Manaaki Whenua
Landcare Research

Impact testing of a proposed suspended sediment attribute: identifying erosion and sediment control mitigations to meet proposed sediment attribute bottom lines and the costs and benefits of those mitigations

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Impact testing of a proposed sediment attribute: identifying erosion and sediment control mitigations to meet proposed sediment attribute bottom lines and the costs and benefits of those mitigations

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Summary

Project and Client

- The Ministry for the Environment (MFE) requires an analysis of the potential impacts (physical and economic) of proposed regulations to be included in the National Policy Statement – Freshwater Management for managing in-stream sediment levels. Manaaki Whenua – Landcare Research has been contracted to 1) provide information on possible erosion and sediment control (ESC) mitigations to meet the proposed suspended sediment attribute bottom lines nationwide, and 2) calculate and describe the economic costs, benefits and co-benefits of those mitigations.

Objectives

- Parameterise the NZeem® model to incorporate ESC mitigations (Whole Farm Plans, afforestation, riparian exclusion).
- Calculate the baseline average annual suspended sediment load for each catchment that has river reaches below the proposed bottom lines.
- Use suspended sediment load reduction requirements from the NIWA-supplied data to calculate the load reduction target based on the NZeem® estimates of sediment load.
- Identify farms for which Whole Farm Plans have been implemented over the past 20 years and evaluate how their full maturation affects sediment loads.
- Calculate, individually and in sum, the potential sediment load reductions achievable through three scenarios for new ESC mitigation for each catchment and each farm within a catchment.
- Identify any catchments where sediment load reduction targets cannot be met by ESC mitigation scenarios.
- Conduct economic optimization (using NZFARM model) to determine the optimal application of the ESC mitigation options within each catchment that could meet the required sediment reduction target at least cost.
- Conduct spatial optimisation of the NZFARM outputs to define the spatially explicit locations of ESC mitigations and their resultant in-stream sediment reductions for NZeem®.
- Evaluate the overall benefits and costs of the proposed policy options by bringing together the outputs of the NZeem®, NZFARM and other modelling and data analysis.
- Report results at national and regional scale and for selected catchments (Waikato, Manawatu, Ruamahanga, Mataura, and Clutha).

Methods

- Catchments were defined as the catchment area contributing to the most downstream segment in the REC stream network (order 3 and above) which exceeds the proposed sediment bottom lines.
- Data on catchments and stream segments predicted not to meet the proposed sediment bottom lines and sediment load reductions (as a percentage of sediment

load) required to meet the bottom lines were supplied by NIWA. The required catchment sediment load reduction was calculated as the average sediment load reduction for all stream segments within the catchment.

- Average annual suspended sediment load was calculated as a baseline value (prior to ESC mitigation by three mitigation scenarios – Whole Farm Plans (WFP), afforestation (Aff) or riparian exclusion (RE) and then following implementation of ESC mitigation. This was estimated for each catchment using the NZeem® model.
- The load after implementation of ESC mitigation was calculated separately for maturation of existing WFPs and for new WFPs on mitigatable land (Highly Erodible Land, class 6e, 7e and 8e land) and for the three different ESC mitigation scenarios.
- Because only regional-scale data were available for RE these were assumed to apply at catchment scale. New RE mitigation was applied to untreated major streams.
- Catchments where the proposed sediment reductions can or cannot be met through implementation of each of the ESC mitigation scenarios were identified.
- For the catchments where the proposed sediment bottom lines could be achieved through application of WFP and Aff mitigations were identified, an optimal allocation of mitigation scenarios to achieve the proposed sediment threshold whilst maximising farm profitability was modelled using NZFARM analysis of the mitigatable land. For those catchments that could not achieve sediment bottom line targets, NZFARM modelling of mitigatable land was used to determine the cost to achieve the greatest reduction in sediment load possible.
- The NZFARM modelling calculated sediment load reductions, nutrient leaching (N and P), greenhouse gas emissions, CO_2 sequestration and farm profits and costs which were summarised at catchment and regional scales.
- NZeem® was parameterised to apply the spatial distribution of WFP and Aff from the NZFARM analysis to produce an estimate of sediment yield after implementation of the NZFARM optimisation. This was used to calculate the load reductions achieved at the stream segment scale.
- Cost benefit analysis (CBA) was used to evaluate the overall change in economic and social welfare from the implementation of sediment reduction practices. The CBA identified the range of potential environmental impacts and either monetised or described their effect. Where they could be monetised a benefit transfer approach was used.

Results

- Of the 627 catchments supplied by NIWA, 585 currently exceed the proposed sediment bottom line targets.
- After existing WFPs mature, 53 of the 585 catchments (9%) in the central to lower North Island will meet their catchment sediment bottom line targets. This includes several large catchments such as the Manawatu, Whanganui, Rangitaiki, Mohaka, Whangaehu, Kaituna and Patea Rivers.
- 331 of the remaining 532 catchments (63%) can meet the sediment bottom line targets under the WFP scenario, 345 (65%) under the Aff scenario, and 155 (29%) under the RE scenario.

- 159 catchments (30%) are unable to achieve the target sediment bottom lines under any of the mitigation scenarios. The majority of these catchments have relatively high sediment reduction targets (>10% to 67%).
- At stream segment scale in the 585 catchments, and excluding glacial source-of-flow segments, there are 77,561 segments (out of a total of 423,352) that the modelling suggested do not currently meet the proposed sediment bottom lines. After implementation of the NZFARM optimisation of WFP and Aff mitigations and maturing of existing Whole Farm Plans, an additional 15,868 stream segments (20% increase) will meet the proposed sediment bottom lines.
- NZFARM modelling results show that to meet the sediment reduction targets, and excluding consideration of riparian exclusion, afforestation could be implemented on about 1.06 million ha and WFP on about 6,055 ha. Afforestation far outstrips WFP due to its high sediment reduction effectiveness and lower establishment costs compared to WFP, as well as C sequestration revenues. The region with the most afforestation is Otago, which requires about 429,000 ha of afforestation. Among the selected catchments, the Clutha requires the largest area of afforestation (375,300 ha).
- Overall, NZFARM-optimised mitigations are predicted to reduce sediment load on mitigatable land by about 4 million tonnes (13% of current modelled NZeem® load from mitigatable land). This is a 3% reduction in total load for all 585 catchments (baseline sediment load of 132 million tonnes).
- In absolute terms, Gisborne would have the largest sediment reduction, of about 1.6 million tonnes (12% reduction in load from mitigatable land). Tasman has the least sediment load reduction among the regions (2% reduction in load from mitigatable land) due to lower sediment reduction targets.
- Of the selected catchments the Clutha catchment has the largest sediment load reduction after mitigation options are adopted (a reduction of 776 tonnes (90% reduction in load from mitigatable land).
- ESC mitigations are predicted to increase carbon sequestration and reduce GHG emissions, nitrogen leaching and phosphorous loss. Carbon sequestration increases through afforestation by 19.8 million tCO_2. Otago has the largest increase in carbon sequestration levels, which is around 37% of the total C sequestration increase.
- GHG emissions reduce by 2.3 million tCO_2, and the largest GHG emission reduction from the baseline would be in the Waikato (625,000 tCO_2 reduction). In contrast, the lowest reduction in GHG emissions is in Tasman (0.6% GHG reduction from baseline).
- Nitrogen leaching is reduced by 338 tonnes. The largest reduction in nitrogen leaching is simulated for Otago (about 91 tonnes of nitrogen leaching reduction). In addition, phosphorous losses decrease by 65 tonnes. The largest phosphorous loss decrease occurs in Waikato (17.3 tonne).
- The total cost of riparian exclusion is estimated at \$3.3 billion, assuming nothing has been implemented, and around \$1.2 billion if we considered what has been implemented so far. Fencing cost represents the highest cost item (\$2.9 billion), followed by planting cost (\$183 million), opportunity cost (\$120 million), and water supply cost (\$26 million). At the regional level (and assuming nothing has been implemented), Canterbury has the largest cost for riparian exclusion (\$627 million). Among the selected catchments, the Clutha has the largest costs for riparian exclusion, which is about \$363 million. If we consider in the analysis what has been

implemented so far by the farmers, the total cost of riparian exclusion will be reduced to $1.2 billion.

- In terms of expected annual impacts, economic modelling suggests that the profit from the mitigatable land area in New Zealand is projected to increase by $253.3 million due to C sequestration revenues from afforestation. The Waikato region is estimated to have the largest profit increase of $50 million. Southland has the largest losses of $5 million from meeting the sediment reduction target. All five study catchments are projected to have an increase in profits due to the large land areas allocated to mitigation. Among the selected catchments, the Clutha has the largest profit increase ($37.4 million).
- A benefit cost analysis was performed on the NZFARM modelling results on afforestation and whole farm plan mitigations over 50 years. Results indicate that net present value of benefits exceeds costs by a wide margin. Total costs, which include lost profits, establishment costs, and other ongoing costs, were estimated to be approximately $5 to 7 billion over 50 years, depending on the discount rate used (6% or 4%, respectively). Benefits were estimates from several categories, including environmental benefits. Using the midpoints of estimated benefit bounds, benefits range from $13 billion (6% discount rate) to $20 billion (4% discount rate).
- The largest category of benefits was carbon benefits, including both reductions in greenhouse gasses and carbon sequestration. Several values were used estimate the value of carbon reductions, ranging from $8 billion to $31 billion at the 4% discount rate, and $5 billion to $21 billion at the 6% discount rate.
- There were also several other significant environmental benefits that were not able to be monetised.

Conclusions

- Catchment bottom lines are achievable in 70% of catchments (81% by area). 9% of catchments will meet bottom lines through maturing of existing mitigations.
- Most of these catchments (11 million hectares) can meet bottom lines through landuse management changes (WFPs or RE). Only 14 (2%) catchments required landuse change (Aff).
- The catchments that do not meet bottom lines under any mitigation scenario tend to be small coastal catchments with no mitigatable land in the North Island, or catchments draining the Southern Alps, with naturally high sediment yields and relatively natural land cover with little available mitigatable land.
- After implementation of the NZFARM optimisation and maturing of existing Whole Farm Plans it is predicted sediment bottom lines will be achieved in 20% of the 77,561 segments which do not currently meet the proposed sediment bottom lines in the modelled catchments.
- Our estimates suggest that sediment reductions that use afforestation and whole farm plans as drivers could yield greater benefits than costs, especially considering non-monetised benefits and cultural values.
- In the modelled scenarios, the range of monetised benefits exceeds monetised costs. These calculations also omit several important environmental benefit categories, suggesting that the benefits could be even higher.

- The bulk of the benefits were from increases in carbon sequestration, although erosion and water quality benefits were also notable.

Recommendations

- We suggest the spatial optimisation of mitigations should consider the downstream impact of the mitigation and select mitigation locations based on a weighting of downstream impact. This could be achieved within the LUMASS framework or NZFARM. This could lead to better achievement of segment-scale bottom lines while also achieving catchment bottom lines. This would require some consideration of how best to weight the downstream impact of mitigations, and would require sediment routing to be run in a model following each individual mitigation being applied within the model to assess the segment-scale reduction achieved by each mitigation, and recalculate what further reductions are required. This was not achievable within the scope of this project.
- The Riparian Exclusion modelling components could be improved to include spatial optimisation of RE through national-scale modelling of bank erosion rates. Smith et al. (2019) recently published a revised bank erosion model for New Zealand designed to use inputs available at the national scale. At the time of writing, the data required to run such a model were not readily available, but may become available in the near future.
- The economic optimisation modelling could be improved by considering different land use types (e.g. dairy, sheep and beef, horticulture), management practices (e.g. stocking rates), and their respective impacts on sediment loads. This would allow the effects of sediment reduction targets to be captured on specific land use types. Also, this would allow assessment of the effect of changes in land use and management practices in reducing the sediment loads. However, to conduct such modelling requires extensive data on sediment loads by land use types and management practices, which are currently not available.
- The benefit cost analysis could be improved in several important ways. First, a thin local literature of studies from which to transfer values suggests a need for additional environmental valuation studies in New Zealand. There is also a need for studies that are better linked to policy levers. For instance, although there are several valuation studies on biodiversity, they are difficult to link to the modelled changes considered here. Finally, since carbon benefits comprise such a large share of the estimated benefits, it would be useful to have New Zealand-specific social cost of carbon estimates from which to transfer.
- More New Zealand environmental valuation studies are needed to improve the monetisation of ecosystem services, as well as to capture other benefit categories that are difficult to monetise.

1 Introduction

The Ministry for the Environment (MFE) requires an analysis of the potential impacts of proposed regulations for managing in-stream sediment levels. The Request for Proposals (RfP) released in September 2018 sought the following components of work:

1. Modelling and statistical analysis of nationwide relationships between sediment loading and in-stream sediment indicators including deposited fine sediment, turbidity and/or visual clarity;
2. Calculation of the sediment loading reduction required to meet proposed regulatory bottom lines for in-stream indicators and identification of catchments where bottom lines have been breached;
3. Analysis of changes in land cover, use, management, infrastructure, and standards possible to meet the required bottom lines;
4. The costs and co-benefits of these mitigations.

The work required both nationwide and catchment-based analysis and included components of review of knowledge of erosion and sediment mitigation effectiveness in reducing sediment loading, and the costs and co-benefits of erosion and sediment mitigations.

Manaaki Whenua – Landcare Research (MWLR) and NIWA responded to the RfP with a joint proposal to complete all four components listed above. Following negotiation with MfE, two contracts were let. NIWA was funded to complete components 1 and 2 above, while MWLR was funded to complete a feasibility study to meet part of the requirements of components 3 and 4 (described in Basher et al. 2019). Following the feasibility study MfE decided to undertake only the nationwide analysis to meet the requirements of components 3 and 4.

This report describes work completed by MWLR to:

1. provide information on the scale and scope of erosion and sediment control (ESC) mitigations possible to meet the proposed sediment attribute bottom lines nationwide,
2. calculate and describe the economic costs and benefits of those mitigations.

2 Background

The National Policy Statement for Freshwater Management (NPS-FM) and National Objectives Framework (NOF) do not currently define attributes to be used for managing sediment in fresh waters. Over the past 3 years MfE has been leading work to develop sediment attributes to include in the NPS-FM, for both suspended sediment and deposited sediment. This is summarised in Basher et al. (2019) and is not repeated here other than to note that the potential suspended sediment attributes (clarity, turbidity) were proposed by Franklin et al. (2019), while Hicks et al. (2019a) described relationships between sediment attributes and sediment load, predicted current state (for turbidity and clarity) across the River Environment Classification (REC) stream segment network, and determined the sediment load reductions required to meet proposed suspended sediment bottom lines. The result of this is that in the work described here suspended sediment load reductions are only evaluated to meet turbidity bottom lines and the sediment load reductions required are those documented in the Hicks et al. (2019a) report. This report and associated data identified all those catchments predicted to not meet the proposed turbidity bottom lines.[1] Hicks et al. (2019a) calculated the required sediment load reductions to meet this bottom line as a percentage of total modelled current suspended sediment load (from Hicks et al. 2019b) at both whole catchment and stream segment scale. The work described here does not consider deposited sediment as Hicks et al. (2019a) did not establish a basis for estimating load reduction requirements to meet potential deposited sediment bottom lines.

Achieving sediment load reduction targets requires implementation of erosion and sediment control (ESC) practices and/or land management change. Basher et al. (2019) summarised information on the range of ESC practices used in New Zealand, the effectiveness of different ESC practices in reducing sediment load, how the effect of ESC practices has been incorporated into erosion and sediment models to provide estimates of sediment load reductions, and information on the costs and co-benefits of ESC practices. They also recommended approaches to undertaking a nationwide cost-benefit assessment of mitigation scenarios that would meet the sediment load reduction requirements necessary to achieve proposed suspended sediment bottom lines. This provides the basis for the work reported here and can be summarised as:

- the NZeem® model (Dymond et al. 2010) be used to undertake an analysis of the effect of erosion mitigation in reducing sediment load to meet the catchment sediment load reduction requirements;
- the NZeem® results be used with the New Zealand Forest and Agriculture Regional Model (NZFARM) economic land use allocation optimization model to assess the costs and co-benefits of erosion mitigation required at national scale to meet sediment load reduction targets.

3 Objectives

- Calculate baseline average annual suspended sediment load for each of the catchments not meeting suspended sediment bottom lines using the NZeem® model.
- Use suspended sediment load reduction requirements from Hicks et al. (2019a) to calculate the load reduction target based on the NZeem® estimates of sediment load.
- Parameterise NZeem® to incorporate ESC mitigations: Whole Farm Plans (WFP), afforestation (Aff), riparian exclusion (RE).

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[1] The bottom line is defined as the turbidity value (median value over 2 years) of the C/D boundary proposed for each of 12 climate-topography-geology classes described by Franklin et al. (2019).

- Calculate, individually and in sum, the potential sediment load reductions achievable through the following mitigation scenarios for each catchment and each farm within a catchment:
  - a WFP and Aff applied to land not yet treated by ESC mitigations (Highly Erodible Land, Land Use Capability class 8e, 7e, and 6e under grassland)
  - b RE applied to untreated major streams.[2]
- Identify any catchments where sediment load reduction targets cannot be met.
- Undertake NZFARM economic modelling using a linear modelling approach to assess the costs and benefits of the ESC mitigations required to meet suspended sediment bottom lines, assuming an Emissions Trading Scheme carbon price of $25/tonne CO_2 equivalent.
- Conduct economic optimisation of the above policy scenarios to achieve the load reduction requirements at least cost and define the spatially explicit locations of ESC mitigations and their resultant in-stream sediment reductions.
- Evaluate the overall benefits and costs of the proposed policy options by bringing together the outputs of the NZeem®, NZFARM, and other modelling and data analysis.
- Report results at national and regional scale and for selected catchments (Waikato, Manawatu, Ruamahanga, Kaipara tributaries, Mataura and Clutha).

4 Methods

4.1 Identifying catchments where sediment load reductions are required

Erosion and sediment control (ESC) mitigations are required to reduce sediment load in catchments containing stream segments which do not meet proposed sediment attribute bottom lines and therefore require a reduction in their suspended sediment load. These segments and catchments were identified by Hicks et al. (2019a), and provided as shapefiles[3] to MWLR. Derivation of these datasets is described in Hicks et al. (2019a, b) and is not repeated here other than to note how catchments and suspended sediment load reduction targets are defined for this study. Catchment and river segment suspended sediment loads are estimated by an updated version of the Suspended Sediment Yield Estimator (SSYE – for detail see Hicks et al. 2019b).

ESC mitigations are required in the catchment area contributing to the most downstream stream segment where the proposed sediment attribute bottom line in a stream network is exceeded. These areas are defined as 'pourpoint' catchments by Hicks et al. (2019a) who based their analysis only on stream segments that were order 3 and above (hereafter

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[2] Defined as Dairy Accord Streams (>1 m wide, >0.3 m deep, permanently flowing).

[3] The files supplied to MWLR included pour_point_catchmentsV2.shp, River_segments3b.shp, Glacial_mountain_mask.shp, doc_conservation_nztm.shp, and nz-coastlines-and-islands-polygons-topo-150k.gdb

referred to as catchments). Areas outside of these catchments are not considered for ESC mitigations in our analysis. We therefore define 'catchments' for this analysis as the 627 pourpoint catchments identified by Hicks et al. (2019a). Sediment load reduction requirements were calculated for each river segment that currently exceeds the suspended sediment bottom line. The required catchment sediment load reduction was then calculated as the average sediment load reduction for all stream segments within the defined catchment (including segments requiring zero reduction).

4.2 Erosion modelling

To identify the potential impact of ESC mitigations on meeting the proposed sediment attribute bottom lines in each catchment, average annual suspended sediment load prior to (baseline load) and after ESC mitigation is estimated for each catchment. Average annual suspended sediment loads for a catchment were assumed to be equivalent to the average annual erosion of fine sediment within the catchment and therefore an erosion model can be used to estimate average annual suspended sediment loads.

4.2.1 Erosion modelling approach

Basher et al. (2019) recommended using the New Zealand Empirical Erosion Model (NZeem®) to estimate erosion rates and incorporate the effect of land cover changes and erosion mitigation. NZeem® is fully described in Dymond et al. (2010). NZeem® models erosion rates on a 15-m grid as:

$$E = aCR^b \tag{1}$$

where E is the erosion rate (t km^{-2} year^{-1}), R is mean annual rainfall (mm year^{-1}), C is the land cover factor (1 for woody vegetation, 10 for non-woody vegetation), a is an erosion terrain[4] coefficient, b = 2.

NZeem® was used to estimate erosion for New Zealand before and after application of ESC mitigations, which were bundled into three classes to simplify the analysis (Whole Farm Plans, Afforestation, and Riparian Exclusion). These ESC mitigations and their effectiveness are fully described in Basher et al. (2016a, b, 2019). The Aff scenario does not account for the effects of forest harvesting, with the 90% sediment reduction effectiveness based on mature closed canopy forest. The impact of each class on erosion reduction and achievement of bottom lines was modelled separately. The three classes of mitigation are referred to as mitigation scenarios. Effectiveness of the three mitigation scenarios used the approach described by Dymond et al. (2016), which applied different values for each scenario (WFP – 70% sediment reduction, Aff – 90% sediment reduction, RE – 80%

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[4] An erosion terrain is a land type with a unique combination of erosion processes and rates leading to characteristic sediment generation and yields. Erosion terrains were derived from New Zealand Land Resource Inventory data and are based on combinations of rock type/parent material, topography, rainfall, type, and severity of erosion processes. They were specifically developed to support the derivation of the Suspended Sediment Yield Estimator (Hicks et al. 2011). Erosion terrains coefficients are listed in Dymond et al. (2010).

sediment reduction) and incorporated the maturity of mitigations for the WFP scenario (see Appendix 1).

Modelling of the effects of WFPs and Aff used spatial data on the current location of these mitigations and mitigatable land for future implementation of these mitigations (defined as Highly Erodible Land, Land Use Capability class 8e, 7e, and 6e under grassland). For RE, spatially implicit data on the location of existing RE are only available at the regional scale as estimates of the proportion of major streams where RE has been implemented (Monaghan et al. 2019). The regional estimates were therefore used to make assumptions of the extent of existing RE within catchments and segments when calculating baseline loads, and to estimate the reductions achievable through implementation of further RE on major streams.

The results from NZeem® were used to estimate the reduction in average annual suspended sediment load achieved by each mitigation scenario, and identify whether the proposed sediment attribute bottom lines were achievable for each catchment and its stream segments. This first required baseline suspended sediment loads to be calculated at the catchment and segment scales so NZeem®-based load reduction targets could be calculated to achieve the bottom lines. The reduction in load from baseline could then be calculated for each mitigation scenario to identify which mitigation scenario was capable of achieving target load reductions in each catchment and stream segment.

NZeem® does not distinguish the processes contributing to erosion. NZeem® data were therefore partitioned into hillslope erosion (affected by WFPs and Aff) and bank erosion (affected by RE) components based on results from the sediment budget model SedNetNZ (see Dymond et al. 2016). This model does account for contributing erosion processes (see Appendix 1) with results of catchment studies showing that the average contribution of bank erosion was 18%.

NZeem® was used to identify which catchments could achieve sediment bottom line targets (referred to as feasible catchments) and whether they would require new ESC mitigation to be implemented or whether the target could be achieved through maturation of existing WFPs. For the land that is mitigatable, NZFARM was then used to determine an optimal application of ESC mitigation scenarios[5] to achieve the proposed bottom lines whilst maximising farm profitability. The resulting spatial allocation of mitigation was then reanalysed using NZeem® to calculate the resulting catchment and segment-scale sediment loads and determine whether sediment bottom line targets were met at segment scale. For those catchments that could not achieve sediment bottom line targets (infeasible catchments), NZFARM modelling of mitigatable land was used to determine the cost to achieve the greatest reduction in sediment load possible.

The erosion modelling methodology is described in summary here (see Fig. 1) and in detail in Appendix 1.

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[5] This was limited to analysis of WFPs and Aff mitigation scenarios since spatial data were not available for existing RE.

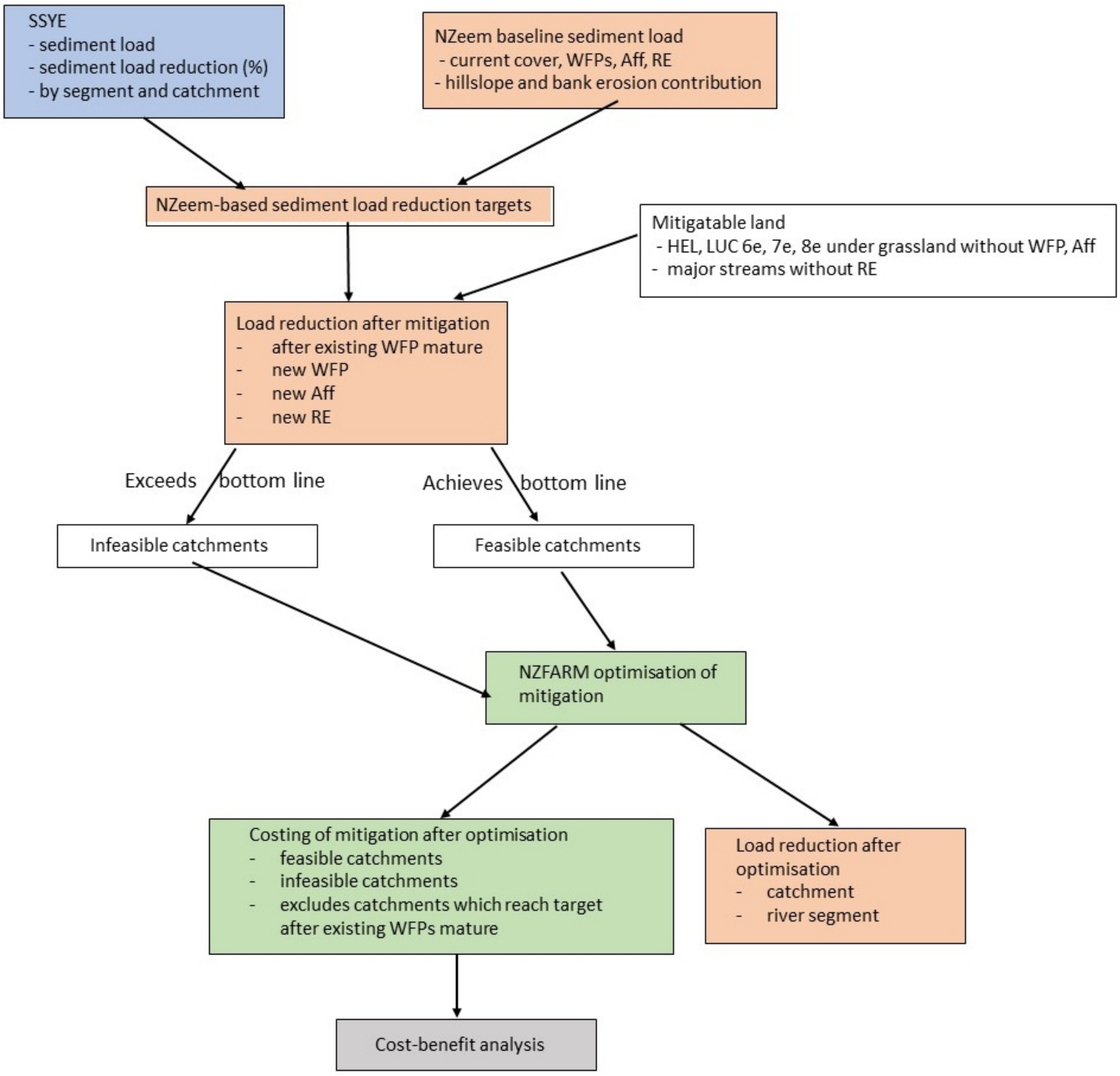

Figure 1 Schematic outline of erosion modelling components and linkage between NZeem® and NZFARM modelling.

4.2.2 Baseline sediment load

Baseline sediment loads were calculated by updating NZeem® (Dymond et al. 2010) to account for contemporary landcover and the extent of implemented ESC mitigation works. The New Zealand Land Cover Database (LCDB) v4.0 was used as input for the land cover factor, *C*, providing national coverage of vegetation at 2012. The extent and effect of existing ESC mitigations in the catchments were accounted for using data compiled by Monaghan et al. (submitted). This included consideration of the extent and maturity of WFPs (sourced from regional councils) and the extent of implementation of riparian exclusion (sourced from the Survey of Rural Decision makers).

Baseline sediment yield (*NZeemB*) was calculated as the yield from NZeem® minus the reduction achieved by existing WFPs and RE, giving:

$$NZeemB = NZeem - R_{WFP2015} - R_{RE2015} \tag{2}$$

where $R_{WFP2015}$ = the sediment yield reduction for a farm with an existing WFP in 2015 and R_{RE2015} = the sediment yield reduction achieved by existing riparian exclusion in 2015.

Baseline sediment loads were calculated for each catchment by taking the average yield of the catchment from *NZeemB* and multiplying by the catchment area using Equation 3:

$$SL_j = \frac{1}{n}\sum_{i=1}^{n} NZeemB_i \ x \ A_j \tag{3}$$

where SL_j is the sediment load (t y^{-1}) of the *j*th catchment, $NZeemB_i$ is the yield at the i^{th} grid cell from the baseline NZeem® layer, *n* is the number of grid cells in the *NZeemB* layer within the catchment, and *A* is the area (km^2) of the catchment.

4.2.3 Sediment load reduction targets

Hicks et al. (2019a) calculated the reduction in suspended sediment load required at a stream segment for the segment to achieve the proposed sediment attribute bottom lines. These targets were provided to MWLR as a proportional reduction in suspended sediment load for each stream segment (*Rmax*), and as the average of the segment reductions required within each catchment (*ave_R*). For the purposes of this analysis MfE defined the target sediment load reduction for a catchment as the average reduction (%) required for the stream segments within the catchment (i.e. the *ave_R* value calculated by Hicks et al. 2019a). The value of *ave_R* was therefore used to define the catchment average sediment load reduction target (t) for each catchment, hereafter referred to as the *catchment average target*.

Because the catchment average target was calculated based on the model described in Hicks et al. (2019b) it had to be converted to a catchment average target based on NZeem®. Absolute catchment average targets were therefore calculated by multiplying the baseline load calculated from NZeem® by the catchment average reduction target (%) for each catchment. The absolute catchment average target is therefore calculated as:

$$SL_{RTj} = SL_j \ x \ ave\_R_j \tag{4}$$

where SL_{RT} is the target absolute reduction in sediment load (t), and *ave_R* is the proportional target reduction in sediment load for the *j-th* catchment.

4.2.4 Calculating potential sediment load reductions achievable through implementation of mitigation scenarios

In order to identify catchments where the required sediment load reduction targets cannot be met it is first necessary to calculate the reduction in sediment load from baseline achieved by maturation of existing WFPs, and then apply mitigation scenarios to all remaining mitigatable land within each catchment to calculate the maximum achievable load reduction under each mitigation scenario.

4.2.4.1 Calculating sediment load reduction achieved after existing WFPs mature

The erosion reduction achieved by WFP mitigations maturing is the difference between the effectiveness of fully mature works and the effectiveness of the immature works at 2015. This is calculated as the difference between a maturity factor of 1 (100% effectiveness at 15 years old) and the maturity factor of the WFP in 2015.

The yield reduction achieved by existing WFPs once they fully mature is calculated as:

$$NZeemM = NZeem - R_{WFPM} - R_{RE2015} \tag{5}$$

where $NZeemM$ is the NZeem®-estimated sediment load after maturation of existing WFPs, R_{WFPM} is the reduction in yield achieved by mature WFPs, and R_{RE2015} is the reduction in yield achieved by existing riparian exclusion. The sediment load in each catchment after maturation of existing WFPs can then be calculated by adapting Equation 3 to multiply the average sediment yield in a catchment derived from $NZeemM$ by the area of the catchment, giving:

$$SL_{WFPMj} = \frac{1}{n}\sum_{i=1}^{n} NZeemM_i \ x \ A_j \tag{6}$$

where SL_{WFPMj} is the average annual sediment load of the j^{th} catchment after existing WFPs mature, and n is the number of grid cells in the $NZeemM$ layer within the catchment. The reduction achieved within each catchment after WFPs mature was then calculated as:

$$\Delta SL_{WFPM} = SL_j - SLM_{WFPMj} \tag{7}$$

where ΔSL_{WFPM} is the reduction in average annual sediment load for the catchment after existing WFPs mature. Where ΔSL_{WFPM} is greater than SL_{RT}, the reduction target has been met for the catchment and no further mitigations need to be implemented. These catchments were then removed from further analysis. Where ΔSL_{WFPM} is less than SL_{RT} the catchment average target has not been met and further mitigations need to be implemented.

4.2.4.2 Calculating remaining reduction target after maturation of existing WFPs

The remaining reduction required to meet target is calculated as:

$$rSL_{RT} = SL_{RT} - \Delta SL_{WFPM} \tag{8}$$

where rSL_{RT} is the remaining sediment load reduction target for the catchment after existing WFPs mature.

4.2.4.3 Calculating reductions achievable by implementation of further ESC mitigations

This component of the modelling identified remaining mitigatable land and calculated the total achievable sediment reduction under the three scenarios (WFPs, Aff, RE). WFPs and Aff were considered to be implementable on erodible pasture with no existing WFPs. Erodible land was defined as land classified as Highly Erodible Land (Dymond & Shepherd 2006) or belonging to Land Use Capability (LUC) classes 8e, 7e, and 6e (Lynn et al. 2009) and represents steep, erosion prone land. WFPs and Aff were considered to only be implementable on high-producing grassland, low-producing grassland, and depleted grassland, as defined by the New Zealand Land Cover Database (LCDB) version 4.0. The effect of RE was treated differently as only regional scale estimates of existing RE are available from the SRDM (see Appendix 4). New RE was applied to the remaining regional proportion of all major streams (see Monaghan et al. submitted).

An NZeem® layer was prepared that reduced erosion on all remaining mitigatable land with no existing mitigation. The mitigation options and their effectiveness are summarised in Appendix 1. The reduction was calculated considering implementation of either WFPs, Aff, or RE as:

$$RFI_{ESC} = NZeem * Prop * Ef \tag{9}$$

where RFI_{ESC} is the reduction achieved after full implementation of either WFPs, Aff, or RE, *Prop* is the proportion of sediment yield as hillslope (for WFP, Aff) or bank erosion (for RE), and *Ef* is the effectiveness (% sediment reduction) of each mitigation scenario.

The sediment load for each catchment after implementation of the WFP or Aff mitigation scenarios ($SLFI_j$) is then calculated as:

$$SLFI_j = \frac{1}{n}\sum_{i=1}^{n}(NZeemM - RFI_{ESC})\ x\ A_j \tag{10}$$

The sediment load of the catchment after RE implementation ($SLFI_{RE}$) is calculated as:

$$SLFI_{RE} = \frac{1}{n}\sum_{i=1}^{n}(NZeem - R_{WFPM} - RFI_{RE})_i\ x\ A_j \tag{11}$$

The absolute reduction in sediment load achieved by implementation of each ESC mitigation scenario (ΔSL_{FIESC}) for each catchment is then calculated using Equation 12:

$$\Delta SL_{FIESC} = SL_j - SLFI_{ESC} \tag{12}$$

where SL_j is the sediment load before ESC mitigations are implemented and $SLFI_{ESC}$ is the reduction in sediment load achieved by ESC implementation.

4.2.4.4 Identifying catchments where targets can be achieved

The methodology above allows identification of catchments where the target sediment reductions can or cannot be met through implementation of each of the ESC mitigation scenarios. Where the load reduction achieved by implementation of each ESC mitigation scenario was greater than or equal to the target load reduction ($SL_{RFI} \geq SL_{RT}$), it was considered the target could be met in that catchment under the given ESC mitigation scenario and that catchment and associated mitigatable land progressed to economic modelling and spatial optimisation as a 'feasible catchment'. The number and location of infeasible catchments was identified.

4.3 Economic modelling and spatial optimisation

Once the feasible catchments (that could meet the target through applying ESC interventions) were identified, we conducted economic optimization modelling (using NZFARM) to determine the adoption rate of ESC mitigation options in each catchment that can achieve the proposed sediment reduction targets while maximising farm profitability. NZFARM is an agri-environmental economic optimization model and has previously been used to assess climate and water policy scenarios across New Zealand (e.g. Daigneault et al. 2012; Djanibekov et al. 2018). NZFARM maximizes the profits from farms subject to available farms' land areas and imposed sediment reduction target constraints (Fig. 2).

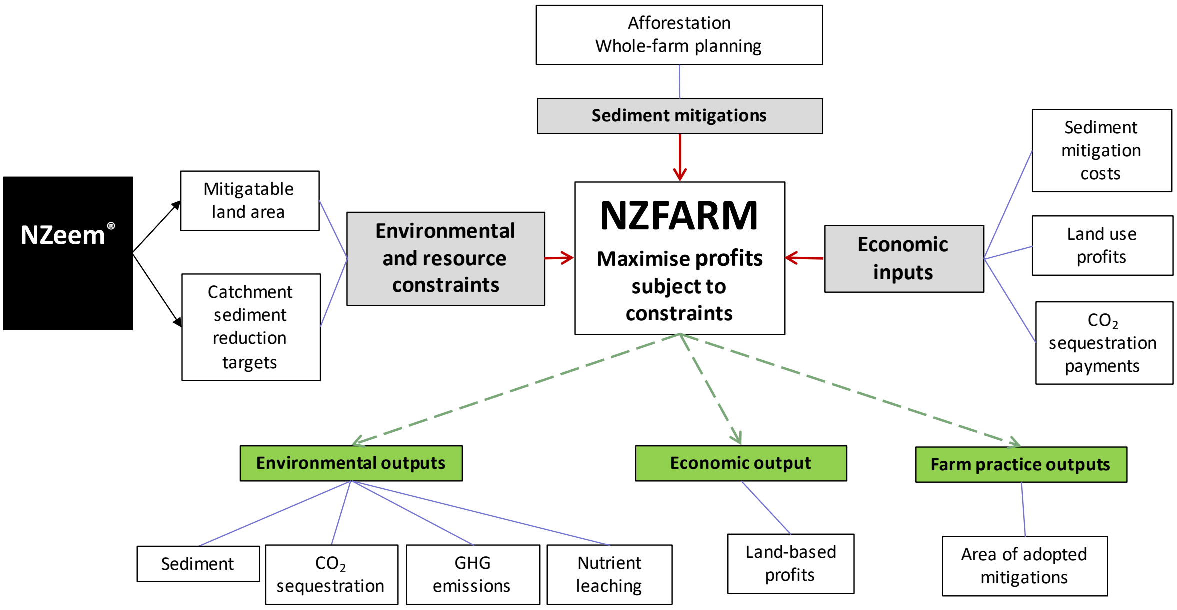

Figure 2 Schematic view of the NZFARM model (adapted from Daigneault et al. 2017b)
Note: Grey boxes show the model input parameters. Green boxes show the outputs of the model. Black box shows the inputs from NZeem® modelling of sediment reduction targets and sediment mitigatable area.

The model estimates costs from introducing sediment mitigation scenarios on the available mitigatable area subject to available mitigatable area and environmental policy constraints such as meeting the sediment reduction targets at catchment scale. The

NZFARM model is spatially explicit and considers all relevant farms across catchments where sediment reduction targets can be achieved (for description of estimation of sediment targets and available mitigation areas see sections 4.1 – 4.2). Performance indicators tracked within NZFARM include economic indicators (e.g. profits, costs and revenues), environmental indicators (e.g. sedimentation, greenhouse gas emissions (GHG), CO_2 sequestration, nitrogen and phosphorous leaching) and sediment reduction intervention practices (i.e. WFPs, afforestation). Nutrient leaching and GHG emissions are modelled in physical units (i.e. not monetised) and thus are not reflected in the cost-benefit structure of farms at this stage. Only CO_2 sequestration from afforestation was monetised in the model at the value of 25 \$/tCO_2. However, in the next stage of the analysis, environmental indicators were monetised using non-market valuation techniques to be reflected in the cost-benefit analysis framework (see section 6). RE was not modelled in NZFARM, and was analysed separately due to the lack of spatially explicit RE data as described in Section 4.2.1. We use AgriBase data for deriving the areas of land use types and consequently to derive the spatial land use type information on profits, GHG emissions, CO_2 sequestration, and nutrient leaching.

We present the results of the NZFARM and costs of RE analyses by region and for selected catchments (Waikato, Kaipara, Ruamahanga, Mataura, Clutha). The detailed results for all catchments are included in 0.

4.3.1 Policy scenarios

NZFARM modelled the following policy scenarios:

- A baseline scenario (Baseline) that includes the present pattern of farms' areas in catchments and sediment generation from NZeem® described in section 4.2. Here we consider land use areas that have not adopted mitigations. In the baseline scenario, we do not simulate any environmental policies. This allows for the distinction between the effects of the sediment reduction target scenario (see below for description) from the baseline scenario;
- A sediment reduction target scenario that includes the target level of sediment reduction for each catchment defined by the NZeem® layer (see section 4.2). A sediment reduction target is included in the model as a constraint on sediment outputs from all farm types in catchments and limits the sediment output from farms in each catchment. In this scenario, erosion is reduced with respect to the baseline sediment levels by implementing appropriate ESC interventions. The interventions included are farms implementing afforestation and whole-farm planning (WFP). These mitigations are considered simultaneously in this scenario, and the model selects the optimal mitigation that allows for the sedimentation reduction target (or the highest sedimentation reduction level) to be achieved while leading to the lowest costs. We assume the cost of afforestation as \$1,000/ha, which reflects capital costs. Additionally, we assume afforestation is not harvested. Afforestation is replacing an alternative land use and thus has an opportunity cost. The opportunity cost is the profit loss from an alternative land use when afforestation is established (i.e. cost of lost production). The cost of whole-farm planning intervention is assumed to be \$300/ha which consist of initial capital costs (Daigneault et al. 2017a). To make the mitigation costs comparable over time, we used the interest rate for establishment

costs of mitigations. This allows us to compare the annual opportunity costs to the initial investment needed for the mitigation costs. We assume interest rates of 20% for afforestation and 6% for WFP. We use a high interest rate for afforestation because it is a longer-term and riskier mitigation than WFP. In addition, to reflect the existing Emission Trading Scheme policy, we include a payment of \$25/tCO_2 for CO_2 sequestration in the afforestation mitigation option. We assume CO_2 sequestration levels in afforestation reflect the permanent sequestration of *Pinus radiata*. The revenue from CO_2 sequestration depends on price (\$25/tCO_2), C sequestration level and afforested area. Table 1 shows the costs, effectiveness in sediment and nutrient leaching reduction, and carbon (C) sequestration of afforestation and WFP.

Table 1. Costs and environmental outputs of afforestation and whole-farm planning mitigations

Mitigation practice	Establishment cost, \$/ha	Establishment cost after applying interest rate, \$/ha	N leaching reduction, %	P loss reduction, %	C sequestration, tCO_2/ha
Afforestation	1,000	166.68	0.04	0.15	23
Whole-farm planning	300	17.90	0.2	n.a.	n.a.

note: n.a. shows that whole-farm planning does not have information on phosphorous loss and C sequestration.

4.3.2 Cost of riparian exclusion

We separately calculated a cost estimate of RE for all major streams in New Zealand. RE includes both fencing and planting to reduce bank erosion. This RE analysis has been done separately from the economic optimization model because RE is applied on areas adjacent to rivers, while WFP and afforestation is applied on erosion-prone areas of farms. In addition, there was no spatially explicit information for RE on what has been done so far on the ground. Only regional-level information was available from the SRDM survey (Brown 2015). Thus, the dataset and assumptions used for calculating the effects of RE is different from WFP and afforestation. In this analysis, we include the fencing cost, opportunity cost of lost production, planting cost, and alternative water supply cost to estimate the total cost of RE. The cost of alternative water supply was only applied to pasture farms. We also assumed that the RE buffer width is 5 meters, and the costs of fencing, alternative water supply and planting are \$8/meter, \$250/hectare, and \$1000/hectare, respectively. The value of the opportunity cost will differ by farm type. (Daigneault et al. 2017b). The analysis was conducted assuming two different scenarios. First, we assumed that nothing has been applied on the ground and second, we incorporated the regional values from the SRDM survey to reflect the costs after considering what has been applied so far by the farmers.

4.4 Resultant in-stream sediment reductions for optimised ESC mitigations

NZeem® was parameterised to apply the spatial distribution of ESC mitigations from NZFARM to allow calculation of the load reductions achieved at the REC2 stream segment scale by the NZFARM distribution of mitigations. As the NZFARM outputs were spatially implicit and reported the proportion of mitigatable land on each farm where WFPs or Aff were applied, the sediment yield from the mitigatable land on each farm was reduced relative to the proportion of each mitigation. The reduction in sediment yield from mitigatable land on a farm after implementation of the NZFARM optimisation (R_{NZFARM_i}) is therefore calculated as:

$$R_{NZFARM} = NZeem_i * \left(1 - \frac{\left(NZeem_i * 0.7 * P_{wfp}\right) + \left(NZeem_i * 0.9 * P_{af}\right)}{NZeem_i}\right) * 0.82 \qquad (13)$$

where i is the i^{th} cell of NZeem®, P_{wfp} and P_{af} represent the proportion of mitigatable land on farm where space planted trees or afforestation is implemented, respectively. Where the i^{th} cell is non-mitigatable land, P_{wfp} and P_{af} are zero.

$$NZeemNZFARM = NZeemB - R_{NZFARM} \qquad (14)$$

Sediment loads for each stream segment were calculated by deriving the local sediment yield for the REC2 watershed associated with the segment from *NZeemB* and *NZeemNZFARM*, calculating the local load from the area of the watershed, and routing the load down the stream network. Routing and accumulation of load at each stream segment was performed using an adaptation of the Upstream Summary tool in the spatial system dynamics modelling component of the LUMASS[6] (Land-Use Management Support System) modelling framework. Reduction in sediment load from baseline at the stream segment scale is then calculated by subtracting the *NZeemNZFARM* accumulated load from the *NZeemB* accumulated load. Where this reduction as a proportion of baseline load is equal to or greater than *Rmax* the sediment attribute bottom line is achieved after implementation of optimised ESC mitigations.

4.5 Environmental valuation and benefits assessment

The cost benefit analysis (CBA) section of this report explores the overall benefits and costs of the proposed policy options, and brings together the outputs of the NZeem®, NZFARM, and other modelling and data analysis. The central goal of the CBA is to evaluate the overall change in economic and social welfare from proposed policies on sediment reduction. The theory and application behind these measures of welfare are drawn from the established literature on welfare economics (Freeman 2003). The analysis proposed in this report uses an effect-by-effect approach, whereby the major effects of a policy are analysed individually, and then the results are summarised at the end (US EPA 2014).[7]

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[6] LUMASS is open source and freely available from https://bitbucket.org/landcareresearch/lumass/wiki/Home

[7] This approach requires a careful consideration of potential double counting, as there may be overlap in some effects.

In a CBA, many direct policy impacts can be monetised or quantified using market-based goods. For instance, the cost of planting trees can be directly calculated. On the other hand, there are often many costs associated with changes in environmental goods that must be estimated using "non-market" methods. For example, it is difficult to monetise the full cost of improved aquatic habitat. In some cases, changes in commercial fish harvest might be used to estimate part of the impact. However, there are still a range of non-market values not captured in commercial catch, such as improved recreation, property values, and bequest value.

In an ideal setting with significant time and budget, an original CBA would be performed, where non-market methods would be used to directly estimate the total economic value of sediment improvements. However, in a more constrained analysis, benefit transfer must be used, where values from existing studies must be transferred to the present context (Johnston et al. 2005).

For this study, benefit transfer must be used in the CBA. There are several potential ways to do this, which depend on data inputs and external choices. It is first important, however, to review some of the market and non-market impacts of the chosen policy option. In this case, we differentiate these impacts from the more direct impacts of the implementation practices themselves. It is more straightforward to calculate the costs of riparian exclusion (including the costs of tree planting and land), for instance, than to estimate the downstream benefits of water quality. Table 2 contains a summary table that contains many of these central impacts. For each item, the final column describes the potential impacts. In a multi-year, large scale CBA, the middle two columns would be filled in based on resources and time available.

The erosion and sediment mitigation options described in other sections of this report will have an assortment of environmental impacts. To the extent possible, we monetise these impacts, and where they cannot be monetised, we quantify or describe the projected effects. Table 2 contains a summary of these impacts and denotes where monetisation or quantification is possible in the middle columns.

Table 2 Impacts of the erosion mitigation options

	Quantify	Monetise	Description
Impacts on Navigational waterways			The accumulation of sediment in navigational channels and harbours can affect transport, shipping, fishing, and other uses.
Reservoir impacts			Reservoirs and other water storage facilities provide drinking water, flood control, and other benefits. Sediment accumulation affects these operations.
Hydroelectric facility impacts	√	√	Sediment can impose additional treatment costs on hydroelectric facilities, as it collects on machinery that pulls in the water. The sediment increases wear on turbines and reduces storage capacity in reservoirs.
Drinking water treatment			Sediment in the water can increase the cost to produce drinking water.
Agricultural water uses			If irrigation water is pulled from waterbodies with high sediment content, it can harm crops and reduce agricultural productivity.

	Quantify	Monetise	Description
Commercial fishing			Sediment in the water can have a negative impact on fish populations through impacts on aquatic habitat. This can affect commercial harvests.
Recreational fishing			Sediment-related reductions in water quality can affect the demand for recreational fishing, as well as the experience of recreational fishing.
Flood damage	√		Accumulating sediment in rivers and streams can increase the frequency and severity of floods.
Water-based recreation	√	√	Sediment can reduce the quality of water-based recreation by reducing water quality and aquatic habitat. Stated preference studies can be used to monetise these impacts.
Reduced aesthetics	√	√	Sediment-related water pollution can make rivers and streams less aesthetically appealing. Stated preference surveys could be used to monetise these impacts.
Water-related non-use impacts	√	√	People who do not directly recreate in the water may still hold values for clean water. They may value bequeathing good water to future generations, or simply value clean water or a healthy environment. Stated preference surveys could be used to monetise these impacts.
Water quality - related biodiversity impacts	√		Water quality has a range of impacts on aquatic animal populations. People may hold non-use values for the preservation of species. Stated preference surveys could be used to monetise these impacts. The NZFARM model outputs include nutrients, which are related to biodiversity impacts. However, they are not monetised here.
Terrestrial biodiversity impacts			The land use changes resulting from the policies can significantly affect habitat and biodiversity.
Carbon impacts from ESC practices	√	√	The mix of ESC practices chosen for the policy option will cause changes in carbon. For example, riparian buffers or afforestation will deploy trees widely, which will reduce carbon.
Carbon impacts from changes in production	√	√	The sediment policy may change the distribution and composition of producers, which can affect carbon emissions.
Reductions in Erosion	√	√	Erosion is associated with a range of negative outcomes, including reduced agricultural production, an increased risk of landslides, and an increased risk of flooding.
Home price increases			Improvements in water quality can produce aesthetic benefits which can improve home prices.
Impacts on Threatened and Endangered Species			Habitat improvements may help threatened and endangered species. People hold additional values for these species.
Landslide impacts			Sediment and erosion policies also decrease the probability of a landslide. This results in a reduction both in damage and in risk perception.
Health Impacts			Primary contact recreation can result in illness. Improvements in water quality will decrease the likelihood of sickness.

The overall approach to the benefits analysis, and subsequent cost-benefit analysis, is summarised in Figure 3. It integrates modelling outputs from several different sources, including both the water quality modelling and the NZFARM outputs.

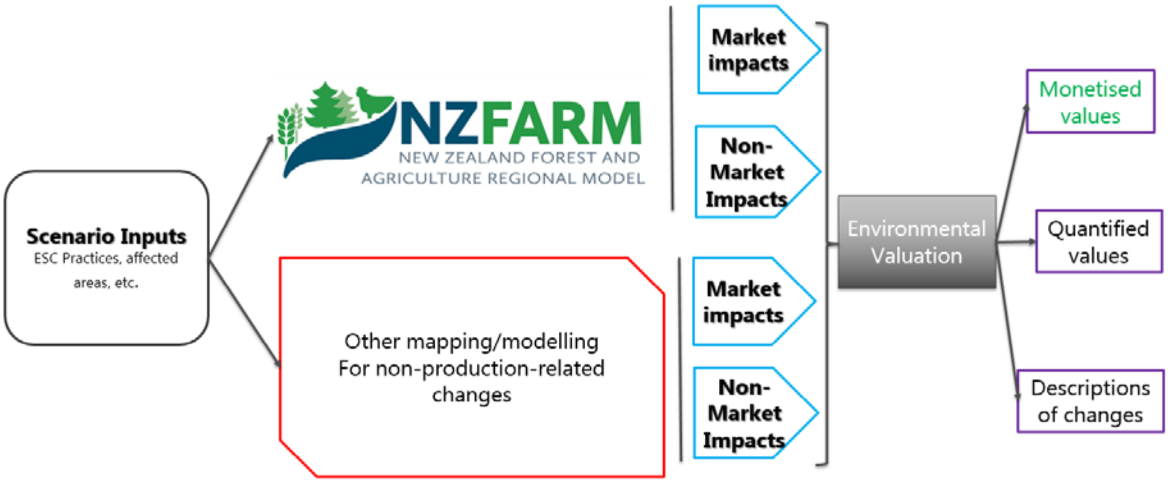

Figure 3 Cost benefit analysis approach.

4.5.1 General Methods

Sediment has a wide range of effects on water resources, including effects on economic productivity, aquatic habitat, recreation, navigation, water storage, electricity generation, biodiversity, commercial fisheries, and several others (US EPA 2009). The general population has been shown to value these categories, and people express a willingness to pay for improvements in their levels. We focus on use and non-use values of non-commercial applications, and the public's willingness to pay (WTP) for those values. Past analyses have found these to be the largest monetizable component of sediment-related improvements in water quality (US EPA 2009, 2015).

There are also many commercial impacts of sediment. Public utilities and hydroelectric companies, for instance, draw in large amounts of river or lake water to support their activities. When there are increased levels of sediment in the water, it imposes additional costs on their operation, through equipment damage, increased filtration costs, and several related processes. These companies regularly conduct dredging in nearby waterbodies to reduce the sedimentation entering their facilities. We use dredging costs as a proxy for the avoided cost of sediment damage.

The methods used to control sediment can also have substantial impacts on carbon emissions and sequestration. Afforestation, for example, represents a central tool for reducing sediment, which can have large carbon-related impacts. There are several different ways to monetise carbon. Carbon emissions have both local and global impacts. Local emissions have been shown to have health impacts from diminished air quality, including increased infant mortality and increased mortality and morbidity in the general population (US EPA 2015). Carbon emissions also cause related global health impacts, as well as extreme weather events and other symptoms of climate change. International estimates of carbon damages have been developed, referred to as the Social Cost of Carbon (SCC) which span a range of values, depending on the assumptions and models used (US EPA 2014). We use the outputs of changes in carbon from NZFARM to characterise the policy scenario.

The policies modelled in this analysis will result in significant reductions in erosion. This is an important regulating ecosystem service that has a range of impacts in New Zealand. We draw on several past studies that analyse erosion to monetise some of these benefits. Most of these papers look at the avoided costs of erosion, as opposed to WTP. We use a conservative estimate of the avoided cost of erosion from Dymond et al. (2012) so that we do not double count the water quality-related benefits of sediment/erosion reductions.

4.5.2 Timeline and Discounting

In any CBA, it is important to specify a timeframe over which to analyse impacts. Generally, the temporal extent of the main effects of a policy should be used to determine the end point of a CBA. At the same time, there may be uncertainty about the duration of the main effects, and political and other considerations may be principal determinants (US EPA 2014). In the present study, we use a timeline of 50 years for analysis. This timeline was developed with MfE in order to represent at least two generations and capture the bulk of the main effects.

Another important component of the timeline of a CBA involves translating impacts that occur in the future into present dollar values. Since we estimate benefits and costs that occur in different time periods, we need to discount those values to the present. This is done through a discount rate and the calculation of net present values. Discounting is used to represent the basic concept that in general, people prefer present consumption to future consumption, and also that capital can be invested today and earn a return for greater consumption in the future (US EPA 2014). We follow current advice from the New Zealand Treasury and use both 4% and 6% discount rates as alternatives.[8]

We also make assumptions about the period over which the effects of the policy are implemented. Much of the modelling described in the other sections of this report describes steady-state conditions, or the state once the policy is fully implemented. In reality, it takes time for the full impacts of a policy to be reached. We therefore model the benefits in the first 10 years using an inverse function, so that the benefits gradually ramp up. For period *i*, for *i* = 1, …, 10, the steady state value is multiplied by the growth factor

$$\frac{1}{10-i}.$$

This allows for an implementation period for the first few years where the total impacts are much smaller than their final values.

4.5.3 Water quality valuation methods

To illustrate some of the general background and methods of a benefits assessment, we use water quality benefits as an example. The water quality improvements resulting from reduced sediment are associated with many non-market benefits and existence values,

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[8] https://treasury.govt.nz/information-and-services/state-sector-leadership/guidance/financial-reporting-policies-and-guidance/discount-rates

including wildlife, habitat, biodiversity, recreation, and many others. Although people have strong values associated with these improvements, it is difficult to place a price on them. Several non-market techniques have been developed to place a price on these changes in water quality, including hedonic pricing (Boyle et al. 1999), recreation demand (Massey et al. 2006), and stated preferences (Moore et al. 2018). Of those techniques, estimates from stated preference studies capture the widest range of people and values in their application (depending on the scope of the study). We therefore focus on stated preference values, which can capture both use and non-use values. Although an original study would be ideal for this, time and budget limitations require a benefit transfer.

We assume that people have values associated with water quality (WQ) and other environmental services (E)[9] and that these vectors of environmental services affect human uses H in the fashion:

$$H = f(WQ, E)$$

The relationship between household utility (U) and water quality (WQ) can therefore be represented by a utility function:

$$U = U(H(WQ, E), O, HC)$$

where O represents other goods and services entering the household utility function, and HC represent individual or household characteristics that influence the shape of the utility function (for example, environmental tastes and preferences). Under assumptions of rationality and constrained utility maximisation, we assume that households maximise that utility function with income constraint (I). That maximisation will produce an indirect utility function (V):

$$V=V(WQ, P, I; HC)$$

The new vector (P) is a vector of prices associated with market goods and services. That indirect utility function can be used to evaluate a particular environmental change, say from WQ_0 to WQ_1. Holding other variables constant, compensating variation (CV) can be used to measure the total dollar value associated with the change in water quality, as illustrated in the following equation:

$$V(WQ_0, P_0, I_0; HC) = V(WQ_1, P_0, I\text{-}CV; HC)$$

This equation essentially shows the amount of money required to keep utility the same under the new environmental quality level. The compensating variation, or willingness to pay, is the goal of environmental valuation, in most cases (US EPA 2014). To calculate the benefits of water quality improvements, we use a benefits transfer from existing literature. The stated preference studies we transfer from are attempting to measure the WTP, as we explain later.

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[9] This theoretical argument can be seen in more detail in Freeman (2003) and US EPA (2009): https://www.epa.gov/sites/production/files/2015-06/documents/cd_envir-benefits-assessment_2009.pdf

5 Results

5.1 Catchments where sediment attribute bottom lines are feasible

Of the 627 catchments supplied by NIWA, 42 catchments are within the Department of Conservation (DOC) estate or urban environments (see Appendix 2) and are therefore considered to be unsuitable for application of the mitigations used in this study. Landcover in these catchments is dominated by indigenous forest, tall tussock grassland, other types of natural vegetation, or is urban. Only the remaining 585 catchments are discussed further. The number and area of these catchments by region are presented in Table 3.

Table 3. Number and area of catchments analysed by region

Region	Total number of catchments not meeting bottom line	Total area (ha) of catchments not meeting bottom line
Auckland	15	54,115
Bay of Plenty	47	973,484
Canterbury	65	2,894,045
Gisborne	23	532,655
Hawke's Bay	18	1,208,075
Manawatu-Wanganui	31	2,152,109
Marlborough	13	886,628
Northland	64	419,594
Otago	35	2,787,413
Southland	53	1,994,964
Taranaki	38	323,569
Tasman	3	459,172
Waikato	64	2,107,461
Wellington	79	599,505
West coast	37	1,350,404
Total	**585**	**18,743,193**

5.1.1 After maturation of existing WFPs

After maturation of existing WFPs, 53 of the 585 catchments (9%) will meet the proposed catchment sediment bottom line. These catchments are listed by pourpoint ID in Appendix 3. These catchments are all located around the central to lower North Island (Fig. 4, Table 4), and make up 18% of the 585 catchments by area. The Manawatu-Whanganui region shows the greatest improvement with 97% of catchments by area achieving catchment sediment bottom lines after maturation of WFPs, followed by Taranaki with 79%. Waikato has the greatest improvement in the number of catchments meeting bottom line (Fig. 5).

On average, these catchments require a 6% reduction in sediment load to meet the sediment bottom line target with a range from <1% (8 catchments) to 28% (Purangiu River in Waikato region). Of note is the expected achievement of catchment sediment bottom lines for the large (>1,000 km^2) Manawatu, Whanganui, Rangitaiki, Mohaka, Whangaehu, Kaituna and Patea River catchments after existing WFPs in these catchments mature. The majority of the 53 catchments are relatively small (<100 km^2) (Fig. 5).

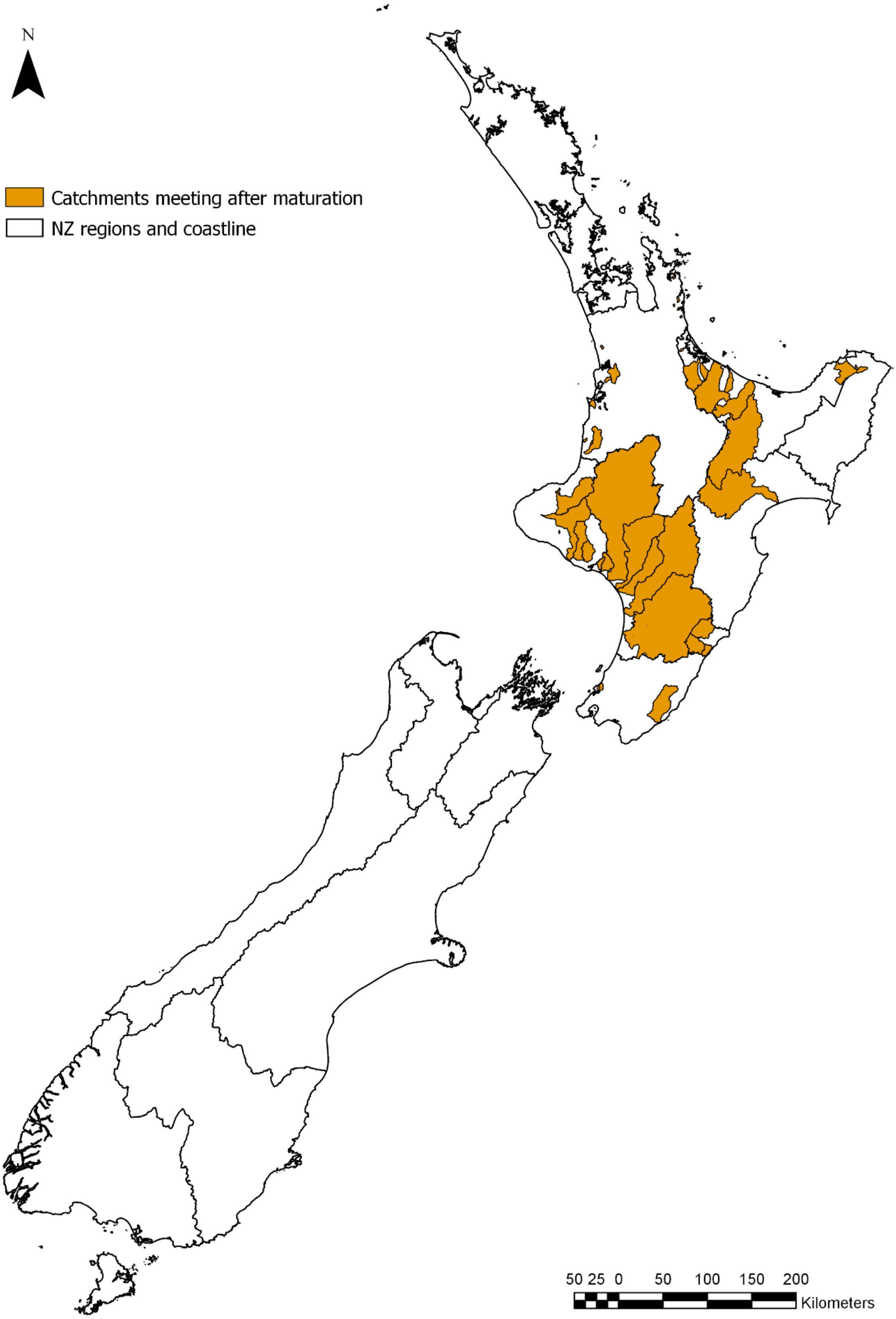
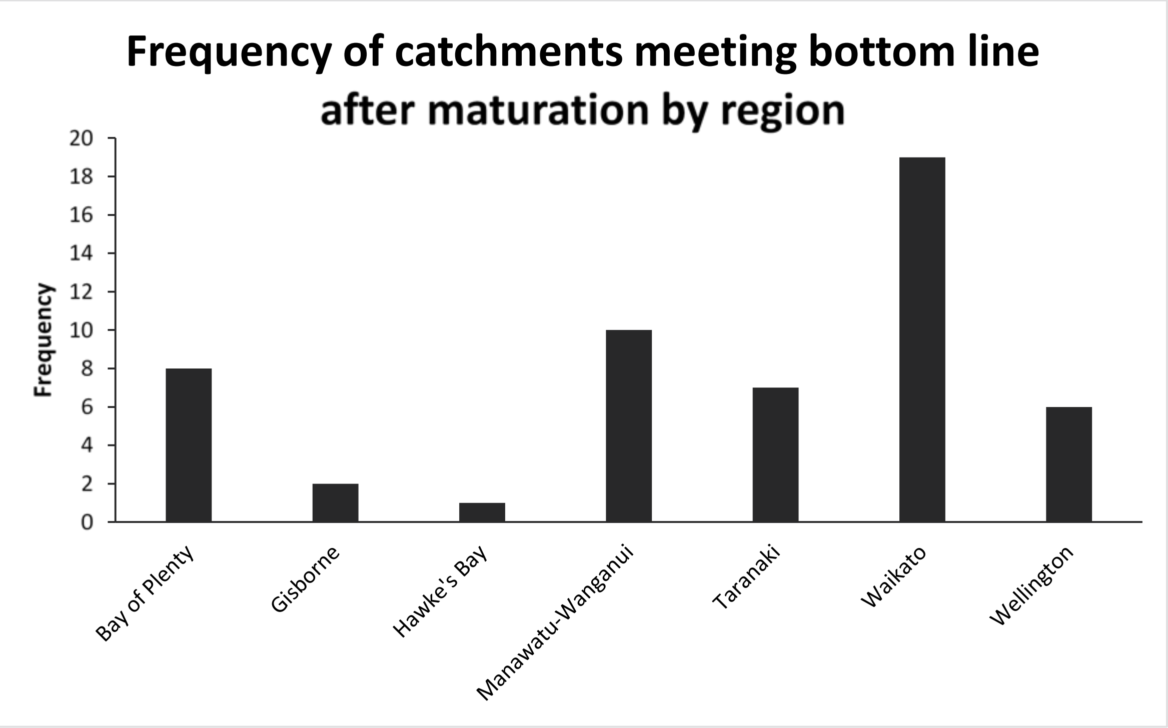


Figure 4 Map showing catchments that meet sediment bottom lines after maturation of existing WFPs.

Table 4 Summary of the catchments meeting sediment bottom line targets after maturation of existing WFPs; summarised by region

Region	Total number of catchments meeting bottom line after maturation of existing WFPs	Total area (ha) of catchments meeting bottom line after maturation of existing WFPs	Proportion of catchments meeting target after maturation of existing WFPs by area	Total number of catchments not meeting bottom line after maturation of existing WFPs	Total area (ha) of catchments not meeting bottom line after maturation of existing WFPs	Proportion by area of catchments still to meet sediment bottom lines
Auckland	0	0	0%	15	54,115	100%
Bay of Plenty	8	599,870	62%	39	373,614	38%
Canterbury	0	0	0%	65	2,894,045	100%
Gisborne	2	6,223	1%	21	526,432	99%
Hawke’s Bay	1	242,843	20%	17	965,232	80%
Manawatu-Wanganui	10	2,088,743	97%	21	63,366	3%
Marlborough	0	0	0%	13	886,628	100%
Northland	0	0	0%	64	419,594	100%
Otago	0	0	0%	35	2,787,413	100%
Southland	0	0	0%	53	1,994,964	100%
Taranaki	7	256,342	79%	31	67,227	21%
Tasman	0	0	0%	3	459,172	100%
Waikato	19	58,403	3%	45	2,049,058	97%
Wellington	6	69,727	12%	73	529,778	88%
West Coast	0	0	0%	37	1,350,404	100%
Total	**53**	**3,322,149**	**18%**	**532**	**15,421,043**	**82%**

a)



b)

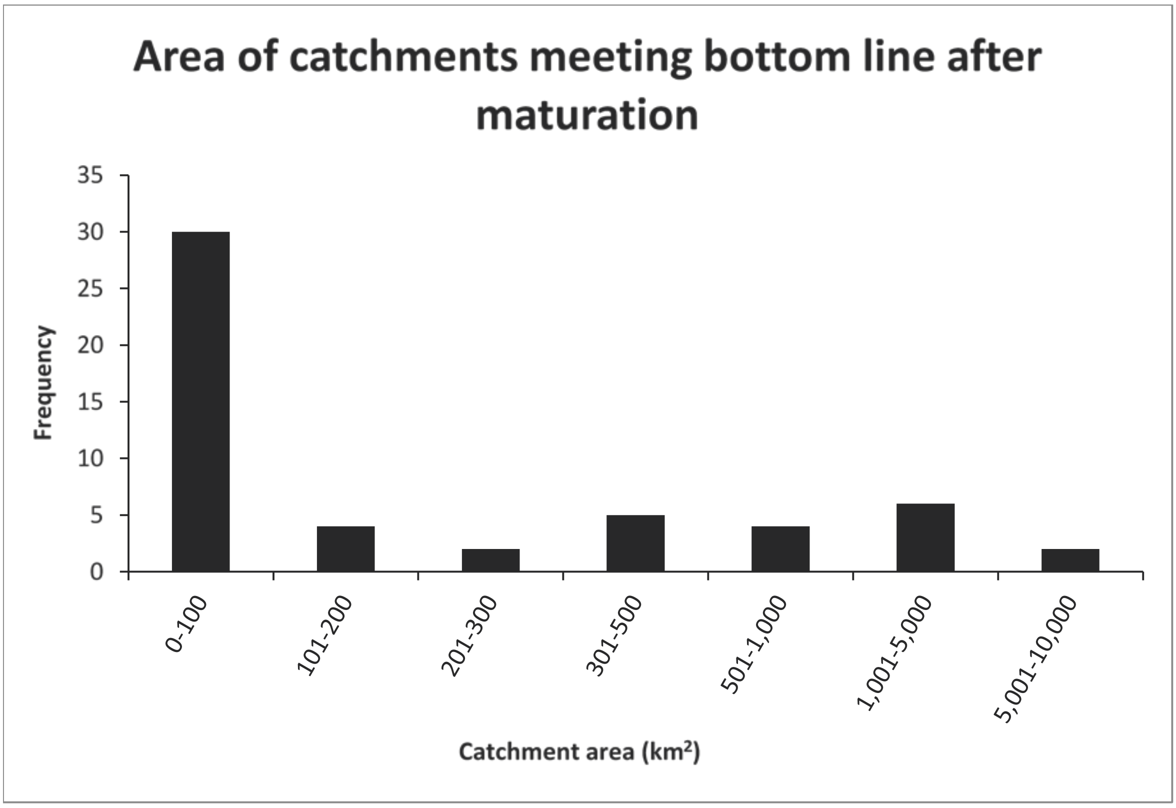


Figure 5 Charts showing a) number of catchments by region and b) area of catchments meeting bottom line after maturation of existing WFPs.

5.1.2 After implementation of ESC mitigation scenarios

After existing WFPs mature, 532 catchments remain that require further reductions to achieve sediment bottom lines (15.4 million hectares). Figure 6 shows the catchments where catchment average bottom lines are feasible and infeasible in the remaining 532 catchments with WFPs, Aff, and RE. Under the WFP scenario, 331 catchments (63%) are able to meet the target (10.8 million hectares), 345 (65%) meet the target under the Aff scenario (11.6 million hectares), and 155 (29%) meet the target under the RE scenario (7.7 million hectares). These are summarised by region in Table 5. In total, 373 of the 532 (70%) catchments requiring mitigations meet the target under at least one of the modelled mitigation scenarios (11.8 million hectares), with 159 catchments (30%) unable to meet sediment bottom line targets under any scenario (3.6 million hectares). Hawke’s Bay and Tasman are the only regions where all catchments achieve sediment bottom line targets under at least one mitigation scenario.

The 159 catchments that cannot meet sediment bottom lines under any of the mitigation scenarios are summarised in Table 5. The majority of these catchments have relatively high sediment reduction targets, with 142 catchments requiring a reduction >10%, with a maximum reduction requirement of 66.7%. Auckland, Manawatu-Whanganui, Taranaki, and Otago have the greatest proportion of catchments by area not meeting sediment bottom line targets under any mitigation scenario (Fig. 7).

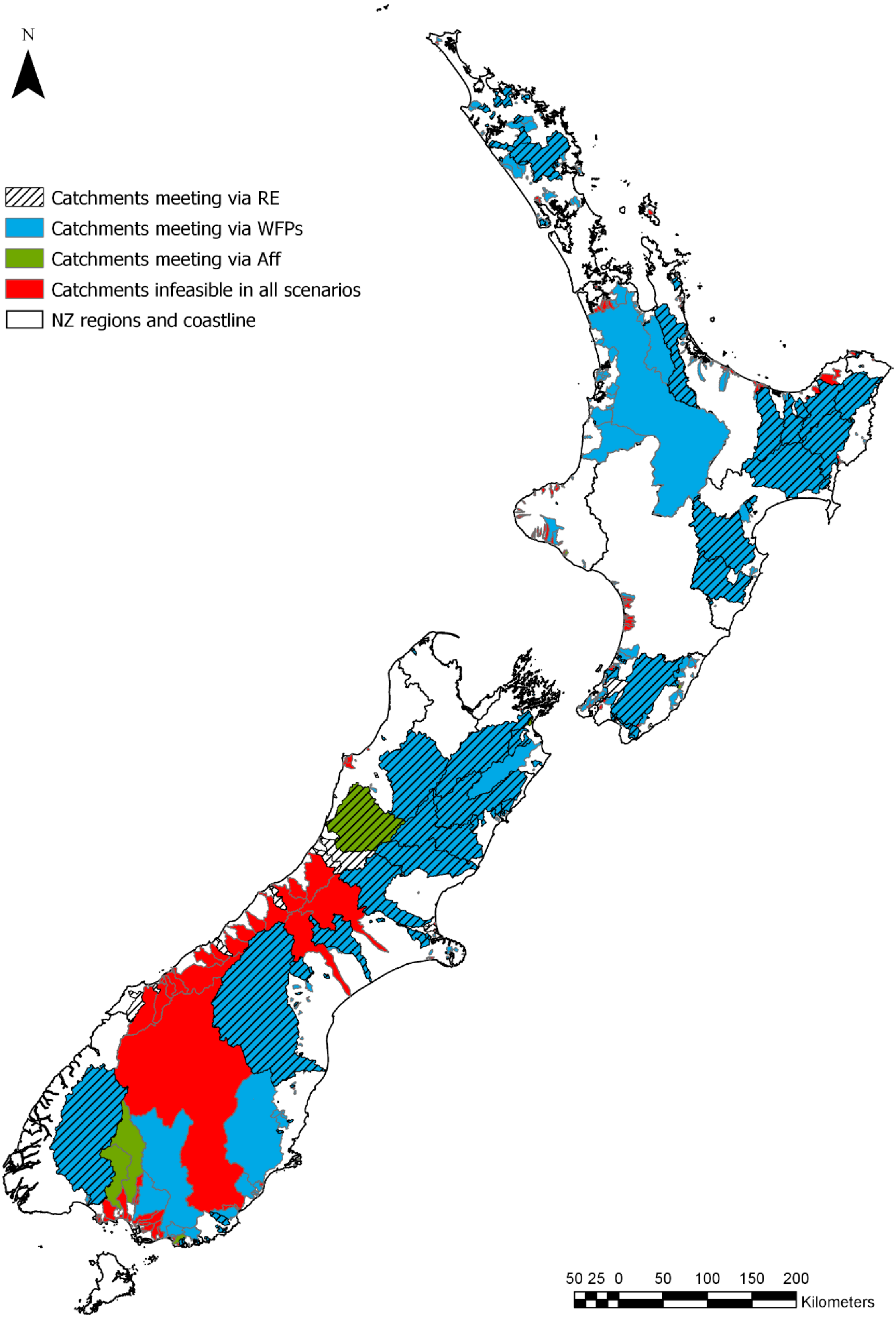


Figure 6. Map showing catchments which are feasible and infeasible under the modelled mitigation scenarios. Note that all catchments which meet the proposed attribute bottom lines under WFPs also meet under Aff.

Table 5 Summary of catchments by region which require further mitigations after existing WFPs mature[10]

Region	No. catchments not meeting sediment bottom lines	No. catchments which achieve sediment bottom lines through implementation of WFPs on mitigatable land	No. catchments which achieve sediment bottom lines through implantation of AFF on mitigatable land	No. catchments which achieve sediment bottom lines through implementation of RE	No. catchments which do not meet sediment bottom line under any mitigation scenario	Proportion of catchments which do not meet sediment bottom line under any mitigation scenario, as a proportion of column 2
Auckland	15	4	4	1	11	73%
Bay of Plenty	39	23	23	3	16	41%
Canterbury	65	52	52	32	10	15%
Gisborne	21	13	14	11	5	24%
Hawke’s Bay	17	17	17	11	0	0%
Manawatu-Wanganui	21	8	8	3	13	62%
Marlborough	13	10	12	10	1	8%
Northland	64	61	61	22	3	5%
Otago	35	24	25	13	6	17%
Southland	53	18	21	10	30	57%
Taranaki	31	7	9	1	22	71%
Tasman	3	3	3	3	0	0%
Waikato	45	40	41	4	4	9%
Wellington	73	49	52	20	13	18%
West Coast	37	2	3	11	25	68%
Total	**532**	**331**	**345**	**155**	**159**	**30%**

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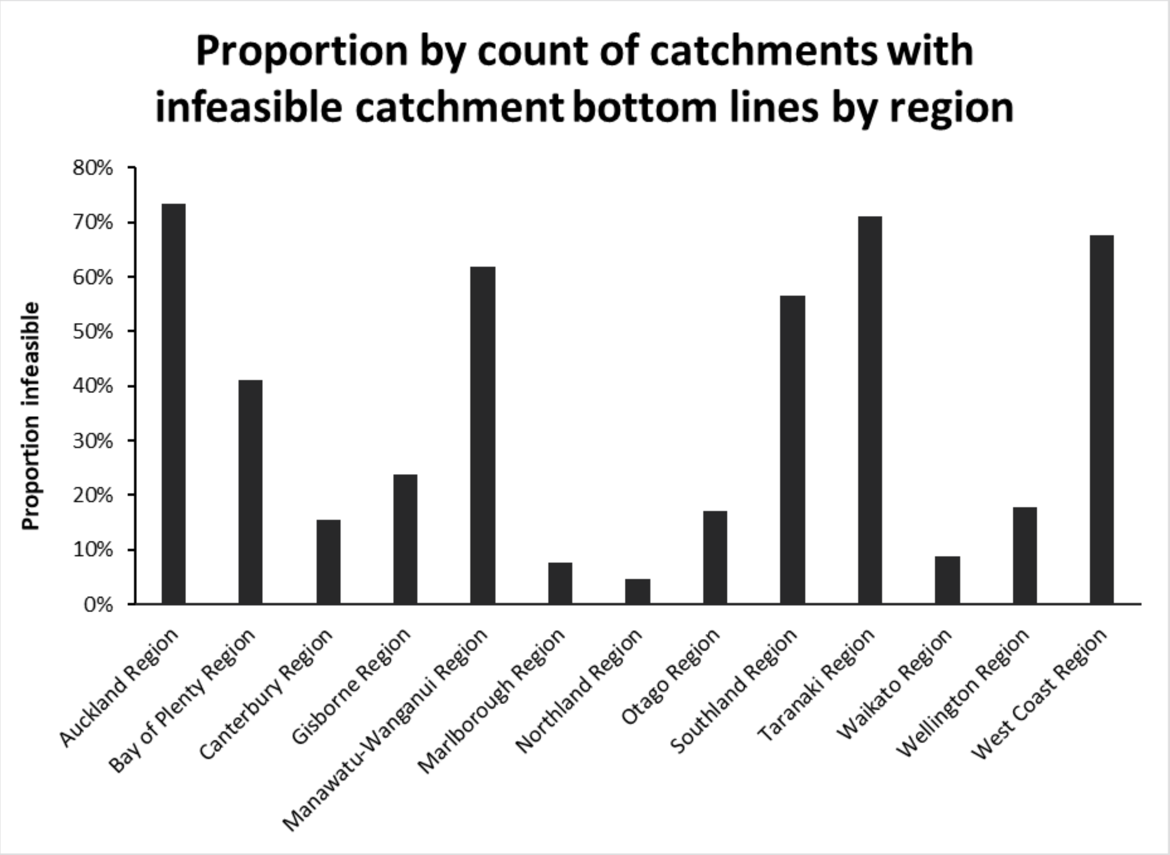
[10] This includes catchments with no existing WFPs.

a)



b)

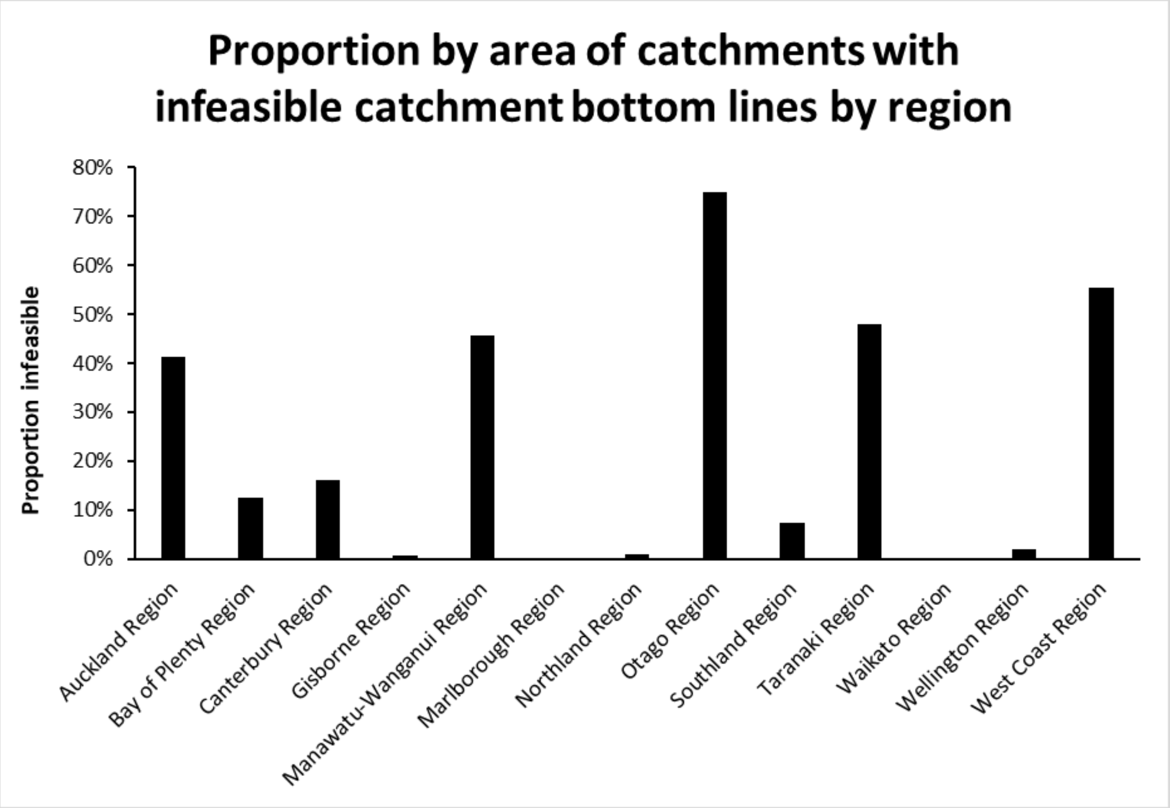


Figure 7 Charts showing proportion of catchments by a) count and b) area with infeasible bottom lines in all modelled mitigation scenarios.

5.2 Economic optimisation

In this section, we present the optimised cost of sediment mitigation required to meet sediment reduction targets using the NZFARM model. We present the NZFARM model results in tabular form by region – Tables 6 and 8) and for five large catchments (Waikato, Ruamahanga, Kaipara, Mataura, and Clutha – see Tables 7 and 9). The detailed results for all catchments are included in Appendix 6. This section describes only the effect of WFPs and afforestation, due to the lack of spatially explicit RE data as described in Section 4.2.1 and 4.3.2. As such, RE was analysed separately and was not included in the NZFARM analysis. The input to NZFARM modelling was only the catchments containing mitigatable land, a total of 444 catchments out of the 585 that currently exceed the proposed sediment bottom line targets.

5.2.1 Area of mitigations

Reaching sedimentation reduction targets requires adoption of afforestation and WFP mitigation options (Table 6). The input to the NZFARM modelling was only the catchments containing land that was mitigatable by afforestation or WFPs. This comprised 444 catchments, of the total of 532 identified by the NZeem® modelling – the remainder have no land mitigatable by afforestation or WFPs and RE is the only mitigation option, and was excluded from the NZFARM analysis because of lack of spatial data.

The results of the NZFARM analysis are given in the columns feasible and infeasible of Table 6. The infeasible area represents mitigatable land that cannot meet the catchment sediment reduction targets even after implementing afforestation, which has the highest sediment reduction potential (90%), on all mitigatable land. The feasible area is mitigatable land in which catchment sedimentation reduction targets can be met through the two mitigation options. In addition, the baseline and scenario results are only presented for the mitigatable areas of the catchments while the required reduction targets are those set for the whole catchment (mitigatable and non-mitigatable land). As such, in some cases when the sediment reduction target exceeds all the sediment generated from all the mitigatable areas (baseline), then those areas are categorised as infeasible. Excluding consideration of RE, in the target catchments about 1.8 million ha of land is suitable for afforestation and WFP mitigations and can meet the sediment reduction targets (i.e. feasible columns in Table 6), and about 0.45 million ha of land is suitable for mitigations but cannot meet the sediment reduction targets (i.e. infeasible columns in Table 6). The latter includes 114 infeasible catchments[11] that cannot meet the sediment reduction targets even after applying the modelled mitigations on their entire mitigatable area. The region that has the largest feasible and infeasible area combined to reduce sedimentation is Canterbury. Hawke's Bay and Tasman are the only regions that can entirely meet the sedimentation reduction targets (i.e. they do not have infeasible catchments).

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[11] This differs from the 159 catchments identified from the NZeem® modelling (section 5.1.2) as many catchments had no mitigatable land or could only meet bottom line sediment targets through the RE.scenario which was not included in the NZFARM analysis.

The NZFARM model results show that to meet the sediment reduction targets, afforestation is needed on about 1.056 million ha and WFPs on 6,055 ha. After meeting the catchment sedimentation reduction targets, about 1.2 million ha do not need any mitigations and remained in the current land use. The area of afforestation in feasible catchments is about 606,000 ha, and the afforestation area in infeasible catchments is about 450,000 ha. Afforestation is needed on the entire infeasible area that is suitable for mitigations to approach as close as possible the sedimentation reduction target levels (see Table 8). The region with the most afforestation is Otago, which needs about 53,000 ha and 376,000 ha of afforestation on feasible and infeasible catchments respectively. Regions such as Canterbury, Southland and Waikato also need afforestation of large areas. Such large scale adoption of afforestation is due to its high sediment reduction effectiveness, revenues from C sequestration and low annualized costs (see Table 1). The region that has the smallest area needing afforestation is Tasman due to its small mitigatable area.

WFP is needed on 6,055 ha in feasible catchments only, because it has lower sediment load reduction effectiveness and does not have revenues from C sequestration in comparison to afforestation (see Table 6). Southland has the largest area with WFP mitigation. WFPs are implemented on land that has high opportunity cost from having afforestation (i.e. profits from certain lands are larger than from afforestation with C revenues, and thus having WFP results in low costs on these lands). Auckland, Gisborne, Hawke’s Bay and Tasman do not need any WFP mitigation.

Table 6 Mitigatable land area allocated for no mitigation, whole-farm planning and afforestation across regions in baseline and sedimentation reduction target scenarios, in 1,000 ha

Regions	Baseline		Sedimentation reduction target scenario			
			Area that does not require further mitigation	Whole-farm planning	Afforestation	
	Feasible	Infeasible	Feasible	Feasible	Feasible	Infeasible
Auckland	4.7	1.1	3.5	0.0	1.2	1.1
Bay of Plenty	39.3	0.6	30.0	0.4	8.8	0.6
Canterbury	501.7	35.1	280.1	0.2	221.3	35.1
Gisborne	134.3	0.1	89.4	0.0	44.9	0.1
Hawke's Bay	245.2	n.a.	215.5	0.0	29.7	n.a.
Manawatu-Wanganui	3.2	3.3	1.4	0.04	1.8	3.3
Marlborough	119.4	0.04	94.1	0.0	25.3	0.0
Northland	63.3	0.2	41.3	0.0	22.1	0.2
Otago	136.6	375.9	83.5	0.5	52.6	375.9
Southland	135.8	30.3	83.1	2.8	50.0	30.3
Tasman	10.5	n.a.	10.1	0.0	0.5	n.a.
Taranaki	2.0	0.7	0.7	0.7	0.6	0.7
Waikato	321.5	0.1	197.1	1.1	123.2	0.1
Wellington	100.9	0.8	76.9	0.2	23.8	0.8
West Coast	0.2	1.4	0.1	0.0	0.1	1.4
Total	**1,818.6**	**449.6**	**1,206.7**	**6.1**	**605.8**	**449.6**

Note: The feasible column includes the area of regions with catchments that can meet the sediment reduction target. The infeasible column includes the area of regions with catchments that cannot meet the sediment reduction target. n.a. for Hawke's Bay and Tasman means there are no infeasible catchments in these regions.

In terms of the results for the five selected catchments (Waikato, Ruamahanga, Mataura, Clutha and Kaipara), the Clutha catchment has the largest mitigatable area followed by the Waikato catchment (Table 7). All five of these catchments are mitigated by afforestation and none of the catchments utilise WFPs. Even if the entire mitigatable land of the Clutha catchment is treated, it cannot meet the sediment reduction target. Accordingly, for the Clutha catchment complete afforestation of the mitigatable land is needed to at least approach the sediment reduction target. Waikato, Ruamahanga, and Mataura catchments, and Kaipara tributaries can meet the sediment reduction targets, by allocating about 83,000 ha, 11,000 ha, 12,000 ha and 29,000 ha to afforestation, respectively. Large areas of the Waikato, Ruamahanga, and Mataura catchments, and Kaipara tributaries do not require further mitigation as they can meet the sediment reduction targets.

Table 7 Mitigatable land area allocated for no mitigation, whole-farm planning and afforestation in Waikato, Mataura, Kaipara tributaries, Ruamahanga, and Clutha in baseline and sedimentation reduction target scenarios, in 1,000 ha

Catchments	Baseline		Sedimentation reduction target scenario			
			Area that does not require further mitigation	Whole-farm planning	Afforestation	
	Feasible	Infeasible	Feasible	Feasible	Feasible	Infeasible
Waikato	213.1	0	130.4	0	82.6	0
Ruamahanga	67.1	0	56.4	0	10.7	0
Kaipara	34.8	0	22.4	0	12.4	0
Mataura	85.6	0	56.8	0	28.8	0
Clutha	0	375.3	0	0	0	375.3
Total	**400.6**	**375.3**	**266.0**	**0**	**134.6**	**375.32**

Note: The feasible column indicates the catchments that can meet the sediment reduction target. The infeasible column indicates the catchments that cannot meet the sediment reduction target.

5.2.2 Sediment load reduction

Sediment mitigations can substantially reduce the sediment load in New Zealand rivers. By implementing afforestation and WFP on mitigatable land in feasible and infeasible catchments, sediment load can be reduced by about 4 million tonnes (13%), as the baseline sediment load on mitigatable land was reduced from 29.5 million to 25.5 million tonne (Table 8). The sediment loads and their reduction levels differ by regions. Baseline sediment loads for mitigatable land are the highest for Gisborne, Hawke's Bay, and Northland, followed by Wellington and Waikato. Even after adopting sediment mitigations (Table 6), sediment load is still the highest for Gisborne, followed by Hawke's Bay, Northland and Waikato. In absolute terms, Gisborne has about 1.6 million tonne (12%) reduction from the baseline. In relative terms, West Coast region has the largest sediment reduction, i.e. about 88% reduction from the baseline. West Coast also has the largest sediment load and sediment reduction targets that are infeasible with the modelled mitigations. For example, 54,000 tonnes of West Coast’s sediments (96% of its total sediment load) are from catchments that cannot meet the sedimentation reduction targets (i.e. infeasible catchments). Sediment reduction targets of infeasible catchments in West Coast is about 2 million tonnes, which is 5% of sediment reduction targets in infeasible catchments of New Zealand. In relative terms, Tasman has the least sediment load reduction among regions (2% reduction) due to lower sediment reduction targets and the absence of catchments that cannot meet the sediment targets (i.e. no infeasible catchments).

Afforestation leads to the largest sediment load reduction due to its 90% sediment reduction effectiveness and the large area of afforestation implementation. WFP has a lower reduction because of lower sediment reduction effectiveness (70%) and smaller implemented area than afforestation. Large areas remained under land uses that did not require any modelled mitigations and thus substantial sediment load is from these areas.

Table 8 Required reduction in sediment load, and the modelled sediment load levels in baseline and sedimentation reduction target scenarios across regions, in 1,000 tonne

Regions	Baseline (loads from mitigatable land)		Required reduction in sedimentation (target for mitigatable and non-mitigatable land)		Sedimentation reduction target scenario (loads from mitigatable land)			
					Sediment load from area that does not require further mitigation	Afforestation		Whole-farm planning
	Feasible	Infeasible	Feasible	Infeasible	Feasible	Feasible	Infeasible	Feasible
Auckland	26.7	1.6	4.0	5.4	22.3	0.4	0.2	0.0
Bay of Plenty	1,114.2	0.6	45.6	4.5	1,063.3	5.0	0.1	0.4
Canterbury	1,032.9	78.7	238.6	277.9	767.4	26.4	7.9	0.5
Gisborne	12,043.2	0.9	1,656.3	5.7	10,202.8	184.0	0.1	0
Hawke's Bay	4,405.5	n.a.	116.0	n.a.	4,276.6	12.9	n.a.	0
Manawatu-Wanganui	6.2	0.8	2.9	1.8	3.0	0.3	0.1	0.1
Marlborough	240.6	0.1	20.8	0.3	217.5	2.3	0.0	0.0
Northland	4,177.4	0.2	166.9	0.3	3,992.0	18.5	0.0	0.1
Otago	134.0	863.0	31.2	1,205.6	99.2	3.4	86.3	0.2
Southland	362.4	38.7	115.8	41.2	232.3	12.3	3.9	2.1
Taranaki	11.9	1.0	2.0	1.7	9.4	0.1	0.1	0.4
Tasman	154.5	n.a.	3.4	n.a.	150.7	0.4	n.a.	0.0
Waikato	2,967.3	0.1	278.8	0.3	2,656.6	30.6	0.0	1.4
Wellington	1,852.5	8.4	286.9	19.7	1,533.5	31.8	0.8	0.4
West Coast	2.1	54.2	0.8	2,051.1	1.2	0.1	5.4	0.1
Total	**28,531**	**1,048.1**	**2,969.7**	**3,615.5**	**25,227.6**	**328.5**	**104.8**	**5.6**

Note: The feasible column includes the sediment load of regions with catchments that can meet the sediment reduction target. The infeasible column includes the sediment load of regions with catchments that cannot meet the sediment reduction target. n.a. for Hawke’s Bay and Tasman means there are no infeasible catchments in these regions. The baseline and scenario results are presented for the mitigatable areas of the catchments while the required reduction targets are those set for the whole catchment (mitigatable and non-mitigatable land).

The Kaipara tributaries have the highest sediment load, followed by the Waikato and Clutha catchments (Table 9). The Clutha catchment has the highest sediment reduction after mitigation options are implemented (a reduction of 776.2 tonnes or 90% from the baseline). The large reduction for the Clutha catchment is because this catchment has insufficient mitigatable land to meet the sediment load reduction target (i.e. catchment is infeasible for achieving the sediment reduction target). Accordingly, for the Clutha catchment afforestation is implemented on all its mitigatable area to at least come as close as possible to the sediment reduction target, but it still cannot reach the target level. In relative terms, Mataura also has large reduction in sediment load (27%). For the Mataura catchment, afforestation of large areas results in a large decrease of sediment load. The catchment with the lowest sediment load decrease is the Ruamahanga catchment (1.7%), due to its small sediment reduction target and implemented afforestation area.

Table 9 Required reduction in sedimentation, and the modelled sediment load levels in baseline and sedimentation reduction target scenarios in Waikato, Mataura, Kaipara tributaries, Ruamahanga and Clutha catchments, in 1,000 tonne

Catchments	Baseline (loads from mitigatable land)		Required reduction in sedimentation (target on mitigatable and non-mitigatable land)		Sedimentation reduction target scenario (loads from mitigatable land)			
					Sedimentation from area that does not require further mitigation	Afforestation		Whole-farm planning
	Feasible	Infeasible	Feasible	Infeasible	Feasible	Feasible	Infeasible	Feasible
Waikato	1,017.5	0	144.2	0	857.3	16.0	0	0
Ruamahanga	545.4	0	9.0	0	535.4	1.0	0	0
Kaipara	2,357.2	0	81.6	0	2,266.5	9.1	0	0
Mataura	228.8	0	62.3	0	159.6	6.9	0	0
Clutha	0	862.5	0	1,204.1	0	0	86.3	0
Total	**4,148.9**	**862.5**	**297.1**	**1,204.1**	**3,818.8**	**33.0**	**86.3**	**0**

Note: The feasible column indicates the catchments that can meet the sediment reduction target. The infeasible column indicates the catchments that cannot meet the sediment reduction target. The baseline and scenario results are presented for the mitigatable areas of the catchments while the required reduction targets are those set for the whole catchment (mitigatable and non-mitigatable land).

5.2.3 GHG emissions, carbon sequestration and nutrient leaching

Achieving sediment load targets indirectly improves other environmental outputs. For instance, GHG emissions from mitigatable areas of New Zealand are lower by 2.3 million tCO_2 (34.5%) than in the baseline (Table 10). The largest GHG emission reduction from the baseline is predicted in the Waikato (625,000 tCO_2 reduction), followed by Otago (608,000 tCO_2 reduction) and Southland (266,000 tCO_2 reduction). This is because these regions have high GHG emissions and have implemented mitigations on large areas, which results in large GHG emission reductions. In most of the regions, there are substantial GHG emission reduction when erosion mitigation is implemented. The largest share of GHG emission reductions are from catchments in regions that cannot meet the sediment reduction targets because these infeasible catchments entirely afforest their mitigatable land area and are thus assumed not to emit GHG. Regions that can meet the sediment reduction target have large land areas where mitigation options are not implemented, and these land areas produce GHG emissions. In relative terms, the lowest reduction in GHG emissions is in Tasman (1.4% GHG reduction), followed by Hawke’s Bay (12% GHG reduction), and Marlborough (13% GHG reduction).

In addition to reducing GHG emissions by converting to less emitting land uses, regions have additional carbon (C) sequestration above the baseline through establishing afforestation. We do not consider C sequestration in the baseline scenario, because in the baseline we assume only pastoral land uses without forestry to be mitigatable land. According to the model analysis, in most of the regions afforestation mitigation is implemented (see Table 6), and as a result most of the regions have C sequestration. In total, about 19.8 million tCO_2 is sequestered by afforestation on all mitigatable land areas. Otago has the largest increase C sequestration levels, which is around 37% of the total C sequestration increase in New Zealand. Other regions that have a substantial increase in C sequestration are Canterbury, Waikato, and Southland. About 39% of C sequestration increase occurs through afforestation in catchments that cannot meet the sediment load reduction targets (infeasible column in Table 10). Almost 83% of C sequestration where sediment reduction catchment targets are infeasible occurs in Otago. The lowest C sequestration levels is observed in Tasman and Hawke's Bay, because these regions have small areas with afforestation.

The net GHG emissions (subtraction of C sequestration from GHG emissions) in the sediment reduction target scenario is 15.4 million tCO_2 sequestrated. This is because, in the sedimentation reduction scenario, the mitigatable areas in New Zealand have more C sequestration than GHG emissions.

Table 10 GHG emissions and CO_2 sequestration levels across regions in baseline and sedimentation reduction target scenarios, in 1,000 t CO_2

Regions	GHG emissions			CO_2 sequestration in afforestation		
	Baseline	Sedimentation reduction target scenario		Baseline	Sedimentation reduction target scenario	
		Feasible	Infeasible		Feasible	Infeasible
Auckland	25.9	17.0	0	0	25.9	26.3
Bay of Plenty	174.5	136.6	0	0	226.8	13.4
Canterbury	650.8	455.3	0	0	3,723.8	596.3
Hawke's Bay	999.7	881.9	0	0	659.9	n.a.
Gisborne	510.5	333.7	0	0	1,058.2	2.3
Manawatu-Wanganui	28.7	6.9	0	0	40.3	73.4
Marlborough	140.1	121.2	0	0	428.5	0.7
Northland	349.6	249.9	0	0	531.8	4.3
Otago	801.1	192.3	0	0	906.5	6,349.8
Southland	570.6	303.7	0	0	928.3	540.6
Taranaki	23.0	6.3	0	0	16.9	19.3
Tasman	43.7	43.1	0	0	9.0	n.a.
Waikato	1,930.4	1,305.0	0	0	3,050.3	1.9
Wellington	446.8	339.3	0	0	482.4	16.9
West Coast	7.3	0.4	0	0	1.2	29.9
Total	**6,703**	**4,393**	**0**	**0**	**12,090**	**7,675.1**

Note: The feasible column includes the GHG emissions and CO_2 sequestration by regions for catchments that can meet the sediment reduction target. The infeasible column includes the GHG emissions and CO_2 sequestration by regions for catchments that cannot meet the sediment reduction target. The baseline and scenario results are presented for the mitigatable areas of the catchments. n.a. for Hawke's Bay and Tasman means there are no infeasible catchments in these regions.

As a result of adopting mitigation options, all the five selected catchments have lower GHG emissions compared with the baseline (Table 11). The largest emission decrease is for the Clutha catchment. The Clutha catchment has zero GHG emissions in the sedimentation reduction target scenario, because it has land areas that cannot meet the sedimentation reduction target (i.e. infeasible areas) and thus afforests its entire mitigatable land area. The remaining catchments also have large GHG emission reductions. The total GHG emissions from the Waikato, Ruamahanga, Kaipara, Mataura and Clutha catchments reduce by 42%.

The C sequestration levels at the Clutha catchment is 67% of the total C sequestration levels from five catchments. Other regions also have large levels of C sequestration. The total C sequestration in the five catchments is 9.45 million tCO_2.

Table 11 GHG emissions and CO_2 sequestration levels in the Waikato, Ruamahanga, Mataura and Clutha catchments and Kaipara tributaries in baseline and sedimentation target scenarios, in 1,000 tCO_2

Catchments	GHG emissions			CO_2 sequestration in afforestation		
	Baseline	Sedimentation reduction target scenario		Baseline	Sedimentation reduction target scenario	
		Feasible	Infeasible		Feasible	Infeasible
Waikato	1,316.8	905.0	0	0	2,070.4	0
Ruamahanga	302.8	253.1	0	0	220.0	0
Kaipara	197.4	142.0	0	0	293.2	0
Mataura	247.8	189.5	0	0	529.3	0
Clutha	517.7	0	0	0	0	6,337.7
Total	**2,582.4**	**1,489.6**	**0**	**0**	**3,112.8**	**6,337.7**

Note: The feasible column indicates the catchments that can meet the sediment reduction target. The infeasible column indicates the catchments that cannot meet the sediment reduction target. The baseline and scenario results are presented for the mitigatable areas of the catchments.

Other environmental benefits from sediment reduction included in the NZFARM model are nitrogen leaching and phosphorous loss (Table 12). Across all the mitigatable areas in the country, the total nitrogen leaching reduces by 338 tonnes from the baseline when sediment mitigations are implemented. The largest reduction is in Otago (about 91 tonnes of nitrogen leaching reduction), due to the large area of afforestation established in this region. Waikato and Southland have about 89 and 38 tonnes nitrogen leaching reduction, respectively. However, it should be noted that due to a lack of data, we did not consider the change in nitrogen leaching from WFP (see (Table 12). Having data on changes in nitrogen leaching as a result of WFPs might lead to different outcomes for this environmental indicator.

Nationally, phosphorous loss reduces by roughly 65 tonnes after the implementation of sediment mitigations. The largest phosphorous decreases occur in Waikato (17.3 tonne) and Otago (17 tonne). The lowest levels of phosphorous decrease occur in Tasman and West Coast, which also have the smallest areas of land allocated for mitigations.

Table 12 Nitrogen leaching and phosphorous loss outputs across regions in baseline and sedimentation reduction target scenarios, in tonne

Regions	Nitrogen leaching			Phosphorous loss		
	Baseline	Sedimentation reduction target scenario		Baseline	Sedimentation reduction target scenario	
		Feasible	Infeasible		Feasible	Infeasible
Auckland	108.3	83.2	23.4	5.1	3.9	0.9
Bay of Plenty	736.2	718.9	11.8	32.8	31.3	0.5
Canterbury	2,984.3	2,800.0	154.1	140.5	126.7	7.9
Gisborne	1,871.7	1,845.2	0.7	94.9	90.0	0.03
Hawke's Bay	3,707.5	3,690.4	n.a.	186.8	183.6	n.a.
Manawatu-Wanganui	145.6	60.6	80.7	5.0	2.2	2.2
Marlborough	564.0	559.4	1.8	27.0	26.5	0.04
Northland	1,506.9	1,489.8	2.6	71.0	68.2	0.1
Otago	2,999.0	1,011.7	1,896.1	150.0	48.2	84.5
Southland	2,142.6	1,638.5	466.5	104.7	77.8	19.5
Taranaki	119.8	87.0	30.9	3.4	2.2	0.8
Tasman	227.2	227.1	n.a.	8.0	8.0	n.a.
Waikato	7,991.7	7,900.3	2.2	350.6	333.2	0.1
Wellington	1,668.4	1,644.0	9.0	82.9	79.5	0.4
West Coast	37.9	2.6	33.8	1.2	0.1	1.0
Total	**26,811**	**23,759**	**2,713.6**	**1,264**	**1,081**	**117.8**

Note: The feasible column includes the nitrogen leaching and phosphorous loss by regions for catchments that can meet the sediment reduction target. The infeasible column includes the nitrogen leaching and phosphorous loss by regions for catchments that cannot meet the sediment reduction target. The baseline and scenario results are presented for the mitigatable areas of the catchments. n.a. for Hawke's Bay and Tasman means there are no infeasible catchments in these regions.

The total nitrogen leaching from the Waikato, Ruamahanga, Kaipara, Mataura, and Clutha catchments reduces by 161.9 tonnes in the sedimentation reduction target scenario (Table 13). The Clutha catchment has the largest reduction in level of nitrogen leaching, because its entire area is afforested to meet the sediment reduction target. Phosphorous loss is reduced by roughly 31 tonnes total in the five catchments in comparison to the baseline. The largest phosphorous decrease is simulated for the Clutha catchment, followed by the Waikato catchment, due to their large afforestation areas.

Table 13 Nitrogen leaching and phosphorous loss outputs in the Waikato, Ruamahanga, Mataura and Clutha catchments, and Kaipara tributaries in baseline and erosion target scenarios, in tonne

	Nitrogen leaching			Phosphorous loss		
Catchments	Baseline	Sedimentation reduction target scenario		Baseline	Sedimentation reduction target scenario	
		Feasible	Infeasible		Feasible	Infeasible
Waikato	5,586.1	5,526.1	0	240.0	228.5	0
Ruamahanga	1,128.6	1,121.4	0	56.0	54.6	0
Kaipara	882.7	874.7	0	41.0	39.5	0
Mataura	914.0	905.8	0	45.4	43.9	0
Clutha	1,964.0	0	1,885.5	99.0	0	84.1
Total	**10,475.4**	**8,428.0**	**1,885.5**	**481.4**	**366.5**	**84.1**

Note: The feasible column indicates the catchments that can meet the sediment reduction target. The infeasible column indicates the catchments that cannot meet the sediment reduction target. The baseline and scenario results are presented for the mitigatable areas of the catchments.

5.2.4 Profits

Implementing the mitigation options (WFP and afforestation) affects the profits from mitigatable land (Table 14). Afforestation and WFP result in different types of costs. The afforestation establishment costs have the largest costs related to mitigations, which amount to about \$176 million (almost 56% of costs) from all mitigatable areas in New Zealand. Opportunity costs are the benefits lost from establishing afforestation. Opportunity costs amount to about \$140 million (44% of costs). If not considering C sequestration revenues (under \$25/tCO_2), the total profits from mitigatable land areas reduce by \$315.7 million (39% reduction) from the baseline. Otago bears the largest costs (\$136 million), followed by Canterbury (\$62 million). These regions have high costs because of their high sedimentation reduction targets. In contrast, Tasman and Auckland bear the lowest costs from establishing mitigations and from opportunity costs because the regions do not have high sediment reduction targets.

Including C sequestration payments generates revenues from afforestation. C sequestration payments generate about \$494 million in revenue from all sediment mitigatable land in New Zealand. Otago has the largest C sequestration revenues, \$181 million (37% of total C revenues). Canterbury, Waikato, and Southland also have substantial C sequestration revenues. As the pine forest are permanent, not harvested, and receive C sequestration payments, this leads to the high revenues (see section 4.3). The regions that earn the least C sequestration payments are Tasman and West Coast, because of their small afforestation mitigation areas.

Taking the difference between the revenues (\$494.1 million from C sequestration payments) and costs (\$240.8 million from establishment and opportunity costs) of the mitigations, \$253.3 million in profits is gained from the mitigations in each year. Thus, modelled sediment reduction mitigations along with C sequestration payments increase land use profits.

Table 14 Annual profit in baseline scenario, and costs and revenues in sedimentation reduction target scenario across regions, in $ million

Regions	Baseline profit		Sedimentation reduction target scenario								
			Profit		Whole-farm planning establishment costs	Opportunity costs		Afforestation establishment costs		C sequestration revenues	
	Feasible	Infeasible	Feasible	Infeasible	Feasible	Feasible	Infeasible	Feasible	Infeasible	Feasible	Infeasible
Auckland	1.53	1.11	1.925	0.51	0	0.005	1.1	0.2	0.2	0.6	0.7
Bay of Plenty	28.99	0.62	32.783	0.22	0.007	0.4	0.6	1.5	0.1	5.7	0.3
Canterbury	98.46	4.38	140.156	8.98	0.004	14.5	4.4	36.9	5.9	93.1	14.9
Gisborne	4.34	0.003	22.94	0.098	0	0.4	0.003	7.5	0.002	26.5	0.1
Hawke's Bay	44.69	n.a.	52.59	n.a.	0	3.6	n.a.	5	n.a.	16.5	n.a.
Manawatu-Wanganui	1.73	3.44	2.329	1.24	0.001	0.1	3.4	0.3	0.6	1	1.8
Marlborough	27.1	0.22	33.1	0.034	0	0.5	0.2	4.2	0.006	10.7	0.02
Northland	50.74	0.001	59.64	0.07	0	0.7	0.03	3.7	0.001	13.3	0.1
Otago	28.09	59.24	36.481	96.04	0.009	5.5	59.2	8.8	62.7	22.7	158.7
Southland	50.74	19.74	56.89	8.44	0.05	8.7	19.7	8.3	5.1	23.2	13.5
Taranaki	6.35	2.47	5.737	0.37	0.013	0.9	2.5	0.1	0.1	0.4	0.5
Tasman	11.54	n.a.	11.64	n.a.	0	0	n.a.	0.1	n.a.	0.2	n.a.
Waikato	329.37	0.15	379.45	0.04	0.02	5.7	0.1	20.5	0.01	76.3	0
Wellington	25.49	0.21	28.686	0.31	0.004	4.9	0.2	4	0.1	12.1	0.4
West Coast	0.07	2.09	0.081	0.49	0	0.01	2.1	0.009	0.2	0.03	0.7
Total	**709.2**	**93.7**	**864.4**	**116.8**	**0.1**	**46.0**	**93.7**	**101.0**	**74.9**	**302.2**	**191.9**

Note: The feasible column includes the profits, costs and revenues by regions for catchments that can meet the sediment reduction target. The infeasible column includes the profits, costs and revenues by regions for catchments that cannot meet the sediment reduction target. The baseline and scenario results are presented for the mitigatable areas of the catchments. n.a. for Hawke's Bay and Tasman means there are no infeasible catchments in these regions.

Among the selected catchments, the Waikato catchment has the largest profits in the baseline followed by the Clutha catchment (Table 15). Adopting mitigations reduces profits for these catchments. The Clutha catchment has the largest costs, $121 million, with $58.4 million in opportunity costs and $62.6 million in establishment costs. At the same time, the Clutha catchment has C sequestration revenues of $158.4 million. Consequently, benefits outweigh the costs for the sediment reduction target scenario. Considering costs and revenues in the sediment reduction target scenario, total profits from the five catchments increase by $82.7 million. The increase in profits is due to the model assumptions in annualising the costs of mitigations, large afforestation area, C sequestration levels in permanent pine trees (i.e. we do not consider harvest of afforestation) and C sequestration payments (see section 4.3).

Table 15 Annual profit in baseline scenario, and costs and revenues in sedimentation reduction target scenario in Waikato, Kaipara tributaries, Ruamahanga, Mataura, and Clutha, in $ million

Catchments	Baseline	Sedimentation reduction target scenario						
		Whole-farm planning establishment costs	Opportunity costs		Afforestation establishment costs		C sequestration revenues	
		Feasible	Feasible	Infeasible	Feasible	Infeasible	Feasible	Infeasible
Waikato	259.8	0	3.9	0	13.8	0	51.8	0
Ruamahanga	17.0	0	2.2	0	1.8	0	5.5	0
Kaipara	34.8	0	0.3	0	2.1	0	7.3	0
Mataura	4.7	0	3.6	0	4.8	0	13.2	0
Clutha	58.4	0	0	58.4	0	62.6	0	158.4
Total	**374.8**	**0**	**10.1**	**58.4**	**22.4**	**62.6**	**77.8**	**158.4**

Note: The feasible column indicates the catchments that can meet the sediment reduction target. The infeasible column indicates the catchments that cannot meet the sediment reduction target. The baseline and scenario results are presented for the mitigatable areas of the catchments.

5.3 River segment scale reductions after NZFARM optimisation

Nationally, with present modelled sediment loads, 97,427 of the total number of REC2 stream segments (423,352) in the catchments modelled in this study do not meet the proposed sediment bottom lines. Of these 87,414 are within the catchments analysed in this study. Those that are not in the catchments are part of stream networks that do not contain third order segments and therefore did not have pourpoint catchments derived for them (see Hicks et al. 2019a).Of the 3,697[12] segments within pourpoint catchments that have glacial sources of flow, 9,853 do not meet sediment bottom lines. Given the naturally high rate of sediment generation, these are not expected to meet bottom lines. Therefore, there are 77,561 remaining stream segments with non-glacial sources-of-flow which do not currently meet the proposed sediment bottom lines within the pourpoint catchments. Here, we consider the feasibility of achieving sediment bottom lines for these 77,561 segments with the NZFARM optimised spatial distribution of mitigations and maturation of existing WFPs.

After implementation of the NZFARM optimisation and maturation of existing WFPs, 15,868 non-glacial source-of-flow stream segments are predicted to meet the relevant sediment bottom line targets (Fig. 8). This represents 20% of the 77,561 non-glacial source of flow stream segments that do not currently meet bottom line at baseline within the pourpoint catchments. Table 16 shows a relatively even proportional achievement of bottom lines by stream order, with 3rd and4th order streams showing the greatest proportion of segments that will meet the target sediment bottom line. Regionally (Table 17) Waikato and Otago are predicted to have the largest number of additional stream segments meeting the relevant sediment bottom line targets (3626 and 4611 respectively), followed by Manawatu-Wanganui (1709), Southland (1602) and Canterbury (1392). On a proportional basis, a little over half the regions are predicted to have 20–-30% of remaining stream segments that meet the relevant sediment bottom line targets.

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[12] It is worth noting some segments are downstream of segments with glacial sources of flow but are not classed as having glacial sources of flow. However, it is assumed these would still have naturally high sediment loads.

Table 16 Achievement of bottom line sediment targets at segment scale in catchments after maturation of WFPs and implementation of NZFARM optimisation, listed by stream order, for non-glacial source of flow segments

Stream Order	Count of Stream Segments Not Currently Meeting Target	Count of Stream Segments Meeting Target After Mitigation	Proportion of Stream Segments Meeting Target After Mitigation
1	35,565	6,842	19%
2	17,561	3,790	22%
3	9,816	2,467	25%
4	5,518	1,360	25%
5	3,140	665	21%
6	3,281	521	16%
7	2,106	151	7%
8	574	72	13%
Total	**77,561**	**15,868**	**20%**

Table 17 Achievement of bottom line at segment scale in catchments after maturation of WFPs and implementation of NZFARM optimisation, aggregated by region, for non-glacial source of flow segments

Region	Count of Stream Segments Not Currently Meeting Target	Count of Stream Segments Meeting Target After Mitigation	Proportion of Stream Segments Meeting Target After Mitigation
Auckland	639	58	9%
Bay of Plenty	2,654	410	15%
Canterbury	6,780	1,392	21%
Gisborne	3,604	771	21%
Hawke's Bay	2,692	277	10%
Manawatu-Wanganui	6,877	1,709	25%
Marlborough	1,244	273	22%
Northland	1,718	397	23%
Otago	15,505	4,611	30%
Southland	9,237	1,602	17%
Taranaki	1,111	233	21%
Tasman	311	5	2%
Waikato	17,835	3,626	20%
Wellington	2,716	468	17%
West Coast	4,638	36	1%
Total	**77,561**	**15,868**	**20%**

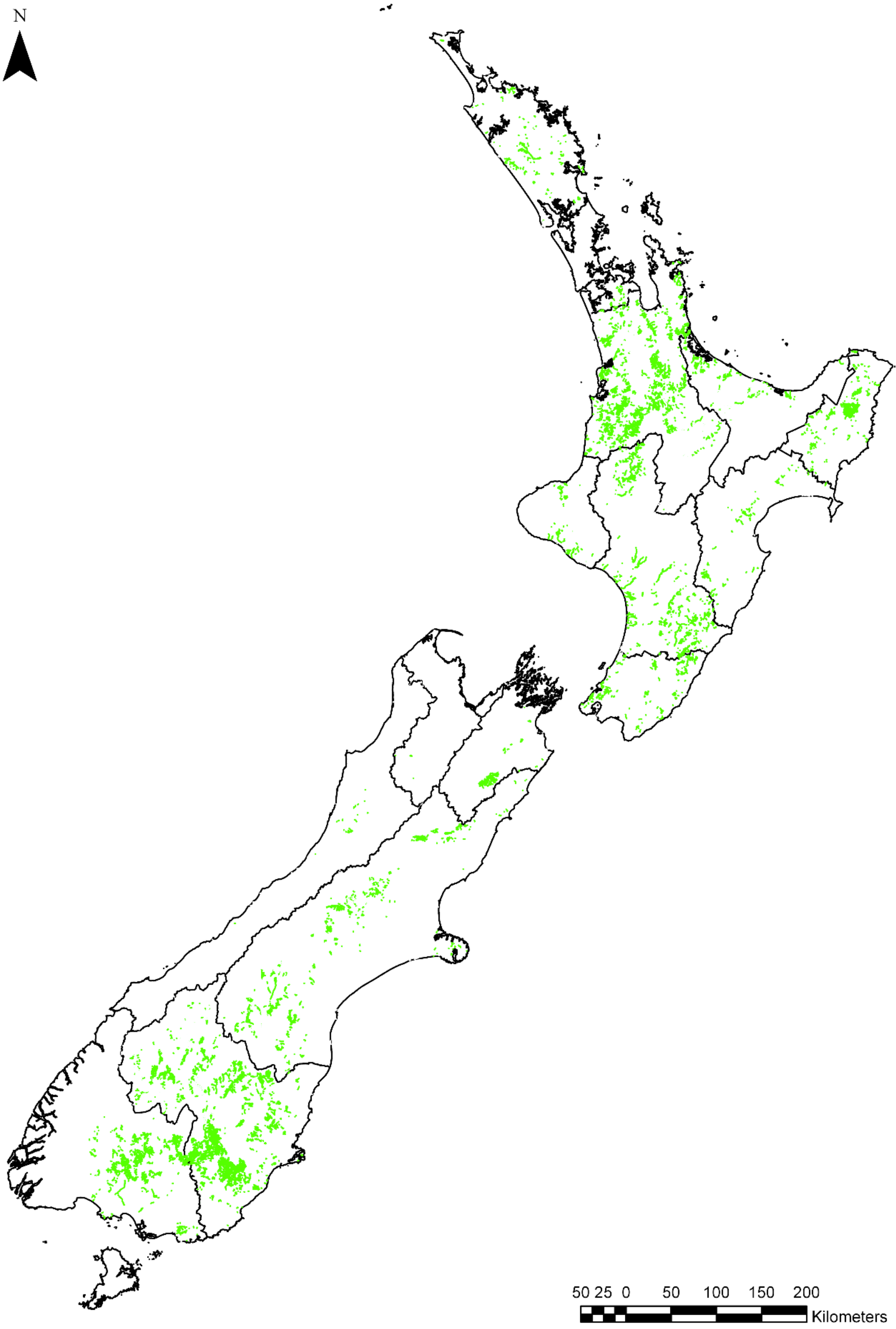

Figure 8 Stream segments which achieve sediment bottom line targets after the NZFARM optimisation. Stream segments with a glacial source-of-flow have been masked out.

5.4 Riparian exclusion

The total area for riparian exclusion and the fencing length is estimated at 182,972 ha and 365,944 km respectively. The total cost of riparian exclusion has been estimated at $3.3 billion assuming nothing has been implemented, and around $1.2 billion if we considered what has been implemented so far (Table 18). Information on the proportions of streams on which riparian exclusion has already implemented is sourced from the Survey of Rural Decision Makers (SDRM) survey (Brown 2015). At the regional level (and assuming nothing has been implemented), Canterbury has the largest cost by far ($627 million) followed by Waikato ($510 million), Otago ($479 million), and Southland ($428 million). The total cost is comprised by fencing costs, the opportunity cost of lost production, planting costs, and alternative water supply costs. At the national level, fencing costs represent the highest cost item ($2.9 billion), followed by planting costs ($183 million), opportunity costs ($120 million), and water supply costs ($26 million).

The Clutha River and Waikato River catchments were estimated to have the highest total cost for implementation of riparian exclusion in the selected catchments, which are $363 million and $356 million, respectively (Table 19).

Table 18 Cost estimates for implementation of riparian exclusion (RE) on major streams

Regions	Fencing length, km	Area, ha	Opportunity cost, $ million	Fencing cost, $ million	Planting cost, $ million	Water supply cost, $ million*	Total cost, $ million	RE already in place (%)[#]	Total cost after RE[@], $ million
Auckland	1,312	656	0.7	10	0.7	0.1	12	64	4
Bay of Plenty	13,509	6,754	3.4	108	6.8	0.6	119	83	20
Canterbury	71,790	35,895	11.9	574	35.9	5.3	627	62	237
Gisborne	9,067	4,534	1.2	73	4.5	0.7	79	29	56
Hawke's Bay	22,242	11,121	3.9	178	11.1	1.7	195	45	107
Manawatu-Wanganui	1,866	933	1.0	15	0.9	0.2	17	62	6
Marlborough	11,540	5,770	5.6	92	5.8	0.9	105	34	70
Northland	10,105	5,053	6.5	81	5.1	1.0	93	71	27
Otago	54,578	27,289	9.7	437	27.3	4.9	479	48	251
Southland	47,800	23,900	18.6	382	23.9	3.5	428	76	103
Taranaki	2,388	1,194	4.1	19	1.2	0.3	25	77	6
Tasman	12,324	6,162	2.8	99	6.2	0.3	108	59	44
Waikato	55,087	27,544	37.4	441	27.5	4.7	510	80	103
Wellington	13,051	6,525	3.5	104	6.5	1.1	116	52	56
West Coast	39,286	19,643	9.9	314	19.6	1.0	345	65	122
Total	**365,944**	**182,972**	**120**	**2,928**	**183**	**26**	**3,257**	**NA**	**1,213**

* Note: Water supply cost is only applied to pasture farms.

[#] Proportions of streams on which riparian exclusion has already been implemented (Brown P. 2015).

[@] This column represents total cost of riparian exclusion if we considered what has been implemented so far.

Table 19 Cost estimates for riparian exclusion on major streams of the selected catchments

Catchments	Fencing length, km	Area, ha	Opportunity cost, $ million	Fencing cost, $ million	Planting cost, $ million	Water supply cost, $ million*	Total cost by catchments, $ million
Waikato	38,576	19,288	25.0	308.6	19.3	3.0	356.0
Ruamahanga	8,463	4,231	2.8	67.7	4.2	0.8	75.6
Kaipara	5,735	2,868	4.4	45.9	2.9	0.5	53.6
Mataura	11,554	5,777	5.8	92.4	5.8	1.2	105.3
Clutha	41,528	20,764	6.8	332.2	20.8	3.5	363.4
Total	**105,856**	**52,928**	**44.9**	**846.9**	**52.9**	**9.1**	**953.8**

* Note: Water supply cost is only applied to pasture farms.

6 Cost-benefits assessment

6.1 Water Quality Benefits

As described in the methods section, we use a benefits transfer to value the impacts of water quality. Our approach uses estimates from the literature to value the changes in water quality from the scenarios modelled here. Several New Zealand-based studies have estimated people’s willingness to pay for improvements in water quality. After reviewing the literature, Tait et al. (2016) was identified as the most appropriate for the present context to be used in a benefit transfer. They focus on sediment reductions in their analysis, and use several measures of water quality, including water clarity. Clarity is important in the present context because of several important attributes. First, sediment is directly associated with changes in water clarity, so the outputs of the modelling results from previous sections can be used. Changes in clarity are also easily perceived and valued by households (Walsh et al. 2011). Clarity improvements are typically correlated with other water clarity benefits such as biodiversity, ecosystem health, and recreation benefits, and so are representative of several different benefit categories.

Our water clarity data were obtained from NIWA, who used national modelling to estimate relationships between sediment loads, turbidity, and water clarity.[13] They model reductions in clarity that result from turbidity criteria being achieved, which map to our policy scenario. Using the outputs of the NZFARM scenario and baseline described previously, we identify which catchments will be able to meet their sediment load reduction. We can then determine the resulting clarity improvements for those catchments. For catchments that were not predicted to meet their limit, we assume that there were still some improvements in clarity that result from the policy tools, even if the catchments did not meet the sediment attribute bottom line.[14] Table 20 shows the changes in waterbodies meeting clarity limits after the sediment reductions, presented at the regional level. Waikato has the highest improvement in waterbodies achieving their limits (also called ‘bottom lines’), at approximately 10 percentage points.

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[13] As detailed in https://www.mfe.govt.nz/sites/default/files/media/Fresh%20water/Sediment_Attributes_Stage%201_0.pdf

[14] We assume that clarity improvements are only a fraction of what they could have been if turbidity limits were achieved. To accommodate uncertainty, we use a random draw from a normal distribution, with a mean of 10% (and a 10% std. dev.) of the full possible improvement. Note that this assumption only affects less than 3% of the data. The final results are therefore quite robust to several different assumptions about this factor.

Table 20 Changes in water clarity at regional scale following implementation of erosion mitigation

Region	Percent of Region Meeting Clarity Limits Before Mitigation	Percent of Region Meeting Clarity Limits After Mitigation
Auckland	88.4	89.2
Bay of Plenty	91.9	93.9
Canterbury	82.8	84.5
Gisborne	77.0	84.9
Hawke's Bay	91.3	93.5
Manawatu Whanganui	72.5	72.6
Marlborough	94.8	96.9
Northland	86.8	88.8
Otago	78.3	82.7
Southland	73.3	74.4
Taranaki	88.6	89.4
Tasman/Nelson	96.5	96.5
Waikato	63.2	73.4
Wellington	87.9	93.3
West Coast	91.4	91.5

Tait et al. (2016) use a choice experiment to identify people's WTP for several different levels of clarity. The work was done for the Ministry for Primary Industries (MPI) and was focussed on a stock exclusion policy. They used a national survey of New Zealand, but also asked several questions about regional council-specific changes. We calculate the value of improved water clarity at the regional level, instead of the national changes in the survey. This limits potential overlap with other values, and represents the preference stated in the survey for local over national changes. Several other national benefit transfers use this approach (US EPA 2009, 2015). For water clarity, they asked respondents about their values for the percentage of waterbodies achieving their clarity criteria. To reflect the fact that thresholds (or bottom lines) differ across areas and different classes of rivers, with some waterbodies having lower clarity thresholds, they sorted values into poor, moderate, and good. Moderate thresholds were defined as clarity between 1.2 and 2.4 metres, good thresholds are 2.5 m or more, and poor are less than 1.2 m.

The WTP estimates can be used in our benefit transfer, after controlling for differences in household income between regions and the date and time of the study. The study results were based in 2016, so the WTP values were first updated to 2019 values via the Reserve Bank of New Zealand's inflation calculator.[15] Then the WTP values were adjusted by

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[15] https://www.rbnz.govt.nz/monetary-policy/inflation-calculator

median household income of the region. Since the WTP estimates are applied at the household level and we are projecting benefits into the future, we also must control for population growth. The NZ Statistics Department provides estimates for population growth, which are used here.[16]

To properly use the WTP values, we first need to know what proportion of the clarity improvements were in waters classified as poor, moderate, or good. Table 21 displays the proportion of waterbodies that went from violating clarity limits to achieving them, by classification. For instance, of the waterbodies in Auckland that changed from violating their limits to achieving them, only 1% were good or poor, while 98% were moderate.

Table 21 Poor, moderate, or good clarity bottom lines

Region	% Good Violate to Meet	% Moderate Violate to Meet	% Poor Violate to Meet
Auckland	1.1	97.9	1.1
Bay of Plenty	48.8	51.2	0.0
Canterbury	83.5	16.5	0.0
Gisborne	88.0	12.0	0.0
Hawke's Bay	65.9	34.1	0.0
Manawatu Whanganui	84.1	15.9	0.0
Marlborough	94.9	5.1	0.0
Northland	0.2	91.5	8.4
Otago	45.8	32.4	21.8
Southland	4.4	67.2	28.3
Taranaki	1.5	98.5	0.0
Tasman Nelson	100.0	0.0	0.0
Waikato	9.0	44.7	46.4
Wellington	76.3	23.7	0.0
West Coast	39.1	60.9	0.0

After applying the WTP estimates from Tait et al. (2016) to the changes in clarity and adjusting as described, we calculate the discounted net present value of benefits over 50 years at the regional level for two different discount rates (Table 22),. The total benefits are approximately $334 to $504 million dollars.

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[16] http://datainfoplus.stats.govt.nz/Item/nz.govt.stats/25baddf1-766b-423a-8a5a-c8f9de8a1d57?_ga=2.102855424.1471651308.1560686816-1198292133.1559078368

Table 22 Net Present Value ($) of benefits from water clarity changes

Region	NPV 4% Discount Rate	NPV 6% Discount Rate
Auckland	59,383,537	38,547,785
Bay of Plenty	26,668,888	17,769,176
Canterbury	64,641,647	42,702,558
Gisborne	16,495,251	11,114,435
Hawke's Bay	14,294,491	9,631,571
Manawatu Whanganui	1,500,577	1,013,877
Marlborough	4,993,731	3,364,756
Northland	8,679,358	5,799,319
Otago	38,394,968	25,654,508
Southland	2,131,294	1,440,027
Taranaki	2,946,841	1,969,002
Tasman/Nelson	71,147	47,404
Waikato	98,021,287	64,939,465
Wellington	165,770,243	110,763,318
West Coast	156,781	105,930
Total	504,150,041	334,863,130

In calculating these estimates, it should be noted that these are likely underestimates of the true values. We calculate the value people have for changes in water clarity in their region. It is likely that they also have use and non-use values for waterbodies outside of their region. We also assume that the changes to water clarity in urban areas are zero, as this study did not consider urban catchments. Since there are many urban areas downstream from catchments where we have modelled sediment reductions, this is a conservative estimate. Furthermore, we also assume that people only value changes in clarity that switch the waterbody from violating a bottom line to achieving it. It is certainly possible that people value improvements in water clarity that don't push them over the threshold. It is also possible that people value water clarity improvements in catchments that are already achieving their criteria.

6.2 Carbon benefits

The New Zealand Government has declared that taking decisive action on climate change, and hence carbon and related emissions, is a priority.[17] The government has recently

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[17] https://www.mfe.govt.nz/sites/default/files/media/Legislation/Cabinet%20paper/framework-for-climate-change-policy-and-key-upcoming-decisions.pdf

stressed the goal of getting to net zero carbon emissions by 2050.[18] We can capture some of changes in GHGs through NZFARM, as described in section 5.3.2. In order to monetise these changes in carbon, there are several options. The New Zealand government has used multiple carbon prices over the last 20 years, starting with a price of $6(US) per tonne in the years following the signing of the Kyoto Protocol.[19]

The most direct approach is to use the price from the NZ ETS scheme. We use this as our main carbon price, with a value of $25 per tonne to reflect recent carbon price averages. However, there are also several important reasons to deploy alternative carbon prices to reflect a range of different values. For example, the NZ ETS price has fluctuated quite considerably over the last 10 years as the programme changed, as well as due to the global downturn in economic productivity and emissions. Given the government goal of Net Zero Emissions by 2050, the price of carbon is expected to increase over time. Since our analysis projects impacts into the future, it is prudent to attempt to capture some of these increases. Additionally, as there are important sectors, such as agriculture, that are not currently incorporated into the NZ ETS market, the ETS price might not fully reflect the true marginal cost of abatement.

There are several alternative approaches used internationally, with many countries recommending the use of multiple carbon prices. Current UK guidance for policy analysis recommends a low, mid, and high estimate for the carbon price.[20] In the US, a range of prices were developed for the social cost of carbon (SCC), which is both discount rate and year dependent. Those prices were developed through an extensive process with national and international experts on non-market valuation.[21] For our analysis, we use the SCC prices of 2.5%, 3%, and 5% as alternatives to the ETS price. These allow a robust comparison of the potential value of carbon changes. We project these prices across the 50-year timeline. As the SCC prices do not go out to the end of our time horizon, we use a linear trend to predict them beyond the year 2050.

To value carbon, we include both changes in GHG emissions and increases in carbon sequestration (Table 10). As described in the methods section, we assume that there is a lag period as new policies are implemented and environmental impacts manifest. The policy impacts are compared to baseline projections across 50 years. Table 23 contains the results of that analysis, discounted back to the present using a 4% discount rate, while Table 24 uses a 6% discount rate. The 50-year NPV of carbon benefits varies across these tables between a low of 5 billion dollars at the 5% SCC rate and a high of 31 billion dollars at the 2.5% SCC rate. The tables present the values by region to better portray the regional distribution of benefits.

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[18] https://mfe.govt.nz/climate-change/climate-change-and-government/climate-change-programme

[19] https://treasury.govt.nz/publications/information-release/carbon-price-information-releases

[20] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48184/3136-guide-carbon-valuation-methodology.pdf

[21] https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

Table 23 NPV ($) of carbon benefits over 50 years using 4% discount rate

Region	Discounted Net Present Value ($) over 50 years			
	ETS Price	SCC 5%	SCC 3%	SCC 2.5%
Auckland	26,025,336	21,956,034	62,634,451	87,911,174
Bay of Plenty	118,260,527	99,769,400	284,614,309	399,473,097
Canterbury	1,920,463,292	1,620,181,095	4,621,925,385	6,487,146,942
Gisborne	526,200,553	443,924,230	1,266,392,180	1,777,456,682
Hawke's Bay	330,721,116	279,009,811	795,937,277	1,117,145,268
Manawatu-Wanganui	57,632,173	48,620,850	138,701,742	194,676,137
Marlborough	190,580,081	160,781,123	458,663,761	643,761,845
Northland	270,381,155	228,104,561	650,718,777	913,322,473
Otago	3,344,959,183	2,821,943,879	8,050,219,875	11,298,961,989
Southland	738,274,033	622,838,060	1,776,783,502	2,493,821,233
Taranaki	22,526,219	19,004,036	54,213,222	76,091,479
Tasman	4,055,880	3,421,706	9,761,174	13,700,387
Waikato	1,564,043,637	1,319,490,949	3,764,140,153	5,283,194,394
Wellington	258,101,665	217,745,083	621,166,071	871,843,494
West Coast	16,174,210	13,645,223	38,926,019	54,634,981
Total	**9,388,399,062**	**7,920,436,041**	**22,594,797,899**	**31,713,141,576**

Table 24 NPV ($) of carbon benefits over 50 years using 6% discount rate

Regional Council	Discounted Net Present Value Over 50 years			
	ETS Price	SCC 5%	SCC 3%	SCC 2.5%
Auckland Region	17,728,606	14,115,189	40,898,727	57,786,823
Bay of Plenty Region	80,559,738	64,140,176	185,846,012	262,586,427
Canterbury Region	1,308,230,427	1,041,588,912	3,018,001,457	4,264,208,909
Gisborne Region	358,450,785	285,391,897	826,922,359	1,168,379,056
Hawke's Bay Region	225,289,090	179,371,014	519,727,097	734,335,270
Manawatu-Wanganui Region	39,259,361	31,257,579	90,568,762	127,966,844
Marlborough Region	129,824,226	103,363,652	299,495,942	423,165,225
Northland Region	184,185,168	146,644,830	424,903,055	600,356,037
Otago Region	2,278,605,063	1,814,183,280	5,256,591,850	7,427,168,646
Southland Region	502,916,435	400,412,780	1,160,195,103	1,639,268,358
Taranaki Region	15,344,987	12,217,396	35,399,875	50,017,359
Tasman Region	2,762,889	2,199,761	6,373,802	9,005,702
Waikato Region	1,065,435,348	848,279,952	2,457,889,195	3,472,812,440
Wellington Region	175,820,310	139,984,885	405,605,879	573,090,579
West Coast Region	11,017,963	8,772,299	25,417,715	35,913,318
Total	**6,395,430,396**	**5,091,923,600**	**14,753,836,831**	**20,846,060,993**

6.3 Erosion Benefits

Several studies in New Zealand have explored the avoided cost of erosion. Krausse et al. (2001) looked at many of the costs of erosion to calculate a value for the national impact of erosion on New Zealand, of approximately $127 million per year. Dymond et al. (2012) later used their estimates to calculate a per-tonne value for the impact of erosion, at approximately $1 per tonne. The main categories they explored in are provided in Table 25. They were not able to monetise, or even obtain data on, all their categories. They also warn of potential double counting across categories, although they also state that their estimate is conservative in several important assumptions. Jones et al. (2008) review the Krausse et al. (2001) study and provide several important recommendations for moving forward. They emphasize a breakdown of costs between on-site (such as agricultural productivity impacts), and off site (such as landslide damages).

Table 25 Categories of economic impact of erosion used by Krausse et al. (2001)

Soil effects	Sediment Effects
Agricultural Production Loss	Increased Flooding severity
Surface Erosion	Insured Loss
Farm Infrastructure Damage	Production Loss
Direct Private Property Damage	Water Storage
Road and Rail Infrastructure	Navigation
Utility Network Damage	Water Conveyance
Power Lines	Other
Telephone wires	
Recreational Facility damage	
Loss of Visual Amenity	
Other Soil erosion Impacts	
Reduced Water Quality	**Avoidance / Prevention Costs**
Consumption	Regional Council
Processing	Private
Recreation	East Coast Forestry Project
Biological Degradation	Research
	Road preventative

An influential international study on the economic costs of erosion in the US is described in Pimentel (1995). They estimate the annual impact of erosion to be approximately US$3 per tonne (in 1995 dollars), which is significantly higher than the Krausse et al. (2001) estimate. A more recent New Zealand-based estimate can be found in Barry et al. (2014), who focus on flood damage and avoided treatment costs. They use a value of $6.50 per tonne, with $0.90/tonne for flooding damage and $5.60/tonne from avoided water treatment costs.

We look at two alternative values for the avoided cost of erosion and use the lower value as our central estimate to remain conservative. The lower value is from the Dymond et al. (2012) estimate of $1/tonne, updated for inflation. For an alternative value, we use the inflation adjusted midpoint between the Dymond et al. (2012) estimate and the Barry et al. (2014), which is slightly over $3/tonne. This value falls within a plausible range and is discussed or used within two recent papers (Monge et al. 2015; Daigneault et al. 2017).

The $1/tonne value was also chosen because it is unlikely to overlap with the water quality-related benefits also presented in this report. It is important not to double count those benefits, and the $1/tonne is easily representative of several non-water quality-related categories. Barry et al. (2014) estimated the avoided costs of flood damage at $0.90/year alone, and that value is likely to increase with climate change.

Using those two values of the marginal avoided cost of erosion, we calculate the net present value of erosion reductions across 50 years. Those results are contained in Table 26. The first two columns are discounted using a 4% discount rate, while the third and fourth columns use a 6% discount rate. The 50-year discounted net present value of erosion benefits spans a range of $51 million to over $226 million dollars.

Table 26 NPV ($) of erosion reductions across 50 years

Region	**4% Discount Rate**		**6% Discount Rate**	
	Erosion Low	**Erosion Mid**	**Erosion Low**	**Erosion Mid**
Auckland	104,193	312,580	70,977	212,932
Bay of Plenty	887,384	2,662,153	604,491	1,813,474
Canterbury	5,961,205	17,883,615	4,060,806	12,182,419
Gisborne	31,924,770	95,774,311	21,747,334	65,242,001
Hawke's Bay	2,234,977	6,704,932	1,522,479	4,567,437
Manawatu-Wanganui	68,626	205,877	46,748	140,244
Marlborough	402,619	1,207,858	274,267	822,800
Northland	3,217,160	9,651,480	2,191,548	6,574,643
Otago	15,563,763	46,691,288	10,602,123	31,806,369
Southland	2,902,058	8,706,174	1,976,898	5,930,695
Taranaki	55,240	165,719	37,629	112,888
Tasman	65,724	197,172	44,771	134,314
Waikato	5,372,476	16,117,427	3,659,761	10,979,282
Wellington	5,671,838	17,015,514	3,863,688	11,591,064
West Coast	954,568	2,863,705	650,257	1,950,772
Total	**75,386,601**	**226,159,804**	**51,353,778**	**154,061,334**

6.4 Dredging Benefits

To calculate the avoided cost of dredging under sediment load reductions, we obtained a list of the lakes and reservoirs that are associated with hydropower generation. Hicks et al. (2019b) estimated the sediment load entering those waterbodies, as well as the sediment retained by the waterbody after its output into other waterbodies. To calculate the potential reduction in sediment load, we first identify which of these waterbodies are in feasible catchments, as identified by NZFARM outputs. That leaves a total of 20 waterbodies.

We assume that the reduction in sediment load is proportional to the catchment-level average reduction in sediment load. For the waterbodies identified here, this resulted in an average reduction of 2 to 16%. That amount is applied to the amount of sediment retained in each waterbody as a result of the modelling. For the 20 waterbodies identified, the average reduction was 10,000 tonnes.

To value the avoided cost of sediment to hydropower stations, MfE consulted with several industry contacts and obtained dredging costs from several projects. Average costs per tonne were calculated from those data, producing a low and high value from several different projects. The dredging is also not typically done annually: industry figures showed that it was done every 5 years, on average. So, we apply the unit costs to the calculated reduction in loads on a 5-year rotation for 50 years. Note that this assumes that all the sediment that is retained in a waterbody would have to be dredged, similar to US EPA (2009).

The results of the avoided dredging cost analysis are given in Table 27. The table presents the values for the low and high unit costs, as well as at 4% and 6% discount rates. The estimates range from $19 million to $31 million.

Table 27. 50-year NPV ($) of avoided dredging costs

Scenario	NPV
Low cost value, 4%	27,278,612
High cost value, 4%	31,290,175
Low cost value, 6%	19,230,945
High cost value, 6%	22,059,027

6.5 Costs

There are several important differences in opportunity cost between the baseline and the modelled scenario. As modelled in NZFARM, these include the lost profit from switching land uses, the additional establishment costs involved with afforestation, and the costs associated with setting up whole farm plans. The annual costs of these are described above in section 5. The NPV of these costs (across 50 years) is presented in Table 28. Depending on the discount rate used, the NPV of costs is approximately $5–7 billion.

Table 28. Net Present Value ($) of lost profit (50 Years)

Region	4% Discount Rate	6% Discount Rate
Auckland	33,488,477	24,967,733
Bay of Plenty	59,218,069	44,150,737
Canterbury	1,386,486,218	1,033,711,321
Gisborne	176,887,774	131,880,788
Hawke's Bay	192,500,601	143,521,117
Manawatu-Wanganui	99,976,343	74,538,554
Marlborough	111,212,832	82,916,052
Northland	98,670,762	73,565,162
Otago	3,060,230,270	2,281,591,143
Southland	941,174,035	701,703,517
Taranaki	80,858,953	60,285,356
Tasman	2,343,209	1,747,008
Waikato	594,883,630	443,522,579
Wellington	207,687,349	154,843,778
West Coast	52,755,482	39,332,478
Total	**7,098,374,005**	**5,292,277,323**

6.6 National summary

The previous section monetises several benefits and costs. When bringing together all the modelling outputs, it is important to emphasize that we are only able to monetise a proportion of the benefit categories. There are several notable ecosystem services that would improve under the proposed policies, which were not monetised due to data, time, or budget constraints. For instance, increases in afforestation and habitat quality would be expected to improve biodiversity in many areas. A summary of the national effects is given in Table 29.

Table 29. National monetised benefits and costs over 50 years – NPV (in $millions)

	4% Discount Rate	6% Discount Rate
Cost		
Lost Profit, Increased Costs	7,098	5,292
Benefits		
Avoided Cost of Dredging	27–31	19–22
Avoided Cost of Erosion	75–226	51–154
Carbon Benefits	8,000–31,000	5,000–21,000
Water Clarity Benefits	504	334
Not Monetised	*Expected Impact*	
Biodiversity Benefits	Increase	
Nutrient Benefits	Increase	
Water Regulating	Improve	
Coastal and marine water quality impacts	Increase	
Irrigation	Decrease (less water available)	
Habitat	Improve	
Threatened and Endangered Species	Increase	
Non-carbon air quality benefits	Increase	
Avoided illness	Improve	
Commercial and recreational fishing	Increase	
Home price changes	Increase	
Cultural benefits – including sense of place, aesthetics, cultural practices, among others	Increase	
Landslide reductions	Improve	
Water treatment costs	Decrease	

7 Discussion

7.1 Feasibility of proposed sediment bottom lines at catchment scale

The results from the erosion modelling scenarios have shown the proposed catchment sediment bottom lines are broadly feasible across the country through erosion mitigation without requiring extensive land use change (Fig. 4 and Fig. 6). In 53 of the 585 catchments that do not currently meet the proposed sediment bottom lines, maturation of existing Whole Farm Plans (WFPs) is all that is required to meet the proposed catchment sediment bottom lines. The latest these WFPs are expected to mature is 2030, based on the youngest ones being implemented in 2015 and taking 15 years to reach full maturity and erosion reduction effectiveness. This modelling has assumed the existing WFPs include space-planted trees on all mitigatable land, and these trees have been planted at the recommended density to achieve a 70% reduction in erosion (see Assumptions and Limitations section for further discussion). It is worth noting that this analysis also excludes any consideration of the likely impact of climate change in increasing erosion rates and sediment loads. Basher et al. (2018) modelled the effect of erosion mitigation and climate change on sediment loads in the Manawatu-Whanganui region and suggested that the increase in sediment load resulting from climate change impacts on storminess will exceed the effect of erosion mitigation by about the middle of this century. This has significant implications for sediment management policy.

A further 373 catchments are expected to achieve the proposed sediment bottom lines through the implementation of either WFPs, afforestation (Aff), or riparian exclusion (RE) on land suitable for the application of these mitigations. The present analysis has not considered a combination of these mitigations except the combination of afforestation and WFPs in the NZFARM analysis.

The catchments that are unable to meet the proposed sediment bottom lines under the WFP or Aff scenarios are typically smaller coastal catchments in the North Island, or catchments draining the Southern Alps. These catchments generally contain no or minor areas of land considered feasible for implementation of the mitigations considered in this study (both highly erodible and with grassland cover), or the reduction required is relatively high.

There are 42 catchments completely within DOC estate that are considered to be under relatively natural conditions, or in completely urban environments, with no land suitable for implementation of mitigations. Given many of these catchments are under native landcover, sediment loads in these catchments are likely to be natural and it is unrealistic to have reduction targets for these catchments.

7.2 Feasibility of proposed sediment bottom lines at the segment scale

Using the results of the NZFARM optimisation scenario, 20% of stream segments achieve the segment scale sediment bottom lines, considerably lower than the proportion of catchments achieving bottom line. There are two key factors for this disparity of outcomes. First, the catchment sediment reduction bottom lines have been calculated as an average of the reduction required for the stream segments in a catchment, including segments where the required reduction is zero. Given 79% of stream segments within the catchments already meet the proposed bottom lines and require zero reduction in average annual sediment load, the catchment targets are skewed toward a reduction of zero. This means the catchment reduction targets may be lower than the majority of non-zero segment reduction targets. Second, the location of erosion reduction in a catchment influences the number of segments which receive a reduction in sediment load. This is demonstrated in Figure 9. For example, if a mitigation is implemented in a first-order watershed the reduction in erosion will cause a reduction in sediment loads for all segments downstream until the catchment outlet, resulting in a reduction achieved at numerous segments. A mitigation implemented at the outlet segment of the catchment may have an equivalent absolute load reduction, but will only affect the last segment in the network. Under the first scenario, a greater number of segments may meet the sediment bottom line, and a greater average reduction in sediment load achieved.

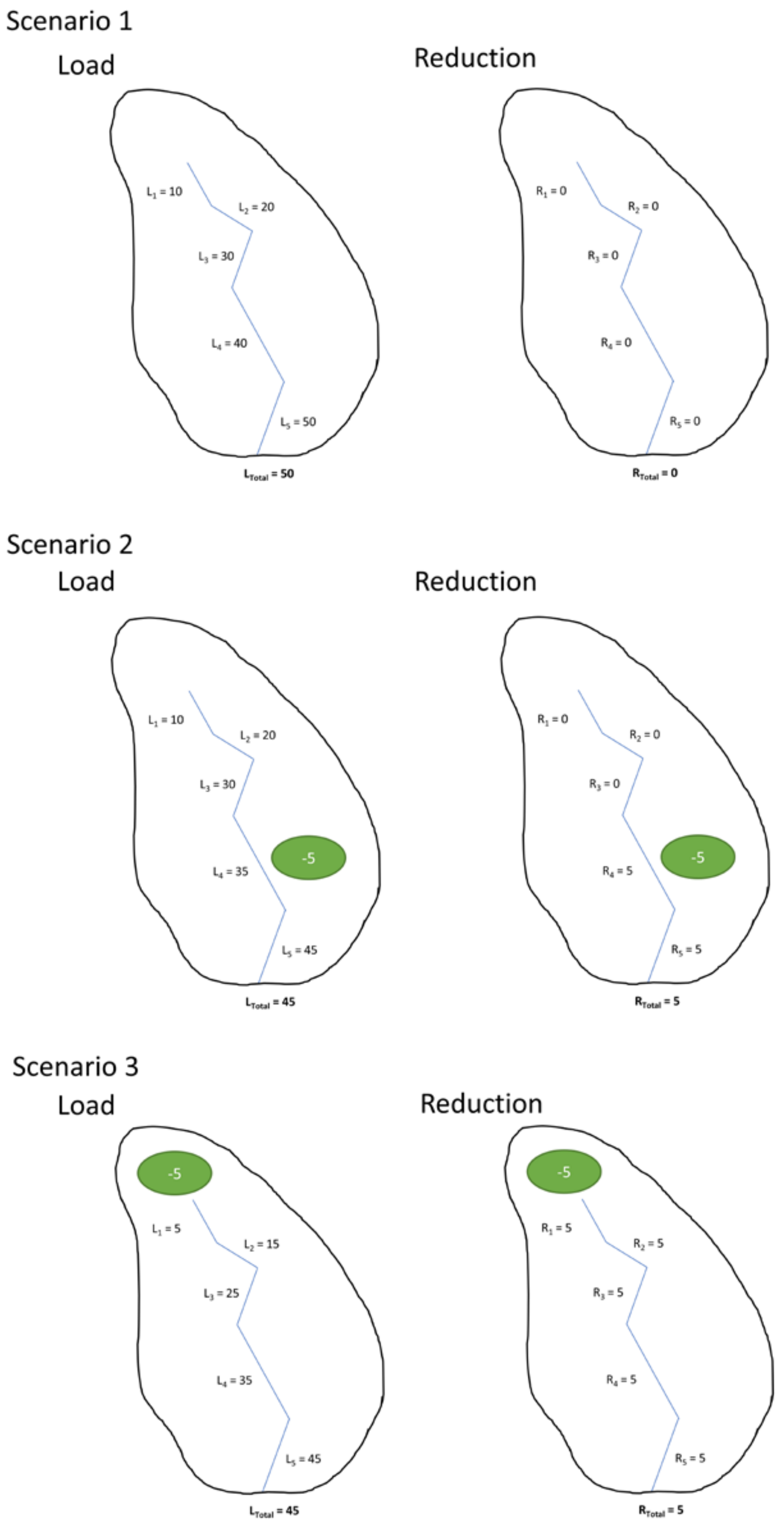

Figure 9. Diagram showing the effect the spatial location of mitigations has on segment-scale sediment attributes within a catchment. Under all scenarios each segment has a local load contribution of 10 t/y, which is propagated down the network and totalled for each segment (L_x) and for the catchment (L_{Total}). Under Scenario 2 and 3 a mitigation is applied (green circle) which reduces load supplied to the local segment by 5 t/y. The load at each segment is then calculated. The right-hand panel shows the reduction in load at each segment (R_x) and at the catchment outlet (R_{Total}) as a result of the mitigation.

Given the achievement of segment load reductions is affected by the location of mitigations in a catchment, the spatial optimisation of mitigations should consider the downstream impact of mitigations when choosing where to apply them. In other words, the optimisation model should consider a weighting factor for each mitigation location based on the number of segments located below the mitigation location, and the reduction required at each of those segments. After a mitigation location is chosen, sediment routing would need to be performed to recalculate segment reductions required, and recalculate the weighting factor. The cost benefit of the mitigations should also consider the benefit of improvements in sediment related attributes for the length of affected stream below a mitigation location. In the present modelling framework these downstream benefits are not included as parameters in the optimisation scenario as the optimisation scenario aimed to achieve catchment bottom lines which are only impacted by the absolute reduction achieved by a mitigation, with the location of that mitigation in the catchment having no impact on the outcome.

7.3 Adoption of mitigations and its economic impacts

We used the sediment load outputs from NZeem® to undertake economic optimisation of sediment mitigation with the NZFARM model. The economic analysis shows that successfully reaching sediment reduction targets requires the adoption of afforestation and WFP mitigations. The adopted areas of mitigation substantially differ across regions, with the afforestation option being most commonly adopted (1.056 million ha). Two reasons for this higher rate of adoption are that afforestation has higher sediment reduction effectiveness (90% reduction) than WFP (70% reduction) and it earns revenues from C sequestration. However, while afforestation can meet the sediment reduction target and generate C sequestration revenues, in many catchments there are some areas where WFP is applied to avoid the opportunity costs of land-use change to afforestation. Also, imposed sediment reduction targets in some catchments are unrealistic to achieve given the current mitigations. All study catchments (i.e. Clutha, Mataura, Ruamahanga, Kaipara, and Waikato) adopt afforestation to meet the sediment reduction targets. The Clutha catchment is the only catchment that fails to meet its target.

Adopting mitigations creates establishment and opportunity costs, with total annual costs projected at $315.7 million for all mitigatable land area in New Zealand. The largest annual costs occur for the West Coast ($182.6 million), followed by Otago ($28.4 million). These regions have large costs because they have high sediment loads and therefore high sediment reduction targets. Moreover, these are substantial costs incurred by farmers who have large areas of eroded land (e.g. pasture farms). These high costs may drive some farmers to change their land use or even shift their employment to non-agricultural work. However, the current erosion levels are modelled by farm areas and do not consider land use types (e.g. differentiating land uses by dairy, sheep and beef). The costs of sediment reduction measures might be lower if the information on sediment loads wa modelled by land use type and took into consideration different management practices (e.g. change in stocking rate).

If we consider C sequestration revenues, then the sediment reduction target scenario is predicted to increase annual profits by $253 million on the mitigatable land area of New

Zealand, assuming a carbon price of $25 per tonne. Otago has the largest C sequestration revenue of $181 million (73% of total C revenue). The large C sequestration revenues are because of the model's assumption that the afforested areas will not be harvested and will continue to sequester C and generate C sequestration payments (see section 4.3). The regions that earn the least C sequestration payments are Tasman and West Coast, because they have small afforestation mitigation areas.

There are several additional environmental benefits from reducing sedimentation. We show that having mitigation options can reduce GHG emissions by 2.5 million tCO_2, nitrogen leaching by 338 tone and phosphorous loss by 65 tonnes, while increasing C sequestration by 19.8 million tCO_2. These environmental outcomes can be considered as additional economic benefits and increase the benefit value of sediment reduction measures.

The study shows high economic and environmental benefits from having sediment reduction measures. Afforestation is established on large mitigatable areas (1.056 million ha) because it can increase profits due to C sequestration revenues, as well as increase environmental services and reduce sedimentation levels. However, afforestation on such large areas might not be possible in a short time frame. Based on historical observations, the largest area of afforestation in a single year was about 90,000 ha (MPI 2018). Institutional support is needed for large scale afforestation, such as credits to farmers to assist with initial planting costs. Additionally, New Zealand currently does not have a sufficient number of nurseries to provide the amount of tree saplings that would be needed for large-scale afforestation. Increasing the number of nurseries will be vital to address the sedimentation reduction objectives. Furthermore, such large-scale afforestation might reduce water yield, which could affect nearby agriculture.

It is important to note here that although the economic optimisation modelling suggests land-use change through afforestation is the most economically feasible way to achieve the proposed sediment bottom lines, the mitigation scenario modelling shows the proposed sediment bottom lines can be achieved in the majority of feasible catchments via changes in land use management practices (WFPs or RE) without the need for extensive land-use change. This is most evident in Figure 6, which shows land use change to afforestation is mostly required in small catchments.

7.4 Assumptions and limitations

Modelling of existing WFP reductions assumes all existing WFPs include space-planted trees on all mitigatable land, and these trees have been planted at the recommended density to achieve a 70% reduction in erosion. Given the data available on existing WFPs consisted of identification of which farm had a WFP and the year of implementation with no detail of the works implemented, we cannot be certain that this is the case. Hawley and Dymond (1988) demonstrated that space-planting does not always achieve a 70% reduction in hillslope erosion due to mortality of trees and/or ineffective tree spacing. We also assume the planting of trees has been completed on all land requiring mitigation in the year of implementation, however it is common for planting to be phased over a number of years. There is therefore some uncertainty around the maturity and effectiveness of existing WFPs in 2015. We also assume these existing farm plans do not contain afforestation on mitigatable land within the farms. It is assumed afforested portions of farms would be mapped as forest cover in LCDB and the sediment yield on these areas would be reduced by NZeem®. If WFP data supplied by regional councils relate to afforestation on farms and not to space-planted trees, it is possible a double reduction has been applied to these areas. It is also possible some space-planting or afforestation has been applied on farms that is not captured in the existing WFP data used in this modelling. If this is the case, baseline loads in catchments where this occurs may be lower than estimated here. This also means the model will apply new mitigation to areas where mitigation already exists, and therefore overestimates what further reductions are achievable from baseline. Furthermore, the 90% effectiveness used in the afforestation scenario does not account for the effect of forest harvesting in elevating erosion rates and reducing its overall effectiveness in reducing erosion.

The reduction in bank erosion by riparian exclusion mitigation has been calculated using spatially implicit data as data were not available to spatially model bank erosion rates at the national scale, and data were not available to locate existing riparian exclusion mitigations. Regional- and catchment-scale parameters have therefore been applied at the segment scale. The reduction in bank erosion achieved by RE was calculated in each catchment and river segment using the assumption that bank erosion was equal to 18% of total load from the watershed, and that riparian exclusion can reduce bank erosion sediment load by 80%, which is not well supported by data (Basher et al. 2016b). However, the 18% is derived from catchment scale estimates using SedNetNZ of the contribution of bank erosion to loads. First, because RE has only been considered to apply in major streams the reduction in bank erosion has only occurred in major streams. Due to the nature of the NZeem® model, the highest erosion rates are likely to occur in steeper catchments which are likely to have lower order streams and be classified as minor streams. Because this modelling has taken the contribution of bank erosion to be 18% in each catchment irrespective of stream order, the model likely represents bank erosion as being high in minor (low order) streams. However, bank erosion rates are typically higher in mid reaches. As a result, the NZeem®-based model used in this report likely under-estimates the bank erosion load coming from major streams, and the reduction in bank erosion calculated at the segment-scale will be less than what would be calculated in a catchment scale model. This analysis was further complicated by the lack of spatial data to detail where riparian exclusion mitigations have already been implemented. Estimates of the extent of existing RE mitigations were derived from regionally aggregated questionnaire survey data. These regional values were then applied equally to all catchments within a region. Proportional reductions from riverbank erosion are therefore linear throughout the catchment. This is likely unrealistic. As a result, the segment scale analysis will not provide a true representation of the effect of bank erosion mitigation.

It is also important to note the spatial optimisation modelling that has been used to assess the reach-scale benefits of hillslope mitigations has been optimised for economic impacts of mitigations to achieve catchment-scale load reduction targets and has not been optimised for reach-scale in-stream benefits. The spatial arrangement of mitigations in the catchment may have a significant impact on the reach-scale sediment attributes, as an equivalent mitigation in the upper reaches of a stream network will impact a greater number of downstream reaches than an equivalent mitigation near the outlet of the catchment. This is demonstrated in Figure 9. As can be seen from this figure, under

Scenarios 2 and 3 the same absolute load and load reduction are achieved at the catchment outlet, but under Scenario 3 a greater number of segments achieve a load reduction. Spatial optimisation of mitigations may look very different if reach-scale reductions were considered. This analysis may be important when considering the net benefit of mitigations for in-stream sediment-related water quality parameters on a per unit stream length basis.

It is also important to note the sediment routing does not consider any storage of sediment, such as through entrapment by dams. In some catchments, such as the Clutha, reach scale distribution of sediment loads may be vastly different to those modelled as a result of dams.

There are also several areas where the economic analysis might be improved. A longer-term research programme could use original studies to generate benefit estimates. For example, an original stated preference study could be created to directly estimate the water quality benefits associated with the sediment reductions modelled here (instead of benefits transfer). There are also several other benefit categories that might be captured, such as biodiversity and habitat benefits, as well as the benefits to threatened and endangered species.

As recommended by Treasury, we use discount rates of 4% and 6% to calculate NPV. However, these rates are fairly high for discounting environmental benefits, as noted in the Social Cost of Carbon literature discussed above. These higher discount rates will reduce the value of longer-term benefits, such as carbon sequestration, and increase the (relative) value of shorter-term costs. There have been several notable calls to use lower discount rates for long term environmental values (Weitzman 1994).

This study considers several alternate estimates of the value of carbon to cover a range of different prices. However, there are currently several policy goals committed to by the New Zealand government that might push carbon prices even higher. For instance, there are current targets negotiated under international treaties that include a 50% reduction in Carbon by 2050.[22] The New Zealand government has also announced an aspirational goal of carbon neutrality by 2050. The carbon benefits in this study may therefore be underestimates. Higher carbon prices could also provide increased incentives for afforestation.

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[22] Current emissions targets can be found at: https://www.mfe.govt.nz/climate-change/climate-change-and-government/emissions-reduction-targets/about-our-emissions

8 Conclusions

- Catchment bottom lines are achievable in 70% of catchments (81% by area). Of catchments, 9% will meet bottom lines through the maturing of existing mitigations.
- Most of these catchments (11 million hectares) can meet bottom lines through land use management changes (WFPs or RE). Only 14 (2%) catchments required land use change (Aff).
- The catchments that do not meet bottom lines under any mitigation scenario tend to be small coastal catchments with no mitigatable land in the North Island, or catchments draining the Southern Alps, with naturally high sediment yields and relatively natural land cover with little available mitigatable land.
- After implementation of the NZFARM optimisation and maturing of existing Whole Farm Plans it is predicted sediment bottom lines will be achieved in 20% of the 77,561 segments which do not currently meet the proposed sediment bottom lines in the modelled catchments.
- Our estimates suggest that sediment reductions that use afforestation and whole farm plans as drivers could yield greater benefits than costs, especially considering non-monetised benefits and cultural values.
- In the modelled scenarios, the range of monetised benefits exceeds monetised costs. These calculations also omit several important environmental benefit categories, suggesting that the benefits could be even higher.
- The bulk of the benefits were from increases in carbon sequestration, although erosion and water quality benefits were also notable.

9 Recommendations

- We suggest the spatial optimisation of mitigations should consider the downstream impact of the mitigation and select mitigation locations based on a weighting of downstream impact. This could be achieved within the LUMASS framework or NZFARM. This could lead to better achievement of segment-scale bottom lines. while also achieving catchment bottom lines. This would require some consideration of how to best weight the downstream impact of mitigations, and would also require sediment routing to be run in a model following each individual mitigation being applied within the model to assess the segment-scale reduction achieved by each mitigation, and recalculate what further reductions are required. This was not achievable within the scope of this project.
- The Riparian Exclusion modelling components could be improved to include spatial optimisation of RE through national-scale modelling of bank erosion rates. Smith et al. (2019) recently published a revised bank erosion model for New Zealand designed to use inputs available at the national scale. At the time of writing this report, the data required to run such a model were not readily available, but they may become available in the near future.
- The economic optimisation modelling could be improved by considering different land use types (e.g. dairy, sheep and beef, horticulture), management practices (e.g.

stocking rates) and their respective impacts on sediment loads. This would allow the effects of sediment reduction targets to be captured on specific land use types. Also, this would allow assessment of the effect of changes in land use and management practices in reducing the sediment loads. However, to conduct such modelling requires extensive data on sediment loads by land use types and management practices, which are currently not available.

- The benefit cost analysis could be improved in several important ways. First, a thin local literature of studies from which to transfer values suggests a need for additional environmental valuation studies in New Zealand. There is also a need for studies that are better linked to policy levers. For instance, although there are several valuation studies on biodiversity, they are difficult to link to the modelled changes considered here. Finally, since carbon benefits comprise such a large share of the estimated benefits, it would be good to have New Zealand-specific social cost of carbon estimates to transfer from.
- More New Zealand environmental valuation studies are needed to improve the monetisation of ecosystem services, as well as capture other benefit categories that are difficult to monetise.

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Appendix 1 - Detailed description of the erosion modelling methodology

A1.1 Erosion modelling

To identify the potential impact of ESC mitigations on meeting the proposed sediment attribute bottom lines in each catchment, average annual suspended sediment load prior to and after ESC mitigation is estimated for each catchment. Average annual suspended sediment loads for a catchment were assumed to be equivalent to the average annual erosion of fine sediment within the catchment. An erosion model can therefore be used to estimate average annual suspended sediment loads. Erosion rates exhibit large spatial variation in New Zealand, primarily driven by factors such as rainfall, rock type, slope, and land cover (Basher 2013). Basher et al (2019) recommended using the New Zealand empirical erosion model (NZeem®) to estimate erosion rates and incorporate the effect of land cover changes and erosion mitigation. NZeem® is fully described in Dymond et al. (2010). NZeem® models erosion rates on a 15-m grid as:

$$E = aCR^b \tag{15}$$

where E is the erosion rate (t km^{-2} year^{-1}), R is mean annual rainfall (mm year^{-1}), C is the land cover factor (1 for woody vegetation, 10 for non-woody vegetation), a is an erosion terrain coefficient, and b = 2.

NZeem® was used to estimate erosion for the North and South Islands of New Zealand prior to and after application of ESC mitigations which were bundled into three classes to simplify the analysis (Whole Farm Plans, Afforestation and Riparian Exclusion). These ESC mitigations and their effectiveness are fully described in Basher et al. (2016a, b, 2019). The bundles of mitigations are referred to as mitigation scenarios. Modelling of the effects of WFPs and Aff used spatial data on the current location of these mitigations and mitigatable land for future implementation of these mitigations (defined as Highly Erodible Land, Land Use Capability class 8e, 7e, and 6e under grassland). For RE, spatial data on the location of existing RE are only available at the regional scale as estimates of the proportion of major streams where RE has been implemented. The regional estimates were therefore used to make assumptions about the extent of existing RE within catchments and segments when calculating baseline loads, and to estimate the reductions achievable through implementation of further RE on major streams.

The results from NZeem® were used to estimate the reduction in average annual suspended sediment load achieved by each mitigation scenario, and identify whether the proposed sediment attribute bottom lines were achievable for each catchment and its stream segments. This first required baseline suspended sediment loads to be calculated at the catchment and segment scales so NZeem®-based load reduction targets could be calculated to achieve the bottom lines. The reduction in load from baseline could then be calculated for each mitigation scenario to identify which mitigation scenario was capable of achieving target load reductions in each catchment and stream segment.

NZeem® does not distinguish the processes contributing to erosion. NZeem® data were therefore partitioned into hillslope erosion (affected by WFPs and Aff) and bank erosion (affected by RE) components. To determine the proportional contribution of hillslope erosion and riverbank erosion, we used the sediment budget model SedNetNZ (see Dymond et al. 2016) which does account for contributing erosion processes. It is available for several regions of New Zealand (Hawke's Bay, Waikato, Northland, Manawatu-Whanganui) and was used to estimate the average contribution of bank and hillslope erosion to sediment budgets. The results showed that the average contribution of bank erosion across these regions amounted to 18%; with 82% from hillslope erosion processes. These proportions were used to partition NZeem®-based loads into hillslope and bank erosion components.

A1.2 Calculating baseline average annual suspended sediment load for catchments

Contemporary sediment loads are considered the baseline for calculating the possible future impact of ESC mitigations. To estimate baseline loads NZeem® was therefore run with the most recently available inputs for landcover and extent of implemented mitigation works.

The New Zealand Land Cover Database (LCDB) v4.0 was used as input for the land cover factor, C, providing national coverage of vegetation at 2012. Calculation of the baseline sediment load also requires the effectiveness of existing ESC mitigations in the catchments to be accounted for. NZeem® was parameterised to incorporate existing ESC mitigations as at 2015, which is the period ESC data were available for. The ESC mitigations for which spatially explicit data were available were WFPs and afforestation (described in Monaghan et al., submitted).

Afforestation is considered to be represented within the LCDB, and the reduction in erosion from afforestation is therefore accounted for in the landcover component of NZeem®. Monaghan et al. (submitted) collated spatial information from regional councils detailing which farms had implemented WFPs and the date (year/decade) the WFP was implemented. It was assumed that where WFP mitigations have been recorded all planned space-planting has been completed (i.e. poles established on all identified erosion prone land requiring space-planting). All farm plans with mitigations 15 years or older (implemented before 2000) were deemed to be fully mature and to reduce erosion by 70%, following Dymond et al. (2016). A linear relationship for the degree of maturity was applied for WFP mitigations younger than 15 years based on Dymond et al. (2016), where the maturity factor in 2015 is calculated as:

$$M_{f2015} = \frac{2015 - Y}{15} \tag{16}$$

where M_{f2015} is the maturity factor of the WFP in 2015, and Y is the year WFP mitigations were fully implemented.

To calculate the reduction in erosion achieved by existing WFPs, the hillslope erosion component of NZeem® within the farm boundary where a WFP existed was reduced by 70% for mature WFP works. Where WFP works were immature, the 70% effectiveness was reduced in proportion to the maturity factor. The reduction in sediment yield from farms with existing WFPs was therefore calculated as:

$$R_{WFP2015} = NZeem\ x\ 0.82\ x\ 0.7\ x\ M_{f2015} \tag{17}$$

where $R_{WFP2015}$ is the sediment yield reduction for a farm with an existing WFP in 2015, *NZeem* is the sediment yield estimated for the hillslope component of the farm using Equation 15, 0.82 represents the proportion of sediment yield derived from hillslopes (Monaghan et al., submitted), 0.7 is the effectiveness factor, and M_{f2015} is the maturity factor.

While spatially explicit data were not available for the location of existing riparian exclusion mitigation, spatially generalised data on riparian exclusion were reported by Monaghan et al. (submitted), based on data from the Survey of Rural Decision Makers[23] (SRDM). The data reported by Monaghan et al. (submitted) were from the SRDM 2015 so were used in this analysis for consistency with the WFP and LCDB data sets. The data are reported at the regional scale, and a summary is reproduced in 0. This regional estimate has been taken as an estimate for the extent of RE at the catchment and segment scale.

NZeem® was parameterised to incorporate the impact of existing riparian exclusion on suspended sediment loads using the estimates of existing riparian exclusion from Monaghan et al. (submitted). Riparian exclusion is estimated to reduce bank erosion by 80% when fully implemented (Dymond et al. 2016). The proportion of the suspended sediment load contributed from bank erosion was calculated for each major stream segment in the REC2 network,[24] calculated as 18% of the load from the segment water shed, following Monaghan et al. (submitted). The 80% effectiveness was reduced proportional to the estimated extent of existing riparian exclusion, which for each segment watershed (i.e. the local catchment for a stream segment) was taken to be equivalent to the regional estimate for the region the watershed belongs to. The reduction in sediment yield achieved by existing RE in each major stream water shed was therefore calculated as:

$$R_{RE2015} = NZeem * 0.18 * 0.8 * RE2015 \tag{18}$$

where R_{RE2015} is the sediment yield reduction achieved by existing riparian exclusion, 0.18 represents the proportion of local load attributed to bank erosion (Monaghan et al., submitted), 0.8 is the effectiveness factor (Dymond et al. 2016), and *RE2015* is the regional estimate of existing riparian exclusion as reported by Monaghan et al. (submitted).

Baseline sediment yield (*NZeemB*) was calculated as the yield from NZeem® minus the reduction achieved by existing WFPs and RE, giving:

$$NZeemB = NZeem - R_{WFP2015} - R_{RE2015} \tag{19}$$

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[23] The Survey of Rural Decision Makers is a regular survey conducted by MWLR. More information is available at https://www.landcareresearch.co.nz/science/portfolios/enhancing-policy-effectiveness/srdm. An overview of the data from the SRDM 2015 is available at https://www.landcareresearch.co.nz/science/portfolios/enhancing-policy-effectiveness/srdm/srdm2015

[24] The spatial layer used to define major streams was supplied by NIWA and is described in Semadeni-Davies & Elliott (2016).

Baseline sediment loads were calculated for each catchment by taking the average yield of the catchment from *NZeemB* and multiplying by the catchment area using Equation 3:

$$SL_j = \frac{1}{n}\sum_{i=1}^{n} NZeemB_i \ x \ A_j \tag{20}$$

where SL_j is the sediment load (t y^{-1}) of the *j*th catchment, $NZeemB_i$ is the yield at the i^{th} grid cell from the baseline NZeem® layer, *n* is the number of grid cells in the *NZeemB* layer within the catchment, and *A* is the area (km^2) of the catchment.

A1.3 Calculating average annual sediment load reduction targets

Hicks et al. (2019a) calculated the reduction in suspended sediment load required at a stream segment for the segment to achieve the proposed sediment attribute bottom lines. These targets were provided to MWLR as a proportional reduction in suspended sediment load for each stream segment (*Rmax*), and as the average of the segment reductions required within each catchment (*ave_R*). For the purposes of this analysis MfE defined the target sediment load reduction for a catchment as the average reduction required for the stream segments within the catchment (i.e. the *ave_R* value calculated by Hicks et al. 2019a). Values of *ave_R* ranged from <1% to c.67% with a little over half of the catchments requiring a sediment load reduction of less than 50%. The value of *ave_R* was therefore used to define the catchment average sediment load reduction target (t) for each catchment, hereafter referred to as the *catchment average target*.

Absolute catchment average targets were therefore calculated by multiplying the baseline load calculated from NZeem® by the catchment average reduction target for each catchment. The absolute catchment average target is therefore calculated as:

$$SL_{RTj} = SL_j \ x \ ave\_R_j \tag{21}$$

where SL_{RT} is the target absolute reduction in sediment load (t), and *ave_R* is the proportional reduction in sediment load target, for the j^{th} catchment.

A1.4 Calculating potential sediment load reductions achievable through implementation of mitigation scenarios

In order to identify catchments where the required sediment load reduction targets cannot be met it is necessary to first calculate the reduction in sediment load from baseline achieved by maturation of existing WFPs, and then apply mitigation scenarios to all remaining mitigatable land within each catchment to calculate the maximum achievable load reduction under each mitigation scenario.

A1.4.1 Calculating sediment load reduction achieved after existing WFPs mature

To calculate the yield reduction achieved by existing WFPs once they all fully mature, Equation 16 was used with the maturity factor set as 1. This can be reworked as:

$$R_{WFPM} = NZeem \ x \ 0.82 \ x \ 0.7 \tag{22}$$

where R_{WFPM} is the reduction in load achieved by mature WFPs.

The sediment yield for catchments after existing whole farm plans mature is calculated as:

$$NZeemM = NZeem - R_{WFPM} - R_{RE2015} \tag{23}$$

where *NZeemM* is the NZeem®-estimated sediment load after maturation of existing WFPs. The sediment load in each catchment after maturation of existing WFPs can then be calculated by adapting Equation 3 to multiply the average sediment yield in a catchment derived from *NZeemM* by the area of the catchment, giving:

$$SL_{WFPMj} = \frac{1}{n}\sum_{i=1}^{n} NZeemM_i \ x \ A_j \tag{24}$$

where SL_{WFPMj} is the average annual sediment load of the j^{th} catchment after existing WFPs mature, n is the number of grid cells in the *NZeemM* layer within the catchment. The reduction achieved within each catchment after WFPs mature was then calculated as:

$$\Delta SL_{WFPM} = SL_j - SL_{WFPMj} \tag{25}$$

where ΔSL_{WFPM} is the change in average annual sediment load for the catchment after existing WFPs mature. Where ΔSL_{WFPM} is greater than SL_{RT} the reduction target has been met for the catchment and no further mitigations need to be implemented. These catchments were then removed from further analysis. Where ΔSL_{WFPM} is less than SL_{RT} the catchment average target has not been met and further mitigations need to be implemented.

A1.4.2 Calculating remaining reduction target after maturation of existing WFPs

Where ΔSL_{WFPM} is less than SL_{RT} the remaining reduction required to meet target is calculated as:

$$rSL_{RT} = SL_{RT} - \Delta SL_{WFPM} \tag{26}$$

where rSL_{RT} is the remaining sediment load reduction target for the catchment after existing WFPs mature. This value is used in the optimisation model NZFARM, which is described in subsequent sections.

A1.4.3 Calculating reductions achievable by implementation of further ESC mitigations

In order to identify where catchment targets are not able to be met through modelled mitigations (hereafter referred to as infeasible catchments c.f. feasible catchments where catchment targets can be met) three scenarios were considered which sought to identify total achievable reduction under application of the three different catchment-wide ESC mitigations: WFPs, Aff, and RE. WFPs and Aff were considered to be implementable on erodible pasture with no existing WFPs. Erodible land was defined as land classified as Highly Erodible Land (Dymond & Shepherd 2006) or belonging to Land Use Capability

(LUC) classes 8e, 7e, and 6e (Lynn et al. 2009) and represents steep, erosion prone land. WFPs and Aff were considered to only be implementable on high-producing grassland, low-producing grassland, and depleted grassland, as defined by the New Zealand Land Cover Database (LCDB) version 4.0. RE was applied to all major streams (see Monaghan et al., submitted).

An NZeem® layer was prepared which reduced erosion on all remaining mitigatable land with no existing mitigation. The mitigation options and their effectiveness are summarised in Table 30. The reduction was calculated for each catchment considering implementation of either WFPs, Aff, or RE.

Table 30 Sediment reduction percentages used for ESC mitigation effectiveness

Mitigation	Sediment reduction (%)	References
Afforestation*	90	Phillips et al. (1990), Hicks (1992), Fransen & Brownlie (1995), Marden & Rowan (1993)
Whole Farm Plans	70	Hawley & Dymond (1988), Hicks (1992), Thompson & Luckman (1993), Douglas et al. (2009, 2013), McIvor et al. (2015)
Riparian exclusion	80	McKergow et al. (2007, 2016), Hughes (2015), Dymond et al. (2016)

* Does not incorporate the effect of forest harvesting

Sediment yield reduction after implementation of WFPs or Aff on all mitigatable land in a catchment were calculated as:

$$RFI_{WFP} = NZeem * 0.82 * 0.7 \tag{27}$$

$$RFI_{Aff} = NZeem * 0.82 * 0.9 \tag{28}$$

where RFI_{WFP} *and* RFI_{Aff} are the reduction achieved after full implementation of either WFPs or Aff, respectively.

The suspended sediment load of catchments after implementation of WFPs or Aff was calculated using Equations 29 and 30, respectively, where $SLFI_{WFP}$ and $SLFI_{Aff}$ are the sediment load after full implementation of WFPs or Aff respectively.

$$SLFI_{WFP} = \frac{1}{n}\sum_{i=1}^{n}(NZeemM - RFI_{WFP})_i \ x\ A_j \tag{29}$$

$$SLFI_{Aff} = \frac{1}{n}\sum_{i=1}^{n}\left(NZeemM - RFI_{Aff}\right)_i \ x\ A_j \tag{30}$$

To calculate the reduction in sediment yield achievable through complete implementation of RE on remaining major streams, Equation 18 was reworked to calculate the reduction achieved by 100% implementation of RE, giving:

$$RFI_{RE} = NZeem * 0.18 * 0.8 \tag{31}$$

where RFI_{RE} is the reduction achieved by full implementation of RE. Equation 31 is applied to NZeem in all major stream watersheds.

The sediment load of the catchment after RE implementation ($SLFI_{RE}$) is therefore calculated as:

$$SLFI_{RE} = \frac{1}{n}\sum_{i=1}^{n}(NZeem - R_{WFPM} - RFI_{RE})_i \ x \ A_j \tag{32}$$

The absolute reduction in sediment load from baseline achieved by implementation of each ESC mitigation scenario (SL_{RFI}) is then calculated for each catchment using Equations 33–35, where ΔSL_{FIWFP}, ΔSL_{FIAff}, and ΔSL_{FIRE} represent the change in sediment load from baseline for the full implementation of WFPs, Aff, and RE, respectively.

$$\Delta SL_{FIWFP} = SL_j - SLFI_{WFP} \tag{33}$$

$$\Delta SL_{FIAff} = SL_j - SLFI_{Aff} \tag{34}$$

$$\Delta SL_{FIRE} = SL_j - SLFI_{RE} \tag{35}$$

Appendix 2 - Catchments removed from analysis due to being completely DOC and/or urban landcover

Pour_point ID
1000282
1031894
1031906
1031965
1031981
2028954
2042326
4068164
4079971
5140104
9260854
9264709
11020183
12068821
12101934
12103536
12117729
12119805
12120386
12123766
12146190

Pour_point ID
12147537
12150353
12156082
12157084
15000880
15001249
15001473
15003764
15180108
15181563
15186737
15206424
15289091
15296505
15298830
15301389
15301549
15310290
15311390
15311693
15316420

Appendix 3 - Catchments which will meet target after maturation of existing Whole Farm Plans

Pour_point ID	River Name	Load reduction required (%)	Area (ha)
3035967	Otama River	2.4	534
3036196	Stewart Stream	1.8	268
3036239	Pitoone Stream	2.4	386
3038474	Purangi River	27.8	680
3042969	Boom Stream	18.3	1234
3044900	Dam Stream	4.3	452
3045549	Otuwheti Stream	8.8	276
3045550	Otuwheti Stream	10.2	62
3045720	Otuwheti Stream	7.2	463
3047651		10.7	486
3056089	Waikorea Stream	14.8	901
3063956	Waitetuna River	4.7	15910
3072777	Te Maari Stream	6.7	2692
3087905	Te Toi Stream	13.5	1184
3088380		8.9	4340
3091228		14.0	518
3122137	Waioroko Stream	7.1	1174
3124069		0.7	834
3131716	Awakino River	4.8	26010
4056467	Te Mania Stream	6.4	1001
4059778	Wairoa River	4.7	45735
4061221	Raukokore River	2.4	35496
4061594	Waimapu Stream	6.5	10634
4062716	Whangaparaoa River	7.7	995
4063161	Kaituna River	7.4	120339
4064766	Pongakawa Stream	2.8	13645
4072216	Tarawera River	5.7	82589
4081057	Rangitaiki River	0.5	290432
5064147	Kopuapounamu River	2.8	5228
6161949	Mangahewa Stream	9.3	1291
6164584	Waitara River	0.4	80836
6196567		14.2	324
6213598	Whenuakura River	0.2	43879
6214346	Patea River	0.9	104842
6215677	Moumahaki Stream	0.1	24468

Pour_point ID	River Name	Load reduction required (%)	Area (ha)
6218194		1.5	702
7219672	Okehu Stream	2.0	6108
7220758	Kai Iwi Stream	0.6	18985
7224208	Whanganui River	1.8	713071
7227612	Whangaehu River	2.6	199028
7228747	Turakina River	1.5	95376
7236544	Rangitikei River	2.0	391669
7241844	Manawatu River	7.0	583457
7243867	Akitio River	4.1	40311
7247269	Owahanga River	4.7	31673
7248786	Owahanga River	3.8	9065
8174783	Mohaka River	0.5	242843
9258963	Kakaho Stream	17.1	1104
9259582	Horokiwi Stream	2.8	3179
9267154		2.3	11
9267189	Pahaoa River	3.1	64865
9267229		2.4	482
9267301	Pahaoa River	3.1	86

Appendix 4 - Summary of existing regional riparian exclusion data

Regional estimates of the proportion of major streams with existing riparian exclusion in 2015 are based on the Survey of Rural Decision Makers as reported by Monaghan et al. (submitted). These values are calculated as the proportion of survey respondents who reported fencing large streams multiplied by the proportion of large streams those respondents reported fencing. For example, in Wellington 75% of respondents reported they had fenced large streams. Of those 75%, respondents estimated on average 68.8% of their large streams had been fenced. These values are multiplied together (0.75 * 0.688) giving 51.6%.

Region	Estimated proportion of major streams with existing stock exclusion (%)
Auckland	64.2
Bay of Plenty	83.3
Canterbury	62.2
Gisborne	28.7
Hawke's Bay	45.1
Manawatu-Wanganui	62.2
Marlborough	33.5
Northland	71.4
Otago	47.5
Southland	75.9
Taranaki	77.3
Tasman/Nelson	59.0
Waikato	79.8
Wellington	51.6
West Coast	64.6

Appendix 5 - NZFARM model description, data sources and caveats

The NZFARM model estimates the costs of erosion reduction policy and mitigation measures. We use a linear programming analysis and restrict the analysis to analyse the adoption rate of erosion reduction mitigations. Hence, the model optimises the adoption levels of mitigation options at farms to have the optimum (maximum) economic returns under erosion reduction target scenario (for description of scenarios see below Scenarios subsection). NZFARM facilitates a 'what if' scenario analysis by showing how changes in environmental policy could affect the uptake of mitigation practices. NZFARM facilitates analysis of a baseline and an erosion target scenario by showing how erosion targets introduced for each catchment affect the adoption of mitigations and costs of achieving that reduction.

Data sources

At national scale, we use sediment data derived from NZeem® for which a coverage is available using land cover in 2012 from the Land Cover Database version 4 and incorporates erosion mitigation implemented to 2015. This can be used to represent current rates of erosion and a basis on which to model the mitigation scenarios available to reduce sediment load to meet the proposed erosion standards. The data on erosion are utilised from the NZeem® model, which is available for all New Zealand and incorporates erosion mitigation implemented to 2015.

The data required to parameterise each farm include financial and budget data (e.g. inputs, costs, and prices), the relevant environmental information (e.g. nutrients leached), and the observed baseline farmland area. Financial data, obtained primarily from the literature, MPI, and industry (Newsome et al. 2008; MPI 2013a, b; Lincoln University Budget Manual 2013; Daigneault et al. 2018), have been verified with agricultural consultants and enterprise experts. Nutrient losses for pastoral enterprises are estimated using the OVERSEERv6 nutrient budgeting tool, while estimates for other enterprises are derived from industry and literature (e.g. Parfitt et al. 1997; Lilburne et al. 2010). GHG emissions are derived using national GHG inventory methodologies (MfE 2017). The baseline farmland area (the recent version of AgriBase) was obtained from MfE.

Assumptions and caveats

This NZFARM model version does not consider land-use change (e.g. shift of sheep and beef farm to dairy). In this approach, not modelling any land-use change allows direct capture of the costs of erosion reduction scenario and of mitigation options, because sediment reduction options and scenarios lead to lower economic returns for farmers. In contrast, modelling land-use changes might lead to the same level or even increase of economic returns from the baseline, where the model will optimise land use allocation for achieving the optimal (maximum) economic returns by replacing the less profitable land uses with the more profitable ones.

The model is linear and assumes constant returns to scale, where the relationship between production and costs, input and output, and production and revenue are linear. These points might lead to drastic shifts in the model results, which might result in drastic change (i.e. adoption area) in mitigation options with the implementation of erosion reduction scenarios. The limitations of linear programming model are not essential elements of the linear version of NZFARM, because the model does not use production functions and mainly addresses the adoption of mitigation options under scenario simulations. In addition, previous application of linear version of NZFARM provided intuitive results and have been widely used for different case studies (e.g. Daigneault et al. 2017; Djanibekov et al. 2018).

Appendix 6 - NZFARM model results by catchments

In this appendix are given NZFARM sediment reduction target scenario results for all catchments. As we do not have all the names of catchments, we present in catchment IDs.

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
3050215	130443	82641	0	17671643	51760022	873295	905012	2070401	5526060	228507
3054043	24	3	0	796	1868	44	139	75	566	28
3054716	806	1329	0	304123	781010	3571	4267	31240	37301	1766
3060683	3390	416	0	74351	267106	27743	17156	10684	66465	3356
3064446	188	277	0	53487	162998	339	1041	6520	8511	380
3064802	357	1024	0	216783	606359	5063	2114	24254	27722	1235
3066004	296	903	84	186982	537674	832	2393	21507	30665	1230
3069797	144	121	0	24530	70962	195	768	2838	5054	244
3071688	23	13	0	2304	7772	54	111	311	643	31
3071689	775	350	0	59819	209174	9435	3835	8367	17412	864
3072105	603	1266	0	242967	749577	1527	3349	29983	34755	1601
3079638	3362	1757	0	315454	1012632	18798	17508	40505	90497	4437
3081497	672	914	0	162486	542986	8066	3834	21719	30999	1364
3087099	29	173	0	35001	103644	111	116	4146	2312	107
3090508	810	185	0	30813	131455	8456	3734	5258	14258	720
3090800	403	80	0	13350	56258	5331	1761	2250	7597	379
3091513	64	10	0	1797	5790	432	298	232	1210	61

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
3091772	527	74	0	12659	45183	5917	2603	1807	10629	533
3099618	45	16	0	2780	9998	533	203	400	959	47
3099716	7574	3736	0	709610	2438322	242629	37061	97533	198822	9660
3102065	232	23	0	4642	14418	3230	815	577	3207	161
3104655	5	4	0	612	2400	32	23	96	138	7
3119069	197	24	0	4847	14843	1722	990	594	3977	200
3119391	115	61	0	10788	38162	325	604	1526	3285	161
3134317	13	44	0	10125	27626	46	69	1105	1051	49
3134917	24192	16082	0	3711987	10056912	1398752	127397	402276	780987	36665
4052333	0	13	251	19723	9446	138	0	378	8833	271
4052810	209	60	0	18196	44656	526	1358	1786	7495	293
4054343	73	10	13	2316	6662	207	304	266	2261	138
4055167	173	17	0	3034	12016	499	919	481	4033	185
4055353	176	24	0	5082	16937	629	1458	677	6769	267
4056732	185	46	0	9903	31864	493	1159	1275	4896	242
4058836	66	88	0	28297	53753	153	536	2150	4061	161
4059081	51	58	0	9994	35286	103	329	1411	1838	84
4059480	25	74	0	23522	47165	45	65	1887	1630	72
4059555	438	88	0	15500	54748	1153	2426	2190	11647	518
4060408	501	319	0	75094	226295	1645	2449	9052	13579	611
4060662	119	82	0	21186	50159	291	827	2006	4443	191

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
4061698	286	60	0	10992	37116	680	1253	1485	5526	284
4063118	31	31	0	5165	16144	13972	71	646	506	24
4064693	1896	414	0	119490	321227	6189	12724	12849	57935	2547
4064694	1003	302	0	115406	227463	3593	8863	9099	46082	1745
4067117	46	6	0	2571	3382	62	411	135	1995	73
4068385	92	4	56	2830	2509	145	159	100	3330	73
4072097	10374	3980	0	694763	2501815	913840	31399	100073	173664	8597
4076811	6143	1516	0	412624	1082009	17079	42223	43280	219317	8582
4080360	249	140	91	40555	92769	649	1825	3711	14658	544
4080597	409	164	0	40003	101869	705	2659	4075	16365	650
4080785	6763	1312	0	236460	680852	107005	21414	27234	101480	4765
4087166	747	42	0	7306	28955	12788	1857	1158	7068	356
5058192	125	96	0	16033	56045	271	522	2242	2833	139
5070075	17034	15684	0	2649994	9430609	7038593	48566	377224	387428	18469
5101975	4	50	0	8412	32355	3953	17	1294	800	36
5102064	66	52	0	15234	29620	2201	255	1185	1492	73
5116306	287	237	0	39535	119464	10577	1197	4779	7823	378
5119443	161	150	0	25049	90813	859	611	3633	4273	205
5121296	126	204	0	33984	110405	1400	433	4416	4257	201
5124226	105	87	0	14473	47641	512	358	1906	2591	125
5142593	69854	28104	0	5004805	16408209	2840574	277892	656328	1418325	69574

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
5143320	2	4	0	715	2333	1	3	93	36	2
5151840	325	1	0	225	838	3954	1134	34	4151	211
6151572	127	9	0	1542	5849	8299	947	234	5829	165
6174327	124	1	0	420	1021	646	1127	41	6006	166
6202913	311	97	372	48785	66485	595	3224	2659	37414	936
6203051	12	8	35	1907	5754	26	115	230	2510	59
6205170	82	108	209	40667	78984	246	709	3159	17086	446
6211525	13	0	91	1745	287	24	92	11	4795	109
6212160	0	215	12	885721	156063	20	0	6243	10959	263
6219036	22	157	0	35983	109114	67	75	4365	2357	105
7225218	77	325	0	74899	186393	32	397	7456	4865	227
7226486	56	46	0	7744	26580	15	135	1063	791	38
7228512	77	4	0	690	2338	19	202	94	1624	45
7230250	180	651	0	171277	324459	78	1057	12978	13639	576
7236600	0	0	5	1153	268	0	0	11	239	5
7247116	666	478	0	106454	279831	2536	3126	11193	22667	782
7247992	296	329	32	85740	187536	635	1989	7501	16762	563
8162240	1310	160	0	34608	110297	469995	2609	4412	10645	535
8170225	117046	10499	0	1907397	6492522	3246783	437340	259701	1740627	87531
8170924	4	1	0	200	695	27	19	28	90	4
8171473	28	2	0	786	1223	84	180	49	725	42

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
8173615	2140	59	0	15459	34914	12704	7376	1397	27444	1391
8176627	182	4	0	1276	2497	728	881	100	3728	173
8181555	3257	144	0	24020	86724	22905	10832	3469	40290	2026
8181701	284	8	0	2339	5328	6131	565	213	2133	108
8185627	332	75	0	29112	51405	3650	1511	2056	6690	333
8189979	3891	800	0	250633	480356	47149	15743	19214	68455	3337
8206192	45506	6094	0	1970117	3066073	267728	210824	122643	894770	44327
8218444	1249	568	0	161903	284190	5037	5579	11368	26008	1287
8219890	87	371	0	148717	223369	394	429	8935	7954	368
8220656	41151	10880	0	3976789	5646003	650580	189210	225840	863087	42220
8222802	202	106	0	37645	62352	21631	900	2494	4877	239
8233005	70	11	0	2484	6424	1893	275	257	1143	57
8234262	60	93	0	33485	52530	2066	267	2101	2416	114
9249343	393	20	0	6435	11215	16836	1710	449	6472	327
9249549	174	145	0	48870	77666	412	1064	3107	7533	254
9249601	744	100	0	30189	51524	12523	3229	2061	13003	653
9250332	572	470	0	149028	240821	26567	2444	9633	15168	734
9250865	93	0	98	1811	65	755	698	3	8468	193
9251382	49	5	118	3987	2793	251	375	112	4987	207
9251488	183	100	0	41555	58382	788	1036	2335	5690	266
9252408	2395	815	0	311766	411220	70243	10658	16449	52091	2570

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
9252934	4323	2146	0	770224	1091519	290896	18583	43661	99993	4894
9253346	166	160	0	51149	77514	13986	733	3101	5038	242
9253587	545	349	0	131740	199366	4635	2474	7975	16060	776
9253751	97	242	0	84241	116010	11414	413	4640	5283	247
9254960	59	45	0	15452	23838	313	257	954	1299	64
9255395	1894	1838	0	642787	863801	162697	8265	34552	57104	2745
9255652	103	25	0	6893	12270	2311	322	491	1430	71
9255871	85	16	0	4609	5828	695	218	233	925	46
9256593	152	42	0	13149	19549	14259	602	782	2759	137
9256598	118	26	0	7312	13768	1443	412	551	1629	82
9256865	3	136	0	49797	66123	385	13	2645	2204	100
9259360	65	57	0	15450	32411	824	140	1296	948	46
9259471	180	69	0	23280	31474	9773	726	1259	3630	179
9259694	656	179	0	66810	105159	8470	2578	4206	12604	592
9259914	253	335	0	148232	199261	1379	1026	7970	8924	471
9260132	109	166	0	74950	84061	806	404	3362	3510	169
9260307	46	53	0	20024	30775	425	149	1231	1011	49
9260659	3	64	0	30119	32296	76	13	1292	887	40
9261527	360	292	0	118981	137070	11731	1628	5483	11039	531
9262132	126	209	0	97252	110396	1065	489	4416	4375	207
9262501	83	39	0	12801	19902	781	260	796	1017	50

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
9262841	927	933	0	313958	473936	57107	3911	18957	27768	1333
9262910	198	63	0	25002	31229	1875	996	1249	4713	233
9262922	848	979	0	445972	492344	4527	4322	19694	27439	1328
9263525	43	31	0	10122	15426	315	82	617	458	22
9263579	14	2	0	868	1208	91	32	48	125	6
9264274	391	192	0	60017	89513	62115	1440	3581	7662	375
9266206	56424	10723	0	4026746	5499465	536447	253080	219979	1121418	54642
9266308	153	23	0	7901	13103	936	823	524	6242	157
9266498	454	13	0	2799	6422	6343	1443	257	5335	269
9266978	192	18	0	3057	10527	1796	723	421	2668	134
9267104	2	25	0	11286	13555	14	0	542	480	22
9267367	69	21	0	6029	10562	482	196	422	941	46
9267430	1532	2570	0	975057	1224413	77341	6166	48977	63967	3010
9267825	1	6	0	1565	3122	11	3	125	69	3
9268228	14	0	0	86	166	1781	65	7	238	12
9268727	308	15	0	4279	7666	7226	963	307	3644	184
9268752	50	2	0	438	894	481	141	36	525	27
9268754	1178	86	0	23185	39880	138203	3862	1595	14832	749
9268765	30	3	0	834	1498	1850	98	60	386	19
1002975	1009	904	0	178827	567338	42045	6365	22694	39656	1805
1003084	2119	2983	0	583020	1881147	878074	11482	75246	97142	4455

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
1003452	78	26	0	5421	16052	212	524	642	3196	146
1004059	302	22	0	6331	13573	1719	1540	543	6272	311
1004427	243	283	0	54061	165066	380	1752	6603	12516	549
1004649	93	16	0	2848	9068	325	727	363	3923	170
1004961	172	27	0	4449	16084	15345	783	643	3248	163
1005031	0	0	0	68	133	218	1	5	6	0
1005034	1495	64	0	11077	39072	18087	7843	1563	33365	1588
1005820	140	46	0	8445	26831	140	767	1073	3475	167
1007640	52	11	0	2038	7099	294	288	284	1213	61
1007941	1163	26	0	4255	15689	59633	6284	628	22877	1161
1008556	642	314	0	73021	194711	48733	4157	7788	22902	1093
1008952	455	149	0	41036	93058	21851	3686	3722	20482	897
1009364	253	368	0	91632	233329	41504	2022	9333	17242	753
1009774	1673	740	0	149448	458335	78434	9122	18333	47844	2290
1010554	146	6	0	921	3001	8784	658	120	2422	123
1011947	271	19	0	3361	11245	14288	1399	450	5422	274
1012491	31	4	0	625	2121	1538	158	85	628	32
1013058	7	37	0	8491	23209	3376	34	928	935	43
1013201	2795	1169	0	267637	754987	199992	18185	30199	99958	4652
1016101	1437	154	0	27277	93158	141983	8990	3726	40317	1876
1016158	171	6	0	1010	3573	7120	827	143	3427	165

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO$_2$	C sequestration, tCO$_2$	N leaching, kg	P loss, kg
1019092	1	0	0	133	267	2	5	11	21	1
1019402	143	6	0	922	3298	193	381	132	1299	66
1019982	278	17	0	3145	10428	357	908	417	3621	180
1020061	40	188	0	39041	110535	16763	154	4421	3653	172
1020313	142	158	0	33376	95722	6334	494	3829	4355	208
1020629	3	104	0	24868	57920	205	9	2317	2077	94
1020927	98	47	0	8017	28139	244	377	1126	1847	91
1021231	83	19	0	3436	11978	15599	335	479	1712	85
1021274	100	52	0	14006	32135	28658	514	1285	3184	158
1021283	858	472	0	80319	275692	917	3524	11028	20908	998
1021513	17	2	1	329	1041	8206	166	42	879	36
1021811	38	86	0	16778	50817	2169	112	2033	1781	83
1021817	10	103	0	19973	60882	504	49	2435	1815	83
1022364	259	65	0	11554	38961	1966	1270	1558	5624	280
1022617	569	182	0	33086	106669	33120	4705	4267	27195	1158
1023190	34	5	0	958	3142	1726	223	126	1097	51
1023537	157	15	0	2526	8570	6963	813	343	2966	150
1023611	112	10	0	2113	5629	3350	659	225	2644	132
1023636	1740	2408	0	443334	1408773	30326	12672	56351	103983	4583
1023921	1876	28	0	5078	16482	6748	10613	659	50810	2364
1024065	16625	9504	0	1860707	5618019	2137178	104080	224721	637044	28950

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
1024472	118	16	0	2779	9402	5996	613	376	2519	126
1024520	173	147	0	29778	81415	7845	945	3257	7213	321
1025534	78	13	0	2259	7529	3780	615	301	3380	146
1025839	88	18	0	3276	10576	4273	469	423	1937	97
1026073	1570	311	0	55386	179348	68185	9929	7174	55703	2446
1026176	29	2	0	399	904	211	190	36	740	37
1026498	411	164	0	28385	96489	18487	2612	3860	16977	716
1028440	408	407	0	76179	246705	7916	2656	9868	21652	970
1028443	221	83	0	14824	49340	8177	1432	1974	8962	411
1030009	2	1	0	356	689	1	7	28	39	2
1030390	0	13	0	3710	7333	1	1	293	139	6
1030726	51	21	0	3516	11611	22	72	464	355	17
1031203	23	3	0	624	1602	9	146	64	698	32
1031294	143	35	0	6232	16978	60	566	679	2454	123
1031693	10	3	0	475	1418	5	18	57	83	4
2028654	37	9	0	1583	5617	76	189	225	810	40
2039998	75	1	0	113	385	283	351	15	1285	65
2040129	2699	644	0	110380	357752	17787	13286	14310	62290	2898
2043724	709	509	0	86706	284715	4611	3127	11389	18851	892
3038132	2	66	38	13581	37890	34	13	1516	2579	93
3039312	1	0	6	101	0	5	6	0	235	7

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
3039317	834	42	0	7063	29263	1635	4673	1171	21783	921
3039382	89	15	0	2490	10109	181	499	404	2920	122
3043094	120	6	0	1039	4037	284	826	161	3753	154
3043461	9	13	0	2133	9072	20	46	363	430	18
3044137	218	25	0	4418	13460	958	1209	538	5315	238
3044654	419	164	0	30712	88171	2263	2292	3527	10866	522
3045417	12530	3102	0	642773	1743543	47971	98053	69742	489903	19312
3046230	157	17	0	2773	8075	745	734	323	2977	146
3046446	55	24	0	4134	12327	209	316	493	1675	75
3046736	1053	389	0	76482	206404	3726	6921	8256	36963	1541
3047691	5891	7804	1017	1642011	4418535	12211	49637	176741	405151	15776
3048904	147	29	0	5546	15221	549	964	609	4580	198
3049225	332	12	0	1931	7447	1290	1623	298	6046	301
10000526	163	10	0	2837	4668	1162	549	187	2068	105
10002246	31	6	0	1683	2521	398	83	101	354	18
11009331	18	6	0	1906	2943	55	63	118	297	15
11010674	2	1	0	435	715	5	6	29	38	2
11015182	28	3	8	891	1115	128	334	45	2326	55
11021753	34994	3721	0	806527	1614939	95623	58428	64598	270451	12595
11024879	8249	202	0	38883	90426	8373	11507	3617	50072	2218
11025139	3924	8	0	1272	3300	4073	5196	132	21105	929

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
11029443	43907	21239	0	3836296	8941716	108489	39553	357669	191898	9500
11029474	0	5	1	9413	2234	1	0	89	125	2
11040851	2713	81	0	15216	37527	2790	5544	1501	20599	1048
11044014	226	40	0	13180	18727	248	595	749	2516	126
12026635	1	0	6	103	0	173	17	0	484	10
12042136	9864	462	0	99705	217307	149496	42476	8692	224678	7889
12054656	102	54	0	20529	30573	1165	389	1223	2126	104
13058076	67784	2266	0	488700	1005974	113776	31024	40239	117939	5952
13067562	1137	241	0	46882	114047	3757	2854	4562	11395	598
13068172	7	2	1	678	747	373	22	30	99	5
13068615	118	7	27	1737	2769	2603	496	111	2183	98
13069513	1	1	0	544	534	61	3	21	23	1
13069649	14	0	13	226	0	672	175	0	1735	39
13070844	389	41	0	11554	18501	10194	953	740	3583	181
13071554	205	25	0	9496	13094	318	503	524	1991	100
13071776	92	10	0	2785	4280	2690	337	171	2338	70
13071792	72	1	0	446	587	35	480	23	2669	73
13072335	68	64	0	19736	32763	81	164	1311	1140	54
13074478	1274	36	0	9686	15522	3672	1884	621	6771	343
13075153	5170	337	0	81922	134102	11812	7088	5364	27500	1387
13088998	147	6	0	1503	3272	187	115	131	430	22

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO$_2$	C sequestration, tCO$_2$	N leaching, kg	P loss, kg
13089033	36676	20073	0	5579983	8474205	283653	96500	338968	467804	21699
13095574	49216	6435	0	1549416	2712404	93882	103783	108496	459862	20815
13097606	150	2	0	402	814	388	103	33	372	19
13098258	175	2	0	359	906	429	67	36	241	12
13107593	10	0	3	56	0	50	34	0	155	8
13119247	5976	18559	0	3891998	8084769	17236	13947	323391	77411	3763
13120856	368	11	0	3483	4179	689	692	167	2498	127
13121588	1347	57	0	9545	23388	2314	2908	936	13054	630
13128047	115	290	0	88104	128719	116	246	5149	3044	138
13128658	304	2	0	273	766	511	876	31	3506	180
13134943	1611	238	0	72077	120869	5289	5023	4835	22476	1010
13135139	1057	9	0	1507	4532	2106	2272	181	10581	466
13137090	905	116	0	26614	54919	2660	2110	2197	9580	423
13138272	289	72	0	20198	34771	888	2024	1391	14019	382
13138658	270	13	0	3758	5983	669	562	239	2323	111
13139159	1544	412	0	89821	163447	1442	4221	6538	22781	1036
13139352	449	201	0	49994	98991	1390	1093	3960	5709	256
13140431	182	14	0	3852	7053	391	326	282	1308	66
13140600	704	111	0	33150	56366	1128	2075	2255	8500	426
13142643	281	47	0	9129	22402	702	631	896	2406	122
13142944	162	17	0	4762	7706	395	342	308	1433	72

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
13148059	1466	78	0	32160	30724	1323	3515	1229	12839	650
13153603	606	0	6	101	0	1469	1799	0	6474	329
13155303	10703	3754	0	955040	1587460	22223	20685	63498	159704	8123
13155392	8183	1294	0	284814	525054	9407	16898	21002	83215	3723
13158211	730	64	0	16199	30883	1166	1399	1235	5229	264
13160635	1506	32	156	8149	12545	2391	5030	502	20895	1069
13161406	424	9	0	1731	4034	464	781	161	2842	145
13165161	849	40	0	9551	18834	585	1556	753	5839	295
13165997	182	75	0	21457	29883	281	494	1195	2470	122
13167295	304	64	0	20049	28750	350	605	1150	2520	126
13167339	689	1	0	119	342	690	1222	14	4220	215
13172402	694	61	0	22001	27808	549	1647	1112	6152	311
13190047	356	33	0	12004	15303	240	750	612	2938	148
13194257	299	29	0	10913	11999	169	1076	480	3942	200
13198746	200	33	0	8609	14046	2392	575	562	2288	115
13199381	3	0	6	107	0	5	10	0	107	5
13199398	65	9	0	3973	4105	73	192	164	751	38
13212509	74588	166045	0	37911574	69399280	183964	111098	2775971	1168735	50138
14220610	69	18	0	5281	7379	29	168	295	789	39
14223185	181	4	0	1058	1504	78	487	60	1758	89
14226278	254	0	26	471	0	331	634	0	2490	124

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
14240194	1826	397	0	68342	165615	1590	2916	6625	10498	533
14240452	64	25	0	4148	10325	88	64	413	224	11
14245682	1013	153	0	26391	63398	989	2060	2536	7327	372
14247357	914	19	0	6102	8509	563	2485	340	10025	530
14254433	4191	977	0	234607	404613	5056	7985	16185	33178	1658
14255935	1030	55	0	17112	21937	2154	2294	877	8395	425
14282792	66	115	0	38720	60933	27	219	2437	1953	92
14294868	62428	43505	0	10784361	18307487	78735	121163	732299	640627	31178
14298451	152	135	0	45031	62296	424	510	2492	3193	154
14302445	56	181	10	79159	84541	44	239	3382	3523	163
14302749	128	119	183	49891	57400	93	678	2296	9737	261
14303535	94	222	0	83316	105846	91	405	4234	4184	197
14304701	1777	3040	177	1092322	1415894	2399	7735	56636	62409	2530
14312492	946	2812	66	1362433	1473914	792	4914	58957	61640	2677
14314658	31	21	32	11380	10853	25	145	434	1392	63
14315991	3272	234	0	89938	124395	2992	15554	4976	62881	2883
14316537	246	1	0	226	228	236	1067	9	3832	195
14317182	524	6	0	2106	3134	458	2071	125	7470	379
14318533	1017	59	0	21978	28794	996	3877	1152	14612	739
14318611	13	1	0	342	470	13	48	19	181	9
14320193	343	22	0	8220	9721	431	1458	389	5508	278

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
15306229	242	45	0	17325	21102	7321	1308	844	6842	195
15308232	541	23	0	7108	10131	19669	2226	405	9340	371
15308725	19438	14484	1117	5721790	6632734	45128	82260	265309	485248	23257
15314950	2668	4522	1526	1924784	2194301	3535	13485	87772	142286	6108
15319283	990	1340	0	619059	712427	1301	4978	28497	38040	1659
15319472	44	93	1	41378	51870	52	295	2075	2636	96
15319769	56796	28778	0	8440582	13231384	166476	189527	529255	905824	43871
15320004	2886	436	0	193995	233977	4145	13154	9359	53907	2670
15320030	10	2	2	633	777	14	61	31	306	10
15320139	80	4	0	1515	1998	116	305	80	1143	58
15320151	43	5	0	836	2222	60	113	89	467	13
15320227	203	0	0	86	112	290	800	4	2866	146
15320323	315	1	0	404	469	447	1301	19	4677	238
15320460	407	10	0	4648	4810	500	1808	192	7819	365
15320520	456	1	0	231	306	614	1750	12	6255	318
15320535	146	588	159	272189	306865	313	872	12275	14706	629
15320609	389	50	0	8296	25070	495	1514	1003	5779	224
15320620	171	16	0	4639	7921	177	592	317	2576	113
15320630	128	8	0	2956	4203	136	458	168	1726	87
1000543	0	168	0	29019	98667	14	0	3947	2372	107
1000681	0	14	0	2483	8390	1	0	336	182	8

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
1003240	0	1	0	166	568	0	0	23	11	0
2029958	0	3	0	458	1641	1	0	66	29	1
2040515	0	1	0	268	700	0	0	28	23	1
2043633	0	197	0	210082	122052	23	0	4882	4666	184
2043658	0	157	0	217912	97994	65	0	3920	3916	148
2043674	0	405	0	457203	241445	50	0	9658	7519	282
2043688	0	113	0	111547	69481	7	0	2779	2524	100
2045053	0	158	0	231735	96588	10	0	3864	3483	141
2046356	0	49	0	61570	28803	4	0	1152	1274	49
3044781	0	22	0	7492	15804	4	0	632	368	16
3064803	0	52	0	150805	30740	9	0	1230	1850	62
4057772	0	101	0	21914	58016	18	0	2321	1356	61
4060646	0	40	0	13761	24028	6	0	961	552	25
4063928	0	10	0	34209	5608	1	0	224	386	12
4072667	0	114	0	199614	63663	6	0	2547	2566	93
4074043	0	134	0	245800	79351	7	0	3174	3656	138
4075699	0	96	0	36263	56974	5	0	2279	1327	60
4079688	0	11	0	29068	6522	6	0	261	369	12
4081177	0	60	0	138525	41837	8	0	1673	1582	52
5059733	0	11	0	1988	6541	2	0	262	110	5
5063447	0	2	0	441	905	17	0	36	16	1

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
5066921	0	18	0	5340	10457	66	0	418	197	9
5140087	0	0	0	4	12	0	0	0	0	0
5142639	0	71	0	11905	38935	2	0	1557	389	18
6158365	0	56	0	240054	41064	10	0	1643	2682	62
6158567	0	19	0	88483	12611	15	0	504	976	23
6158599	0	82	0	147301	54712	15	0	2188	2642	87
6161508	0	0	0	192	29	0	0	1	2	0
6164438	0	5	0	20518	3505	0	0	140	251	6
6185900	0	0	0	1158	180	0	0	7	13	0
6185959	0	2	0	9845	1481	0	0	59	112	3
6202828	0	255	0	1144125	191301	35	0	7652	12947	304
6203178	0	0	0	1861	263	0	0	11	21	0
6204844	0	78	0	339534	59206	8	0	2368	3896	92
6211358	0	166	0	586739	117532	13	0	4701	7335	179
7230912	0	81	0	30599	40880	2	0	1635	1107	46
7231456	0	432	0	127133	232355	11	0	9294	5853	264
7232049	0	62	0	91471	34803	2	0	1392	1781	49
7232996	0	60	0	54727	33474	1	0	1339	1548	43
7233072	0	232	0	354790	126239	6	0	5050	6422	158
7233847	0	462	0	222671	248464	11	0	9939	7526	305
7236671	0	78	0	15375	43880	2	0	1755	1008	45

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
7237537	0	71	0	12086	39693	1	0	1588	787	35
7237568	0	648	0	1067359	360421	15	0	14417	19620	462
7238710	0	482	0	857084	267646	11	0	10706	14792	325
7239577	0	287	0	430868	158973	6	0	6359	7513	180
7241541	0	439	0	734340	246859	9	0	9874	12759	286
7241791	0	3	0	454	1499	0	0	60	6	0
9250205	0	4	0	1348	2309	32	0	92	61	3
9252141	0	82	0	44632	43454	9	0	1738	720	34
9252987	0	0	0	138	211	3	0	8	5	0
9253162	0	83	0	29170	44363	3	0	1775	609	27
9256122	0	78	0	27139	39517	77	0	1581	867	39
9257103	0	2	0	516	810	19	0	32	25	1
9257433	0	0	0	4	11	0	0	0	0	0
9261049	0	9	0	4276	4648	3	0	186	119	5
9261355	0	0	0	32	41	0	0	2	1	0
9261622	0	279	0	128660	144518	113	0	5781	3558	160
9263433	0	149	0	57384	83067	123	0	3323	1230	53
9263528	0	14	0	5544	7103	6	0	284	131	6
9263880	0	6	0	1930	3214	7	0	129	32	1
9264234	0	11	0	4743	5286	5	0	211	125	6
9266250	0	0	0	76	202	0	0	8	6	0

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
9266330	0	16	0	6662	8317	1	0	333	281	13
9267048	0	17	0	7403	9102	1	0	364	310	14
9267558	0	52	0	20114	25323	437	0	1013	871	39
11015134	0	20	0	91052	8963	9	0	359	1143	25
11022023	0	17	0	131637	8183	1	0	327	702	15
12032559	0	1	0	2970	313	1	0	13	39	1
12035614	0	3	0	563	1992	16	0	80	10	0
12038557	0	0	0	1652	182	2	0	7	19	0
12040303	0	9	0	1475	5341	55	0	214	1	0
12046406	0	0	0	1270	143	1	0	6	16	0
12058752	0	3	0	780	1352	6	0	54	19	1
12073942	0	953	0	1562559	511394	2819	0	20456	23007	652
12079639	0	93	0	56037	46595	756	0	1864	977	35
12080988	0	0	0	9	20	0	0	1	0	0
12084752	0	130	0	193374	66868	567	0	2675	2724	69
12087049	0	102	0	249426	57433	624	0	2297	3328	84
12099646	0	31	0	81449	13027	68	0	521	1074	27
12103425	0	9	0	43405	4415	65	0	177	514	11
12104130	0	9	0	35201	3891	52	0	156	466	10
12107612	0	11	0	11360	5766	53	0	231	207	7
12116561	0	16	0	61479	9100	111	0	364	755	17

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO$_2$	C sequestration, tCO$_2$	N leaching, kg	P loss, kg
12123859	0	28	0	20594	16460	197	0	658	608	33
12126555	0	4	0	1954	1988	17	0	80	72	3
12132823	0	0	0	192	177	5	0	7	7	0
12160445	0	1	0	165	267	5	0	11	4	0
13138708	0	21558	0	5356014	9141990	5656	0	365680	54577	2527
13141814	0	20	0	8599	9531	3	0	381	141	6
13143849	0	69	0	23715	30377	3	0	1215	312	14
13163678	0	13482	0	4849188	5726284	2209	0	229051	99050	5308
14213227	0	0	0	333	47	0	0	2	3	0
14225237	0	0	0	49	38	0	0	2	1	0
14234358	0	18	0	9789	7550	1	0	302	164	7
14278944	0	140	0	37212	79611	4	0	3184	1034	47
14295613	0	8	0	4835	4057	13	0	162	104	5
14311478	0	375300	0	121000152	158441736	86254	0	6337669	1885482	84135
14312177	0	418	0	838712	212895	25	0	8516	9310	297
15307831	0	3139	0	3943756	1455683	298	0	58227	62753	2483
15307930	0	15549	0	9930395	7034812	1970	0	281392	222898	9765
15311073	0	11033	0	10197931	4743320	1543	0	189733	171427	6926
15313386	0	2	0	1660	1032	0	0	41	52	3
15314517	0	74	0	218362	37238	9	0	1490	1948	53
15314780	0	286	0	322699	133621	28	0	5345	4709	178

CatchmentID	Area that does not require further mitigation, ha	Afforestation, ha	Whole-farm plan, ha	Costs, $	C sequestration revenues, $	Sediment load, t	GHG emissions, tCO_2	C sequestration, tCO_2	N leaching, kg	P loss, kg
15314790	0	12	0	5291	5959	1	0	238	167	7
15315272	0	21	0	49273	8880	1	0	355	424	10
15315369	0	118	0	74778	49694	12	0	1988	971	37
15315467	0	5	0	3176	2593	1	0	104	83	4
15316716	0	0	0	18	44	0	0	2	0	0
15319853	0	69	0	45825	37894	8	0	1516	1068	45
15320625	0	9	0	1481	4811	1	0	192	0	0

Note: P is phosphorous; N is nitrogen.