0 |
| Stream Fencing | 0 | 200,073 | 0 | 291,615 | 0 | 267,326 | 2,281 | 7,520 | 5,697 | 7,286 | 0 | 0 |
| Wetlands | 0 | 0 | 0 | 0 | 0 | 0 | 2,273 | 12,582 | 3,907 | 389 | 0 | 137,042 |
| Riparian Planting | 0 | 0 | 0 | 0 | 291,652 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Farm Plan & Fencing | 0 | 0 | 0 | 0 | 0 | 48,652 | 1 | 1,504 | 977 | 75,625 | 0 | 0 |
| Riparian Fencing & Wetlands | 0 | 0 | 0 | 0 | 0 | 0 | 48 | 710 | 0 | 712 | 0 | 0 |
| Farm Plans & Wetlands | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 |
| Farm Plans, Fencing & Wetlands | 0 | 0 | 0 | 0 | 0 | 0 | 173 | 7 | 0 | 0 | 0 | 0 |
| Pine Afforestation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 464,989 | 0 |
| Native Afforestation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Native Afforestation + Wetlands | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 464,989 |
| **Total Area** | **602,031** | **602,031** | **602,031** | **602,031** | **602,031** | **602,031** | **602,031** | **602,031** | **602,031** | **602,031** | **602,031** | **602,031** |

**Table A.5.6:** Total Annualized Mitigation Cost by Land Use (million $/yr)

| Land Use | Baseline | Current Mitigation | Soil Cons Plan - All HEL | Stock Exclusion Rules | Stock Exclusion Rules + Planting | Stock Exclusion + All HEL Plans | Freshwater 10% | Freshwater 30% | Marine 15% | Marine 2mm above 'natural' AASR | Full Afforestation (Pine) | Full Afforestation (Native) + Wetland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dairy | $0 | $1.399 | $0.604 | $1.673 | $19.682 | $2.277 | $0.070 | $0.326 | $0.163 | $0.461 | $233.236 | $288.765 |
| Sheep & Beef | $0 | $4.849 | $1.901 | $8.096 | $19.725 | $9.997 | $0.114 | $0.794 | $0.355 | $5.281 | $0.125 | $11.123 |
| Deer | $0 | $0.054 | $0.021 | $0.103 | $0.290 | $0.124 | $0.000 | $0.004 | $0.085 | $1.270 | $1.804 | $3.001 |
| Lifestyle | $0 | $0.298 | $0.032 | $0.592 | $1.568 | $0.624 | $0.007 | $0.048 | $0.033 | $1.677 | $0.012 | $1.118 |
| Arable & Hort | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0.026 | $20.006 | $22.174 |
| Forestry | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0.0 | $3.125 |
| Native Bush | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0.0 | $1.337 |
| Other | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0.142 | $0.206 |
| **Total** | **$0** | **$6.600** | **$2.557** | **$10.464** | **$41.265** | **$13.022** | **$0.191** | **$1.173** | **$0.636** | **$8.715** | **$255.326** | **$330.850** |

**Table A.5.7:** Total Annualized Mitigation Cost by Land Use (million $/yr)

| Erosion Type | Baseline | Current Mitigation | Soil Cons Plan - All HEL | Stock Exclusion Rules | Stock Exclusion Rules + Planting | Stock Exclusion + All HEL Plans | Freshwater 10% | Freshwater 30% | Marine 15% | Marine 2mm above 'natural' AASR | Full Afforestation (Pine) | Full Afforestation (Native) + Wetland |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Land-based | 358,510 | 339,123 | 164,658 | 358,510 | 269,983 | 164,658 | 329,618 | 273,823 | 296,765 | 296,765 | 123,573 | 34,444 |
| Streambank | 332,982 | 270,904 | 332,982 | 244,092 | 208,536 | 244,092 | 323,787 | 303,406 | 291,288 | 291,288 | 98,019 | 51,026 |
| **Total** | **691,492** | **610,028** | **497,640** | **602,602** | **478,519** | **408,750** | **653,405** | **577,229** | **588,053** | **588,053** | **221,592** | **85,470** |

# Appendix 6 – Sensitivity Analysis

**Table A.6.1:** Mitigation effectiveness assumptions (as % change in load relative to no mitigation)

| Mitigation Option | Land-based/Hill Erosion % | Streambank Erosion % |
|---|---|---|
| No Mitigation | 0 | 0 |
| HEL Farm Plan – Base Effective | –70 | 0 |
| HEL Farm Plan – Less Effective | –50 | 0 |
| Fencing – Base Effective | 0 | –50 |
| Fencing – Less Effective | 0 | –30 |
| Fencing – More Effective | 0 | –80 |
| Fence + Riparian – Base Effective | –50 | –70 |
| Fence + Riparian – Less Effective | 0 | –50 |

**Table A.6.2:** Mitigation effectiveness model sensitivity estimates

| Scenario | Total Mitigation Cost (mil $/yr) | Mitigation Cost ($/ha/yr) | Land-based Erosion (t) | Stream bank Erosion (t) | Total Erosion (t) |
|---|---|---|---|---|---|
| No Mitigation | $0.00 | $0.00 | 358,510 | 332,982 | 691,492 |
| *Change From No Mitigation Baseline* | | | | | |
| HEL Farm Plan – Base Effective | $2.6 | $13 | –54% | 0% | –28% |
| HEL Farm Plan - Less Effective | $2.6 | $18 | –39% | 0% | –20% |
| Fencing - Base Effective | $10.5 | $118 | 0% | –27% | –13% |
| Fencing - Less Effective | $10.5 | $196 | 0% | –16% | –8% |
| Fencing - More Effective | $10.5 | $74 | 0% | –43% | –21% |
| Fence + Riparian - Base Effective | $41.3 | $194 | –25% | –37% | –31% |
| Fence + Riparian - Less Effective | $41.3 | $464 | 0% | –27% | –13% |

### A.6.1 Comparison of practice-based scenarios to 'current' mitigation scenario

As noted several times in the report, we chose to use the 'no mitigation' scenario to define the 'baseline; to measure the relative impacts of all other scenarios against. This is because it follows the same assumptions that were used for estimating the long-run average sediment loads in SedNetNZ (Dymond 2016) as well as for the sub-catchment level load levels that were used in Green et al's (2017) marine attribute estimates, both of which are included in NZFARM. This approach was taken to define the baseline as there was no information on the specific farms in the catchment that are currently fenced or how effective that fencing is. Thus, the NZFARM sediment mitigation results may overestimate the actual reduction that could occur under the different model scenarios as well as the cost to achieve certain attribute targets.

As a result of the potential uncertainty about what the effect that additional mitigation may have on erosion in the catchment over what is already being implemented, we compare results from the practice-based scenarios relative to the 'current mitigation' scenario. This is done by taking figures presented in Table 10, and then adjusting the mitigation figures (both cost and erosion reduction) to account for what could be achieved on top of the fencing and HEL farm management plans assumed to already be implemented in the catchment (Table A.6.3). As a result, the total cost of each scenario was reduced by the amount that the 'current scenario' already contributed to (e.g., 10% of farm management plans assumed to be implemented, thereby reducing total cost Scenario 2 by $0.3 million/yr). Making a comparison across scenarios in this manner resulted in much lower annual costs for the stock exclusion rules case (approx. $6.3 million/yr less), but it did not necessarily result in lower per tonne mitigation costs. This is likely because of the *ad hoc* manner in which fencing and HEL-based mitigation percentages for the 'current' mitigation scenario were assigned to eligible farms in the catchment (i.e., as a proportion implemented on each eligible farm as opposed to 100% implementation on a select but specific number of farms in the Kaipara Harbour catchment).

**Table A.6.3:** Comparison of key outputs from practice-based scenarios to 'current mitigation' scenario

| Scenario | Net Revenue (mil $) | Total Mitigation Cost (mil $/yr) | Average Mitigation Cost ($/t/yr) | Land-based Erosion (t/yr) | Stream bank Erosion (t/yr) | Total Erosion (t/yr) |
|---|---|---|---|---|---|---|
| Current Mitigation | $365 | $0 | $0 | 339,123 | 270,904 | 610,028 |
| *Change from Current Mitigation* | | | | | | |
| Farm Mgmt Plan – All HEL | –1% | $2.3 | $13 | –51% | 0% | –29% |
| Stock Exclusion Rules | –1% | $3.9 | $144 | 0% | –10% | –4% |
| Stock Exclusion + 5m riparian | –9% | $35 | $264 | –20% | –23% | –22% |
| Stock Exclusion + All HEL Plans | –2% | $6.2 | $31 | –51% | –10% | –33% |
| Full Afforestation (Pine) | –68% | $249 | $640 | –64% | –64% | –64% |
| Full Afforestation + Wetland (Native) | –89% | $324 | $618 | –90% | –81% | –86% |

Note that we were not able to estimate the impacts for the outcome based scenarios. Doing so would have required re-calibrating NZFARM with the ‘new’ baseline and then re-running each scenario individually with the new outcome targets.

## Appendix 7 – Auckland Unitary Plan – stock exclusion rules

A scenario was run to test the impact of implementing the stock exclusion rules under the Auckland Unitary Plan (AUP) (Operative in part). Under rule E3.6.1.25(1) – (4), which came into effect in November 2016, all livestock must be excluded from the full extent of permanent streams, wetlands, lakes and rivers by 2021 and from all intermittent streams by 2026. The rule applies to any production land that is grazed at a stocking rate equal to, or exceeding 18 stock units per hectare. A stock unit is proportional to the size of the animal, for example a 75 kg ram is equivalent to 1 stocking unit, while a 450 kg dairy cow is equivalent to 10.4 stock units.

Due to limitations in the resolution of the data available to inform the model, bank erosion estimates could not be calculated for intermittent streams, only for permanent streams. Therefore, the modelled scenario only expressed the potential fencing costs under this rule and not the potential environmental gain. However, with the large proportion of intermittent streams in the Auckland region (see Fig A.7.1) the environmental gains of excluding stock from pastures with high stocking rates may be significant. Consequently, this identifies a further avenue of information that could be collected in future.

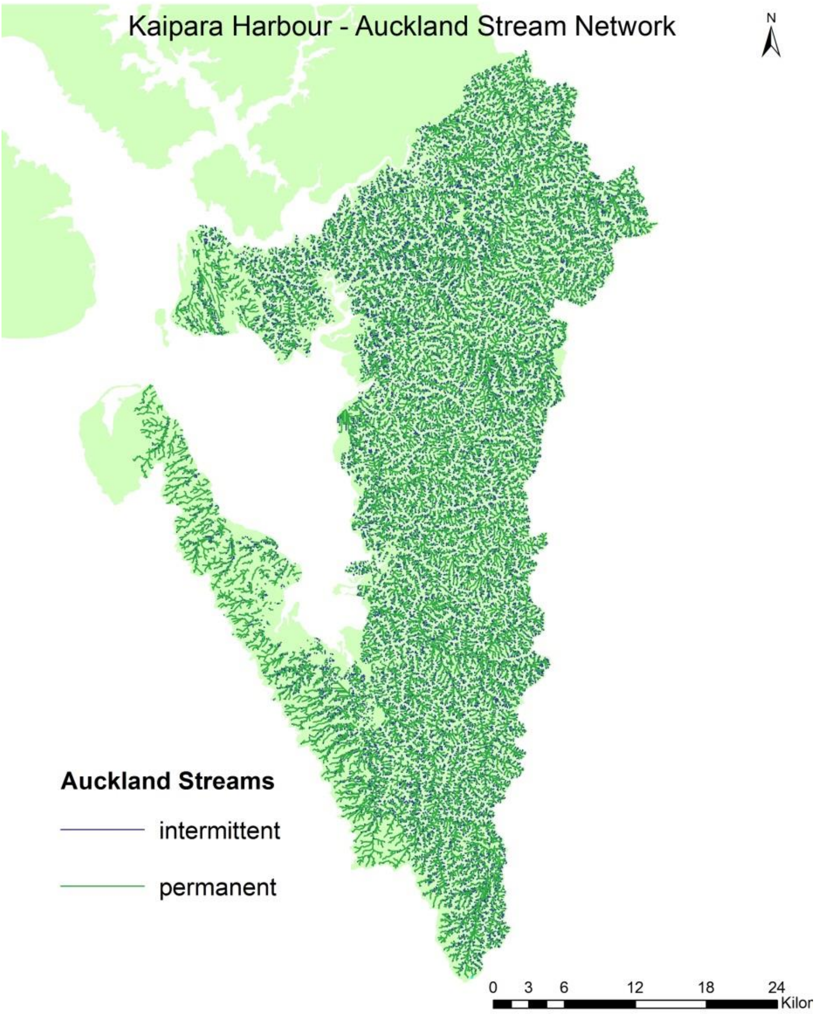


**Figure A.7.1:** Auckland permanent and intermittent stream network for Kaipara Harbour catchment.