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ENVIRONMENTAL

Kaipara Harbour Sediment Mitigation Study: Summary

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Key messages

The study

The key purpose of the Kaipara Harbour Sediment Mitigation Study was to assess the economic costs and environmental benefits of a range of scenarios for reducing catchment sediment loss.

Nine sediment-mitigation scenarios and two catchment-afforestation scenarios were compared to a present-day baseline scenario.

Five of the sediment-mitigation scenarios were practice-based, such as fencing all streams for stock exclusion, and the other four were outcome-based, for instance, reducing the catchment sediment load at each of the freshwater nodes by a certain percentage.

Sources of sediment

Sediment loss from the land to Kaipara Harbour and to rivers and streams in the surrounding catchment is almost an order of magnitude higher than in pre-human times, and this has caused significant changes in the harbour and in river and stream ecosystems.

Sediment loss presently is split about equally between land-based erosion and streambank erosion, so measures that address both sources are likely to be most effective.

Pastoral landuses occupy about 70% of the catchment by area (sheep & beef 47% of the catchment and dairy 23% of the catchment), with the remainder primarily in native or plantation forest.

About 13% of the catchment is identified as “highly erodible land”, which produces about 77% of the land-based erosion.

About half of the sediment loss comes from sheep & beef farms, and about one quarter comes from dairy farms.

Mitigation

Sheep and beef farms face the largest total and per-hectare costs for nearly all scenarios investigated.

Targeting highly erodible land results in significant reductions in sediment loss at relatively low cost.

Mitigation can be targeted to the land in a cost-effective way to achieve specific outcomes.

Findings

Re-afforesting the catchment could reduce sediment loss substantially (68–88%), and provide catchment-wide improvements in stream and river ecosystem health, at a cost of between $255 and $331 million per year, which is mostly opportunity cost.

A combination of stock exclusion rules (fencing but no riparian planting) and stabilising large tracts of highly erodible land in pasture with poplars could reduce total catchment sediment loss by 41% at a cost of about $13.0 million per year. This would yield beneficial outcomes for aquatic ecosystems (and potentially recreation due to improved water clarity) in rivers in certain subcatchments, which could be prioritised for mitigation efforts.

Annual-average sedimentation rates are particularly high in the three depositional basins in the southern sector of the harbour that were examined. Reducing sedimentation rates to less than or close to 2 mm per year above the "natural" rate in these basins should result in benefits to the benthic ecology and improved ecosystem functioning.

However only three scenarios are predicted to achieve this: both full-afforestation scenarios, and the outcome-based scenario that is designed to bring sedimentation rate down to this threshold. This scenario would cost about $9 million per year, equivalent to about a 2.3% decline in net revenue compared to currently.

Annual-average sedimentation rate is predicted to be smaller in the northern sector of the harbour. Nevertheless, this sector will be experiencing some level of sediment stress and will benefit from management interventions to reduce catchment sediment runoff.

Limiting catchment sediment loss is a necessary first step towards improving the harbour's ecological health, where there will likely be multiple benefits to ecological health and functioning.

Uncertainties and caveats

There are many uncertainties and assumptions associated with the study around, for example: sediment loads, mitigation efficiencies and costs, relationships between catchment sediment loads and instream and harbour sediment attributes, and ecological thresholds.

Despite uncertainties, the results of the study demonstrate, at least, the relative effectiveness and costs of the mitigation scenarios examined.

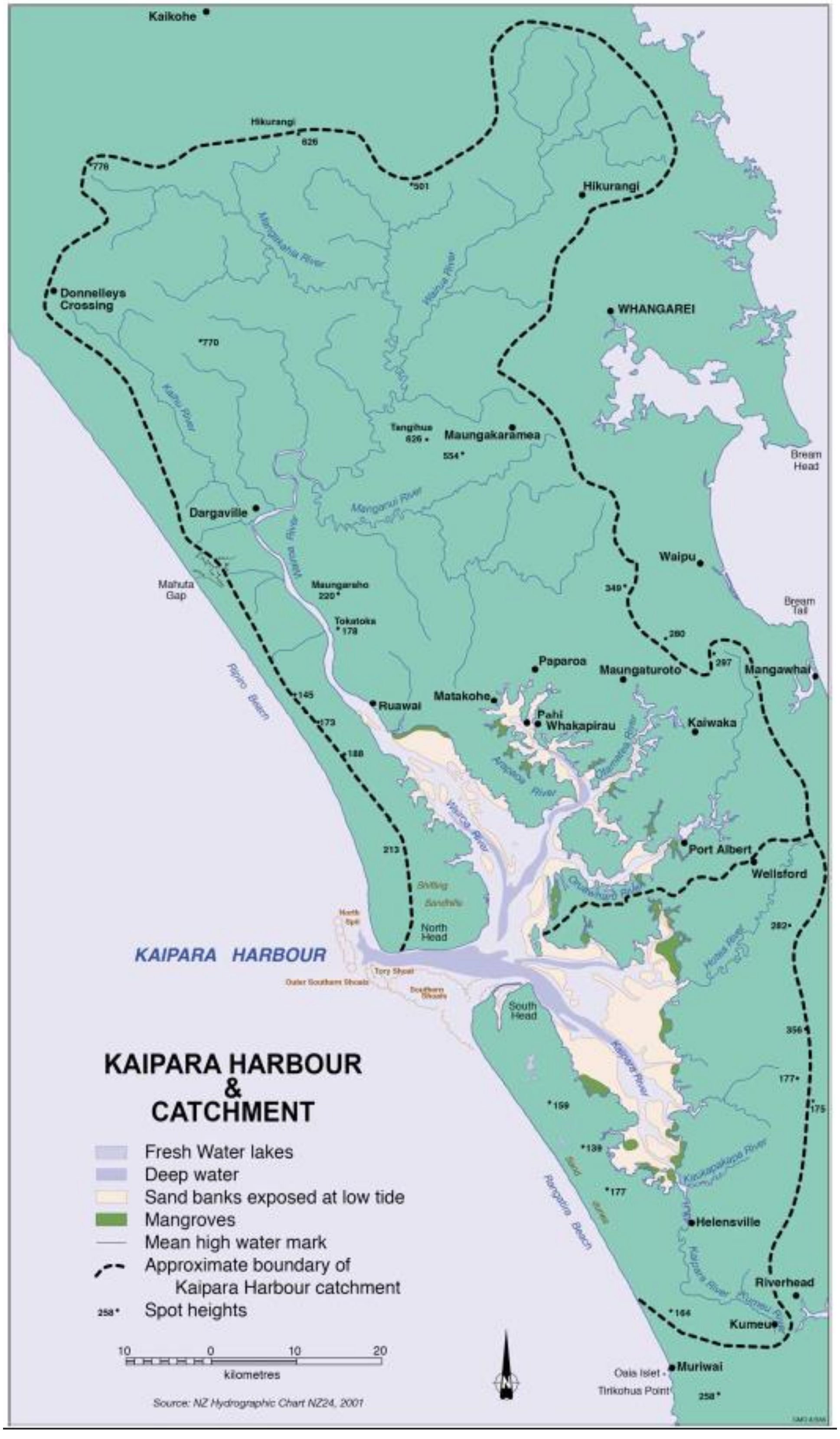
Interventions to reduce sediment loss may not generate positive ecological effects in the short term; the legacy of sediment may impinge on the ecology for decades after management interventions are initiated.

Furthermore, sediment is not the only cause of environmental degradation of freshwater and estuarine ecosystems.

Further work

Targeting mitigation is a cost-effective way of achieving specific outcomes.

While the study demonstrates initiatives based on stock exclusion and stabilising highly erodible land can be effective in reducing sediment loss, further fine-grained analysis is needed to target mitigations at the location and scale that will maximise benefits in a cost-effective manner.



Source: NZ Hydrographic Chart NZ24, 2001

Executive Summary

Landuse change has significantly increased soil erosion in the catchment of Kaipara Harbour, which has degraded stream and harbour habitats and ecosystems. There is a range of practices and actions that can be used to mitigate the adverse effects of sediments, including retiring steep land from production and planting with native trees and/or poplars as appropriate, changing from pastoral farming to production forestry, planting riparian margins, and building and maintaining wetlands.

The New Zealand Forest and Agriculture Regional Model (NZFARM) catchment economic model was used to assess the economic costs and environmental benefits of a range of scenarios for managing the catchment of Kaipara Harbour to reduce soil erosion.

A baseline scenario was established for comparison with nine sediment-mitigation scenarios and two landuse-change scenarios.

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

*Fencing is not an explicit requirement of the Clean Water stock exclusion rules; however, we have assumed that fencing will be a key element of any on-the-ground implementation of the rules.

- The baseline scenario comprised 2014 catchment landuse and corresponding catchment sediment loads assuming no mitigation in the catchment.

- Five of the sediment-mitigation scenarios were “practice-based” (e.g., fencing all streams for stock exclusion) and the other four were “outcome-based” (e.g., reducing sediment load by a certain percentage).

    - Two of the sediment-mitigation scenarios involved mitigation targeted to “highly erodible land”, and two scenarios involved implementing the Government’s proposed regulations for excluding stock from permanently flowing waterways.

    - Key mitigation options included farm management plans largely consisting of pole planting on hilly slopes on highly erodible land, fencing streams for stock exclusion, and constructing wetlands.

    - Only load-reduction targets (i.e., outcomes) were investigated for freshwater (Scenarios 6 and 7). Both a load-reduction target (Scenario 8) and an attribute target (Scenario 9) were investigated for the harbour. Attribute targets were not investigated for freshwater.

- Both landuse-change scenarios involved full-catchment afforestation, with one additionally including reconstruction of the likely extent of pre-human wetlands. These scenarios were designed to establish minimum feasible catchment sediment loads and best possible state of the environment.

For the practice-based scenarios, mitigation was prescribed. For the outcome-based scenarios, NZFARM selected the most cost-effective way to meet the prescribed outcome. As a result, landowners (in the model) implemented a mix of mitigation practices, depending on their collective cost and effectiveness.

For each scenario, costs were estimated and catchment sediment runoff was predicted. The latter was translated into sediment attributes.

- The attributes applicable to freshwater were suspended-sediment concentration (mass of sediment in suspension per volume of water), visual clarity (the distance that animals and humans can see in the water) and euphotic depth (the depth in the water to which sunlight penetrates).

- The harbour attribute was annual-average sedimentation rate (millimetres of accretion per year), which is indicative of a wide range of adverse ecological effects.

Changes in freshwater attributes under each of the scenarios were predicted at each of seven freshwater reporting nodes and changes in harbour attributes were predicted in each of nine harbour depositional basins (six in the northern sector of the harbour and three in the southern sector).

Environmental and amenity benefits under each scenario were inferred from the attributes.

Baseline scenario

Baseline total[1] catchment sediment load is about 692,000 tonnes per year, of which 52% is predicted to originate from land-based erosion, with the other 48% from streambank erosion. This relatively even split suggests that management options that target only one type of erosion process or landuse may not achieve large changes in sediment loads.

Sheep and beef farms contribute 53% of the *Baseline* total catchment sediment load, followed by dairy (24%), plantation forestry (10%), and native bush (6%). A noticeable amount of sediment comes from forested land because forest is generally located on less productive areas with steeper slopes that are highly erodible.

Approximately 74% of the catchment is in pasture, which contributes 79% of the *Baseline* sediment load. Hence, many of the farm-based mitigation options explored in the study with NZFARM will have a noticeable effect on catchment sediment loads.

Although dairy makes up only 23% of total landuse in the catchment, it produces about 78% of the total net revenue, followed by forestry (12%) and horticulture and arable (6%). Sheep and beef farming largely occurs on steep and low-productivity land, and produces only 3% of total net revenue.

Mitigation

Nearly all of the mitigation options are estimated to be implemented on what is currently pastoral land. Between 13% and 62% of the total area in the catchment will have some mitigation implemented on a part of the land, depending on scenario.

Sheep and beef farms face the largest total and per-hectare costs for nearly all scenarios. This is expected, as sheep and beef farms comprise the largest area of productive land and pasture in the catchment, are often located on land with high erosion rates, and have the greatest length of streams running through them.

Higher per-hectare costs are generally for the scenarios that account for opportunity costs due to taking some land out of production (e.g., by riparian fencing or wetland construction).

Afforestation scenarios

Afforesting the 77% of the catchment that is currently not covered with woody vegetation (both afforestation scenarios) could reduce total catchment sediment load by 68–88%. The cost is between $255 and $331 million per year, much of which is attributed to opportunity cost.

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[1] Total catchment sediment load is defined as the sum of land-based sources of sediment and streambank sources of sediment.

Practice-based scenarios

Most of the practice-based scenarios require mitigation to be implemented on a much greater area of the catchment compared to the outcome-based scenarios, yielding average mitigation costs of $46/tonne or more.

The exception in the case of the practice-based scenarios is *Farm Management Plan, All HEL*, which targets areas with relatively high erosion rates, resulting in significant reductions in sediment loss at relatively low cost.

Implementing the NZ Government's "Clean Water" stock exclusion rules (*Stock Exclusion Rules* scenario) is estimated to cost about $10.5 million per year, which is equivalent to a 3% reduction in net revenue in the catchment compared to the *Baseline* scenario, and which will achieve a 27% reduction in sediment from streambank sources and a 13% reduction in total catchment sediment load.

Extending the stock exclusion rule to require 5 m stream buffers with riparian planting (*Stock Exclusion Rules + Riparian Planting*) would reduce total catchment sediment load by 31%, at an added cost of $41.0 million per year.

Combining the stock exclusion rules (with fencing but no riparian planting) with farm management plans on all HEL (*Stock Exclusion Rules + All HEL Plans*) reduces total catchment sediment load by 41% at a cost of about $13.0 million per year.

Outcome-based scenarios

For three of the four outcome-based scenarios, the average cost of mitigation is between $5 and $10 per tonne of sediment mitigated. Costs are generally less than under the practice-based scenarios because the model targets areas with the most cost-effective mitigation potential and hence requires less total area in the catchment to implement mitigation practices.

Load-reduction targets under the *Freshwater Node 10%* and *Freshwater Node 30%* scenarios could be achieved at a relatively small cost of $0.2 to $1.2 million per year. This is because reductions can be achieved by specifically targeting farm plans, stream fencing and wetland construction on 6,000 to 32,000 ha of pastoral land with very high erosion rates and relatively low implementation costs per tonne of sediment mitigated.

Attribute targets were not investigated for freshwater.

Reducing by 15% the amount of catchment sediment that reaches all of the harbour depositional basins (*Marine Deposition 15%*) could be achieved for $0.6 million per year, and could be achieved by targeting about 15,000 ha of farms with a relatively even split of farm plans, stream fencing, and wetland construction.

The *Marine AASR 2 mm Above 'Natural' State* scenario has a much higher cost than the other outcome-based scenarios: $8.7 million per year, equivalent to about a 2.3% decline in net revenue relative to the *Baseline* scenario. This is primarily because three of the nine basins, all of which are in the southern sector of the harbour, all require significant reductions (from 28% to 55%) in catchment sediment load to achieve the annual-average sedimentation rate target.

Benefits – freshwater

In terms of achieving improvements in the freshwater sediment attributes, only the two full-afforestation scenarios really stand out above the *Baseline* scenario.

The performance of *Full Afforestation (Pine)* is not much below the maximum attainable under *Full Afforestation (Native) + Wetland Restoration*, which would require considerably more effort without any potential future economic return.

It is reasonable to expect that stream invertebrate and fish communities would become significantly healthier if one of the full-afforestation scenarios were implemented.

Stock Exclusion + All HEL Plans also has the potential to yield beneficial outcomes.

The predictions for visual clarity improvements under several of the mitigation scenarios that did not involve full afforestation have encouraging implications for human contact recreation in rivers.

Benefits – harbour

The predictions of annual-average sedimentation rate (AASR) were assessed against an adverse-effects threshold of 2 mm of sediment accumulation per year above the “natural” rate under native-forested catchment.

With the exception of both of the afforestation scenarios and the *Marine AASR 2 mm Above ‘Natural’ State* scenario (which achieves a specific target sedimentation rate), AASR is mostly not predicted to reduce by more than about 1 mm/y in any of the harbour depositional basins.

In five of the depositional basins, all within the northern sector of the harbour, *Baseline* AASR is within a fraction of a millimetre per year of the adverse-effects threshold. These basins will be experiencing some level of sediment stress and will benefit from management interventions to reduce catchment sediment runoff.

Baseline AASR exceeds the adverse-effects threshold by more than 1 mm/year in all three of the depositional basins that are in the southern sector of the harbour.

Only a few scenarios are predicted to reduce AASR to less than or close to the adverse-effects threshold in all three of those basins: both full-afforestation scenarios and *Marine AASR 2 mm Above ‘Natural’ State*. Both *Freshwater Node 30%* and *Stock Exclusion Rules + All HEL Plans* are predicted to reduce AASR to close to the threshold on the intertidal flats at the mouth of the Hoteo River.

Reducing AASR to less than or close to the adverse-effects threshold should result in benefits to the benthic ecology, and will include increases in shellfish population and improvements in associated ecosystem functions and services such as nutrient cycling and water filtering.

Glossary

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

Annual-average sedimentation rate (AASR): The rate at which the seabed rises each year as a result of sediment deposition. Expressed as millimetres per year.

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

Euphotic depth: The depth in the water column to which sunlight penetrates.

Farm management plan: In this study, a farm management plan means planting poplar or willow poles on Highly Erodible Land (defined as land where sediment loss is an average of at least 1.0 tonne of sediment per hectare per year). It does not include riparian management.

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

Highly erodible land (HEL): Pastoral land where sediment loss is an average of at least 1.0 tonne of sediment per hectare per year.

Catchment sediment load: Mass (tonnes) per year of sediment that is lost from the land to waterways by erosion.

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

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

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

Suspended-sediment concentration (SSC): Mass of sediment per unit volume of water that is suspended above the bed in the water column.

Turbidity: Roughly, the “murkiness” of the water.

Visual clarity: The horizontal distance that animals and humans can see in water.

1. The Kaipara Harbour Sediment Mitigation Study

Northland Regional Council and Auckland Council contracted a consortium led by Streamlined Environmental Ltd and consisting of Streamlined Environmental, Landcare Research, NIWA and the University of Otago, to conduct the Kaipara Harbour Sediment Mitigation Study.

An aim of the study was to assess the economic costs and environmental benefits of a range of scenarios for reducing catchment sediment losses to Kaipara Harbour and to rivers and estuaries within the surrounding catchment.

Herein, we summarise the study methods and results.

1.1 Reports arising from the study

Daigneault, A., Dymond, J. and Basher, L. (2017). *Kaipara Harbour Sediment Mitigation Study: Catchment Economic Modelling*. Landcare Research Contract Report LC2905, Auckland, 107 pp.

Dymond, J.R. (2016). *Sediment Loads in the Kaipara Harbour Catchment and Translation to Freshwater Sediment Attributes*. Landcare Research Contract Report LC2413, Palmerston North, 31 pp.

Green, M.O. and Phillips, N.R. (2016). *Kaipara Harbour Sediment Mitigation Study: Project Initiation Workshop*. Report NRC1601–1, Streamlined Environmental, Hamilton, 51 pp.

Green, M.O., Swales, A. and Reeve, G. (2017). *Kaipara Harbour Sediment Mitigation Study: Methods for Evaluating Harbour Sediment Attributes*. Report NRC1601–2, Streamlined Environmental, Hamilton, 77 pp.

Lohrer, A.M. (2017). *Kaipara Harbour Sediment Mitigation Study. Harbour Benthic Ecology Narrative*. NIWA Report 2017395HN, August 2017, NIWA Hamilton, 36 pp.

Matthaei, C. (2017). *Kaipara Harbour Sediment Mitigation Study: Narrative Assessment of Freshwater Sediment Attribute Predictions*. University of Otago, Department of Zoology, Dunedin, 31 pp.

2. Background

2.1 Kaipara Harbour and its catchment

Kaipara Harbour, located on the west coast of Northland, is the largest estuary in New Zealand and one of the largest in the southern hemisphere. At high tide, its surface area is approximately 950 km^2, of which about 43% is intertidal. The harbour contains a diverse range of estuarine environments, which include extensive wave-exposed intertidal flats, sand barriers, extensive mangrove forests, salt-marsh habitats and large tidal creeks. It is challenging to describe the ecology of the harbour as it almost resembles a miniature ocean.

The harbour's catchment is approximately 6,000 km^2. Native forest dominated by kauri, totara, taraire, puriri and rata characterised landcover at the time of European settlement in the mid-1800s. Manuka–kanuka and fern scrublands occurred along the harbour margins (Beever, 1981).

Landuse change began following the arrival of Polynesians about 700 years ago and accelerated with the arrival of Europeans from the 1830s. Kauri gum extraction and timber harvesting, the conversion of native forests and the draining of extensive wetland systems for pastoral farming dramatically changed the nature of catchment. Most of the land suitable for agriculture was cleared by the early 1900s. Now, the main landuses in the catchment are sheep and beef farming (47%), dairy (23%), plantation forestry (14%) and native bush (9%).

The major landuse changes resulted in a significant increase in the catchment sediment loads to the rivers in the harbour catchment and ultimately to the harbour itself, particularly during and soon after the conversion of native vegetation and wetlands to pasture.

The current annual-average sediment load to the harbour is estimated to be approximately 700,000 tonnes per year, compared to approximately 120,000 tonnes per year in pre-human times. The significant increase in the amount of sediment entering the harbour over the last 180 or so years has affected the harbour.

Historical accounts and other information indicate that the upper reaches and arms of the harbour have become muddier and shallower, certain habitats such as seagrass meadows and shellfish beds have been reduced in size or lost in certain areas, and the ranges in the upper harbour of species such as snapper and trevally have retracted (Morrison et al., 2014).

2.2 Adverse effects of sediment

Sediment eroded from catchments exerts a wide range of adverse effects on freshwater and estuarine ecosystems.

Suspended fine sediment in streams and rivers increases turbidity (roughly, the "murkiness" of the water) and reduces both visual clarity (the distance that animals and humans can see in the water) and euphotic depth (the depth to which sunlight penetrates), which can result a number of adverse ecological effects. Clapcott et al. (2011) review the adverse effects of fine sediments on river and stream ecosystems in New Zealand.

- Certain migratory fish species may avoid highly turbid rivers.
- Reduced visual clarity impairs the foraging efficiency of fish and birds that are visual hunters.
- Suspended sediment damages the gills of freshwater fish.
- Reduced euphotic depth causes decline of benthic plants.
- Deposited fine sediment smothers river beds and degrade benthic habitats.

Thrush et al. (2013) note that “profound changes to estuarine ecosystems have been wrought by the runoff of terrestrial sediment”. Gibbs and Hewitt (2004) review the adverse effects of sediments on estuarine ecosystems.

- High levels of suspended sediments block the feeding and breathing structures of animals, including shellfish and fish.
- Reduction in visual clarity reduces the ability of birds to feed.
- Reduction in light penetration degrades seagrass.
- Muddying of the seabed changes its biogeochemical functioning and its suitability as a habitat for benthic organisms.
- Smothering of the seabed by mud kills plants and animals.

Opportunities for human recreation can also be reduced by fine sediments.

- The Ministry for the Environment (1994) guidelines state that visual clarity should be greater than 1.6 m for contact recreation.
- Batstone et al. (2010) found that people prefer hard, sandy substrate and are put off by having to walk over or stand on muddy substrate while bathing.

Adverse effects of fine catchment sediments on aquatic ecosystems – freshwater and estuarine – and degradation of human amenity can be mitigated by reducing soil erosion in the catchment. There are numerous ways that this can be achieved, including by retiring steep land from production and planting with native trees, changing from pastoral farming to production forestry, planting riparian margins, and building and maintaining wetlands. However, these come with costs.

The question faced by resource managers, landowners and communities alike is this: how much do these actions cost, can they be targeted to provide good value for money, and do they really provide benefits at the desired level?

3. Methodology

The New Zealand Forest and Agriculture Regional Model (NZFARM) catchment economic model was used to assess the economic costs and environmental benefits of a range of scenarios for reducing losses of sediment from the catchment of Kaipara Harbour.

The NZFARM model – the technical details

NZFARM is a mathematical catchment-scale model of New Zealand landuse developed by Landcare Research (Daigneault and Samarasinghe, 2015; Daigneault et al., 2017). Amongst other things, the model is designed to provide information on the economic impacts of environmental policy, and can be used to assess how policy could affect a host of economic or environmental performance indicators that are important to decisions-makers and rural landowners. The model can analyse a wide range of policy options, and can identify the optimal mix of land management for meeting targets. Key land management options in the version of NZFARM version used for the study include implementing farm plans, fencing streams, and constructing wetlands, all for the purpose of reducing sediment loss to waterways.

A baseline scenario was established for comparison with the other scenarios.

Nine scenarios involving the application of specific sediment-mitigation options and two scenarios involving landuse change (afforestation) were investigated.

Costs associated with each scenario were estimated by NZFARM.

For each scenario, annual-average load of catchment sediment delivered to both freshwater and the harbour was predicted.

The sediment load under each scenario was transformed into estimates of three freshwater sediment attributes:

- suspended-sediment concentration (SSC),
- visual clarity,
- euphotic depth,

and one harbour sediment attribute:

- annual-average sedimentation rate (AASR).

Environmental and amenity benefits were inferred from the predicted changes to the set of sediment attributes.

Mitigation / landuse change in the catchment ⟶ reduces catchment sediment load ⟶ causes changes in sediment attributes such as visual clarity and sedimentation rate ⟶ delivers improvements in ecology and human amenity

Comment

While the scenarios were defined with the assistance of Northland Regional Council and Auckland Council, the findings of this report should be interpreted more as an illustration of the range of options and impacts that could occur in the catchment as opposed to a formal regulatory analysis of a specific policy or rule change.

Sediment attributes – the technical details

For **freshwater**, we assessed environmental and amenity benefits by looking at three sediment attributes: suspended-sediment concentration, visual clarity and euphotic depth. Suspended fine sediment in streams and rivers increases suspended-sediment concentration and reduces both visual clarity and euphotic depth.

> Suspended-sediment concentration (SSC) and total suspended solids (TSS) are often used interchangeably to describe the concentration in water of solid-phase material (units of kg/m^3 or mg/L). They vary by analytical method: SSC is estimated by measuring the dry weight of all the sediment from a known volume of the water–sediment mixture, and TSS is estimated by measuring the dry weight of sediment from a known volume of a subsample of the original (Gray et al., 2000).
>
> Visual clarity is the sighting range as it affects human recreational users and visual habitat for fish and aquatic birds. It is expressed as the horizontal sighting range of a black target (y_{BD}, units of metres), which can be measured directly using, for example, a Secchi disk. y_{BD} can also be inferred exactly from the light-beam attenuation coefficient C as $y_{BD} = 4.8/C$. Light attenuation (units of m^{-1}) is defined as the proportional loss of photons from a light beam by absorption plus scattering per unit length of light path. C is measured using a beam transmissometer operating at a wavelength of 550 nm, which corresponds to the peak sensitivity of the human eye, and is also applicable to fish and birds as well. Davies-Colley et al. (2014) note that "y_{BD} [measured directly or inferred from C measured at 550 nm] is an excellent index for protecting the visual ecology of waters, as well as their suitability for human recreational use".
>
> Euphotic depth is typically defined as the depth below the water surface (units of metres) at which the light intensity falls to 1% the intensity at the surface. Euphotic depth depends directly on light penetration, which is expressed as the irradiance attenuation coefficient (K_d), which is defined as the proportional decline of downwelling irradiance per unit depth (Kirk, 2011). Light penetration is reduced mainly by multiple scattering extending the pathlength taken by photons per unit depth, which increases the opportunity for photons to be absorbed by the water (Kirk, 1985). Suspended particulate matter is a primary cause of multiple scattering, and therefore of reduced light penetration.

For the **harbour**, we assessed environmental and amenity benefits by looking at one sediment attribute: annual-average sedimentation rate (AASR). Elevated sediment loads from the catchment increase AASR.

> Sedimentation rate (units of mm/y) is the vertical rate at which the seabed rises above an arbitrary datum due to the net deposition of sediment. Sedimentation rate inevitably varies from year to year, and is typically expressed as an annual average over many years.

Sedimentation rate is indicative of a broad spectrum of adverse sediment effects, meaning that where it is high – relative to the "natural" rate under native-forested catchment – adverse sediment effects are expected, and vice versa. Green (2013) argued that managing for sedimentation rate will reduce the broad spectrum of adverse sediment effects and deliver a wide range of environmental outcomes. In 2015, fifteen researchers from a broad cross-section of New Zealand institutions developed draft ANZECC guidelines for estuary sedimentation (Townsend and Lohrer, 2015). An adverse-effects threshold of 2 mm of fine-sediment accumulation per year above the "natural annual sedimentation rate" was proposed. The natural annual sedimentation rate that is factored into the threshold is defined as the rate under native-forested catchment prior to human occupation. The natural annual sedimentation rate may vary between estuaries and in different parts of an individual estuary; hence, the adverse-effects threshold may be different between estuaries and in different parts of an individual estuary.

4. *Baseline* scenario

The *Baseline* scenario, against which the other scenarios are compared, comprises:

- 2014 catchment landuse,
- catchment sediment loads corresponding to 2014 catchment landuse with no mitigation,
- present-day suspended-sediment concentration, visual clarity and euphotic depth at each of seven locations in the catchment,
- present-day annual-average sedimentation rate in each of nine harbour depositional basins.

The no-mitigation assumption is significant:

- No mitigation was assumed for the *Baseline* because we were not able to precisely quantify and locate present-day efforts at sediment mitigation in the catchment (e.g., fences to exclude livestock from water bodies, poplar or willow trees planted to stabilise highly erodible pasture, or constructed wetlands).

Because the *Baseline* does not account for present-day mitigation, costs and benefits (e.g., net revenue and reductions in catchment sediment load) that are shown as, for instance, percentage change relative to the *Baseline*, will be overstated.

Caveats on the *Baseline* scenario

Daigneault et al. (2017) discuss caveats associated with the definition of the *Baseline* scenario.

Appendix 6 of Daigneault et al. (2017) explains in detail why a no-mitigation baseline was used instead of a current-mitigation baseline.

4.1 2014 catchment landuse

The 2014 landuse was based on a 2014 GIS-based landuse map created by Landcare Research using the latest information from Agribase and the NZ Land Cover Database version 4 (LCDBv4) (Figure 4-1).

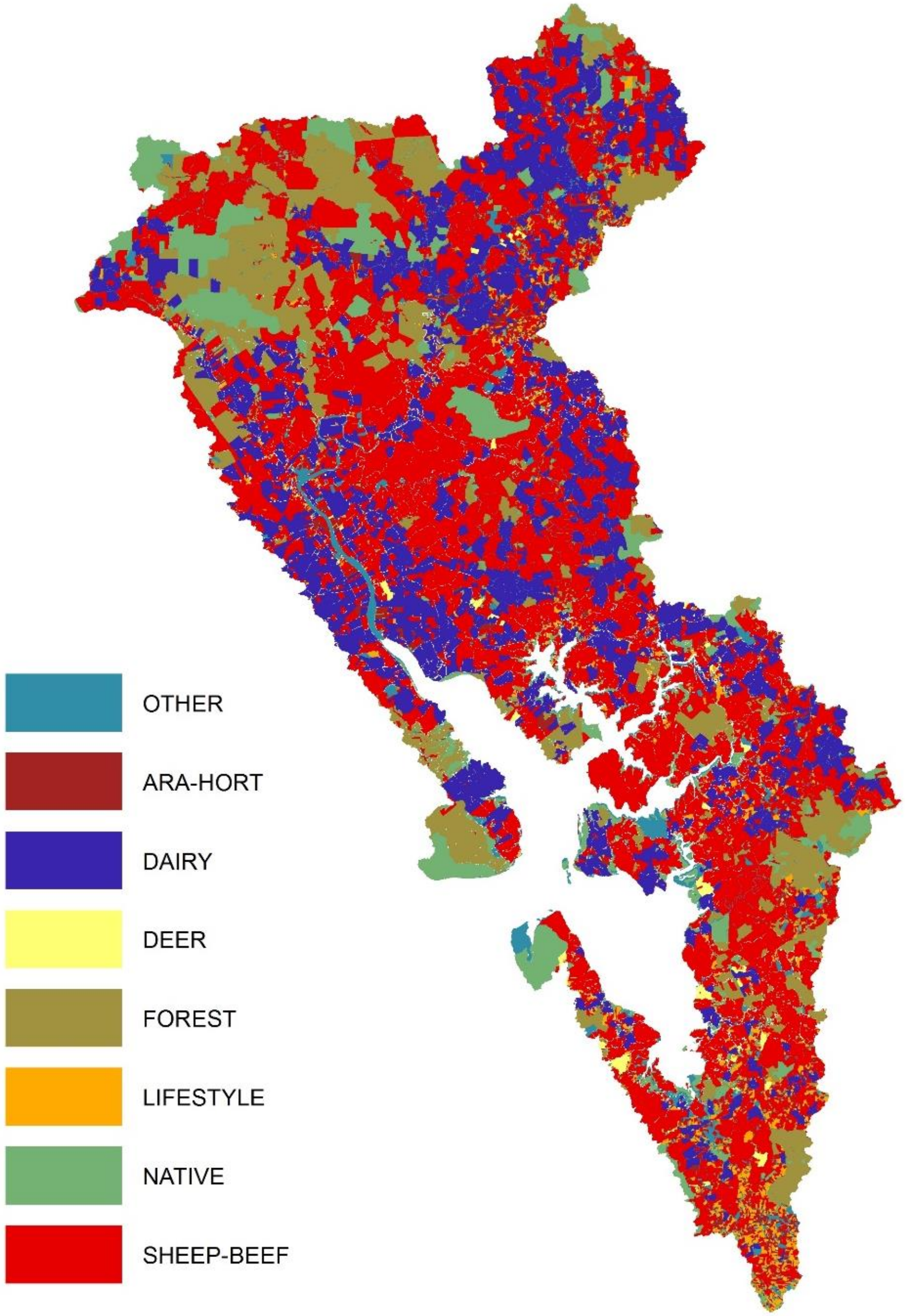


Figure 4-1. 2014 landuse based on information from Agribase and the NZ Land Cover Database version 4 (LCDBv4).

4.2 Catchment sediment loads

The SedNetNZ catchment sediment model was used to predict catchment sediment loads for the *Baseline* 2014 landuse with no mitigation.

Predictions of sediment load were made for each of 21 subcatchments of Kaipara Harbour (Figure 4-2).

- Catchment sediment load (tonnes per year) was divided by two sources: land-based erosion (surface, landslide, earthflow, gully erosion), and streambank erosion.

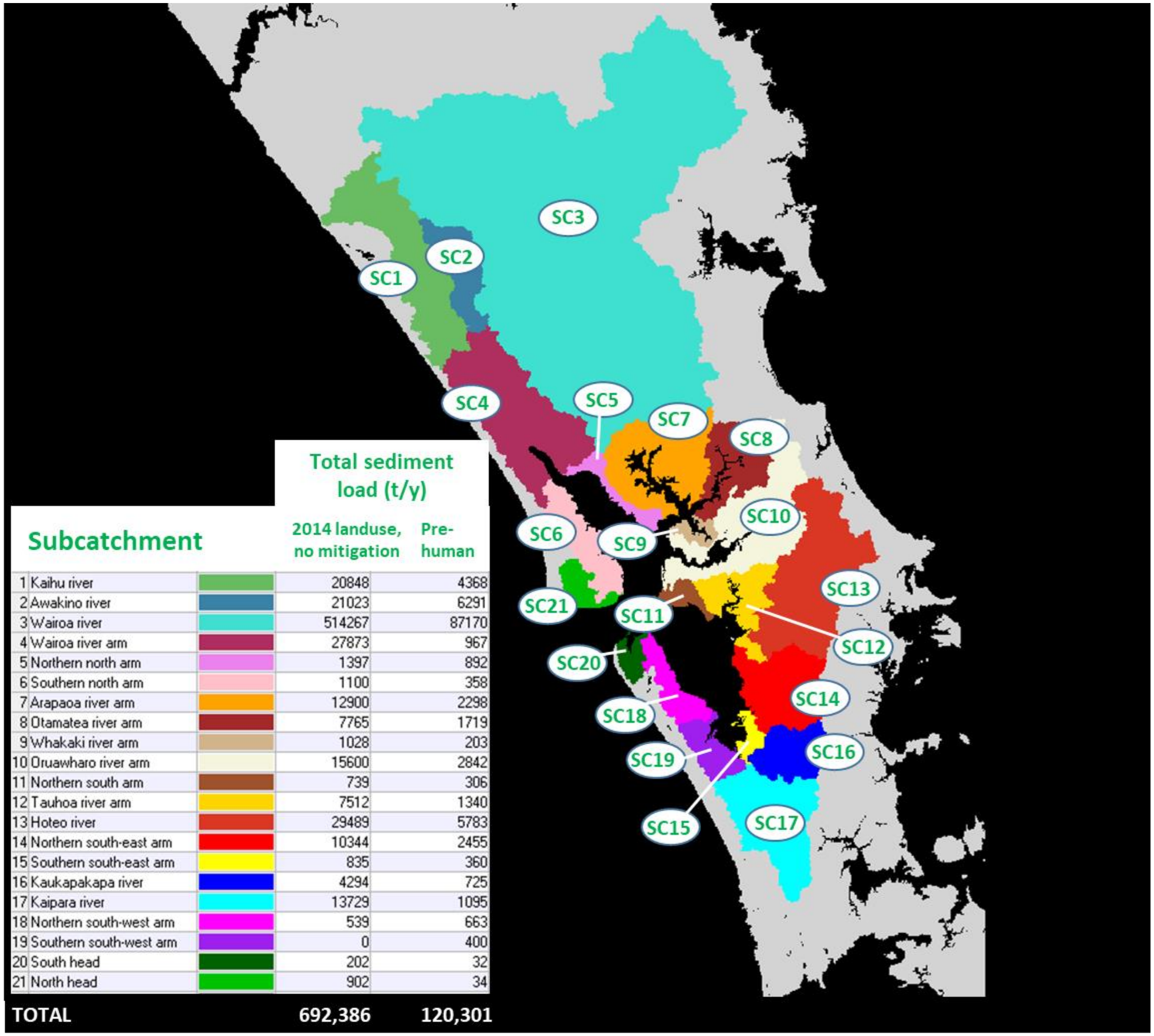
- Total catchment sediment load is defined as the sum of land-based sources of sediment and streambank sources of sediment.

SedNetNZ was also used to predict catchment sediment load under the pre-human landcover (i.e., native forest).

The SedNetNZ model – the technical details

SedNetNZ predicts sediment loss from the catchment by a range of erosion processes, including surface, hillslope, gully and bank erosion, landslides and earthflows. Eroded sediment is routed through the river network using a sediment budgeting method, accounting for losses in water bodies (reservoirs, lakes) and deposition on floodplains and in the river channel.

Sediment loads in tonnes per year are predicted for each "stream link" in a river network, including at the base of the catchment where the river discharges at the coast.



Subcatchment			Total sediment load (t/y) 2014 landuse, no mitigation	Total sediment load (t/y) Pre-human
1	Kaihu river	■	20848	4368
2	Awakino river	■	21023	6291
3	Wairoa river	■	514267	87170
4	Wairoa river arm	■	27873	967
5	Northern north arm	■	1397	892
6	Southern north arm	■	1100	358
7	Arapaoa river arm	■	12900	2298
8	Otamatea river arm	■	7765	1719
9	Whakaki river arm	■	1028	203
10	Oruawharo river arm	■	15600	2842
11	Northern south arm	■	739	306
12	Tauhoa river arm	■	7512	1340
13	Hoteo river	■	29489	5783
14	Northern south-east arm	■	10344	2455
15	Southern south-east arm	■	835	360
16	Kaukapakapa river	■	4294	725
17	Kaipara river	■	13729	1095
18	Northern south-west arm	■	539	663
19	Southern south-west arm	■	0	400
20	South head	■	202	32
21	North head	■	902	34
TOTAL			692,386	120,301

Figure 4-2. SedNetNZ subcatchments, with corresponding total sediment loads (t/y) predicted by the model for the 2014 landuse with no mitigation, and for pre-human landcover (i.e., native forest).

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4.3 Freshwater sediment attributes

Table 4-1 shows present-day 50th percentiles for suspended-sediment concentration (kg/m^3), visual clarity (m) and euphotic depth (m) for each of seven freshwater reporting nodes, which are shown in Figure 4-3.

The freshwater reporting nodes were the only monitoring sites in the catchment where there were sufficient data to establish the present-day state of the attributes and relationships amongst the attributes (see section 5.3).

Table 4-1. Present-day 50th percentiles for suspended-sediment concentration (kg/m^3), visual clarity (m) and euphotic depth (m) for each of seven freshwater reporting nodes, derived from data. Data for suspended-sediment concentration were not available for Manganui River at Mititai.

	Attribute		
Node	SSC (kg/m3)	Visual clarity (m)	Euphotic depth (m)
Hoteo River at Gubbs	3.52	1.30	2.00
Kaihu River at Gorge	2.60	1.60	2.20
Kaipara River at Waimauku	1.83	2.10	2.60
Kaukapakapa River at Taylor	3.36	1.30	2.00
Mangakahia River at Titoki	11.10	0.66	1.50
Manganui River at Mititai		0.87	1.80
Wairua River at Purua	7.30	0.75	1.50

Figure 4-3. The seven freshwater reporting nodes where freshwater sediment attributes are reported. The map also shows the catchment drained by each river with a node.

4.4 Harbour annual-average sedimentation rate

Figure 4-4 shows the present-day annual-average sedimentation rate (AASR) for each of the nine harbour depositional basins in Figure 4-5, and how AASR is broken down by catchment sources of sediment and marine sources of sediment. Marine sources of sediment include sand washed in through the mouth of the harbour and shell material that is produced *in situ*. Our confidence in each estimate of AASR is also shown on the graph.

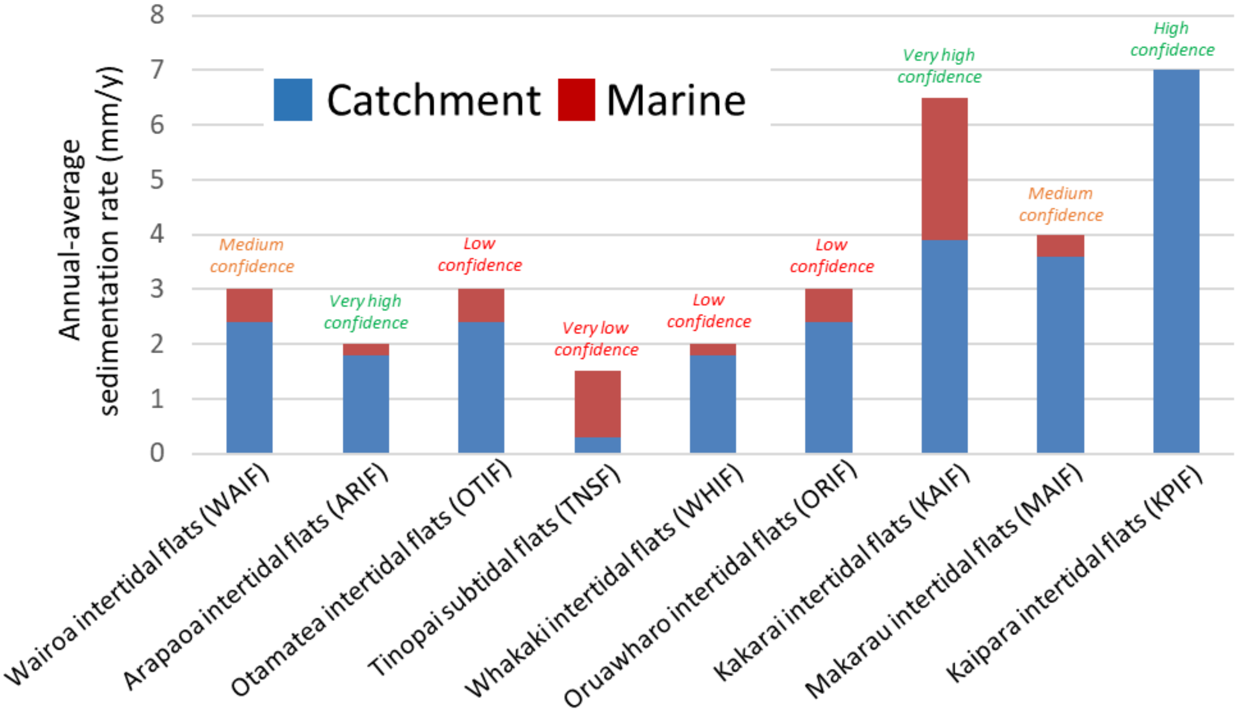


Figure 4-4. Present-day AASR (mm/y) for each of the nine harbour depositional basins. The blue bar shows the proportion of the sedimentation due to catchment sediment and the red bar shows the proportion due to marine sources of sediment (marine sands plus shell hash). "Confidence" refers to our confidence in each estimate of AASR.

Comment

The nine depositional basins were chosen by consensus to include a balance of locations between the northern and southern sectors of the harbour, locations of particular significance to tangata whenua, a range of representative harbours, and locations with particularly high ecological and/or human amenity values. The locations also were chosen with a view to availability of data.

Figure 4-5. The nine depositional basins of Kaipara Harbour where AASR is reported.

4.5 Summary of key economic and environmental variables under the *Baseline* scenario

Table 4-2. Summary of the key economic and environmental variables under the *Baseline* scenario.

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

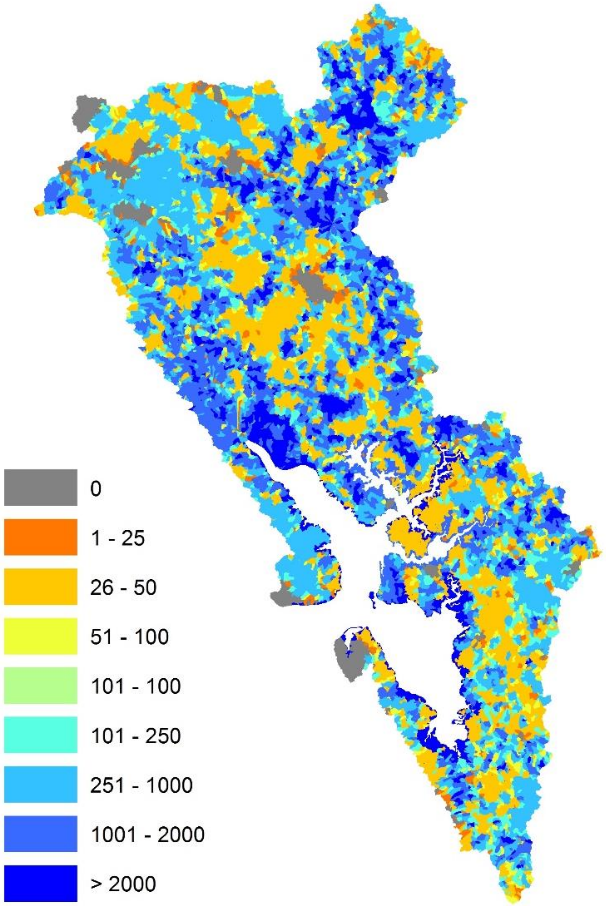


Figure 4-6. *Baseline* scenario (2014) net revenue ($ per ha per year).

Notes on economic calculations

Baseline scenario farm financial budgets, which are based on estimates for production yields, input costs and output prices that come from a wide range of literature and national-level databases, form the foundation of the *Baseline* net revenues earned by landowners. Revenues are specified as earnings before interest and taxes (EBIT), and assume that landowners currently face no mitigation costs, such as fencing streams or constructing wetlands.

Net revenue is used to estimate the opportunity costs of taking land out of production in order to implement certain mitigation options, specifically, wetlands and retention bunds. Most of the pasture-based mitigation assumes an increase in capital and maintenance expenses, but no opportunity costs for production losses, and hence do not take net revenues into account.

Features of the *Baseline* scenario

1. The catchment covers approximately 602,000 ha.
2. The major landuses in the catchment are sheep and beef (47%), dairy (23%), plantation forestry (14%) and native bush (9%).
3. *Baseline* total catchment sediment load is about 692,000 tonnes per year, of which 52% is predicted to originate from land-based erosion, with the other 48% from streambank erosion. This relatively even split suggests that management options that target only one type of erosion process or landuse may not achieve large changes in sediment loads.
4. Sediment load under the pre-human landcover is predicted to be about only 15% of the *Baseline* (2014/no-mitigation) sediment load.
5. Sheep and beef farms contribute 53% of the *Baseline* total catchment sediment load, followed by dairy (24%), plantation forestry (10%), and native bush (6%). A noticeable amount of sediment comes from forested land because forest is generally located on less productive areas with steeper slopes that are highly erodible.
6. Approximately 74% of the catchment is in pasture, which contributes 79% of the *Baseline* sediment load. Hence, many of the farm-based mitigation options explored in the study with NZFARM will have a noticeable effect on catchment sediment loads.
7. *Baseline* total net income from land-based operations is estimated at $372 million/y or $618/ha for all land and $697/ha for land that is currently earning revenue from farming and plantation forestry.
8. Although dairy makes up only 23% of total landuse in the catchment, it produces about 78% of the total net revenue, followed by forestry (12%) and horticulture and arable (6%).
9. Sheep and beef farming largely occurs on steep and low-productivity land, and only produces 3% of total net revenue.

5. Sediment-mitigation and landuse-change scenarios

5.1 Overview

Nine sediment-mitigation scenarios and two landuse-change scenarios were investigated using NZFARM (Table 5-1).

Table 5-1. The scenarios investigated using NZFARM.

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

*Fencing is not an explicit requirement of the Clean Water stock exclusion rules; however, we have assumed that fencing will be a key element of any on-the-ground implementation of the rules.

- There were nine **sediment-mitigation scenarios**. Five were practice-based, such as fencing all streams for stock exclusion, and the other four were outcome-based, for instance, reducing the catchment sediment load at each of the freshwater nodes by a certain percentage. None of these scenarios addressed landuse change, only mitigation.

Comment

Note that, for the freshwater nodes, only load-reduction targets (i.e., outcomes) were investigated (Scenarios 6 and 7). Both a load-reduction target (Scenario 8) and an attribute target (Scenario 9) were investigated for the harbour. Attribute targets were not investigated for freshwater.

- Two additional **landuse-change scenarios** were investigated. Both of these involved afforestation, with one additionally including reconstruction of the likely extent of pre-human wetlands. Both were designed to establish minimum feasible catchment sediment loads and best possible attribute states.

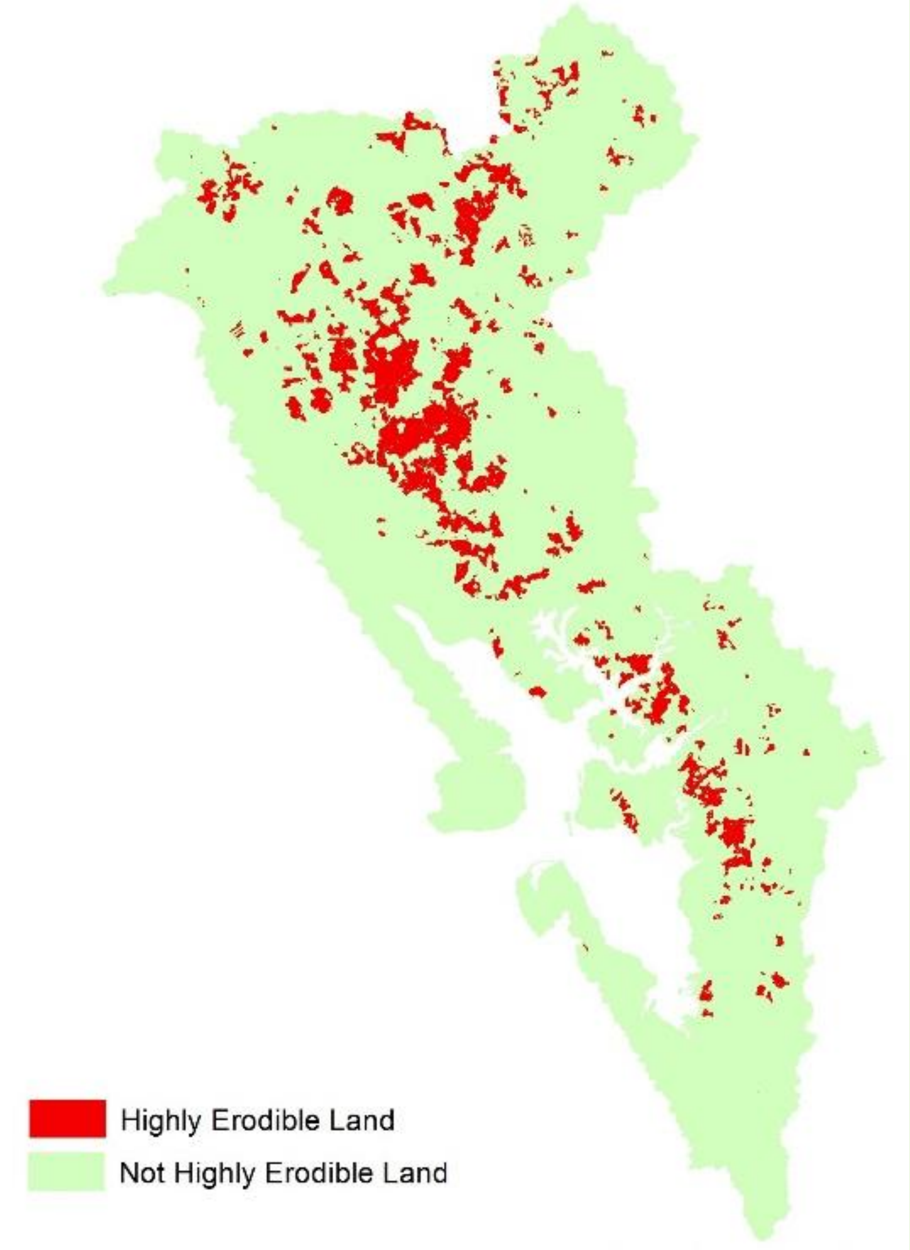
All scenarios were designed so that attributes states would always be maintained or improved.

For the practice-based scenarios, mitigation was prescribed. For the outcome-based scenarios, NZFARM selects the most cost-effective way to meet the prescribed outcome. As a result, landowners (in the model) implement a mix of mitigation practices, depending on their collective cost and effectiveness

Highly erodible land

80,910 ha, or 13.4% of the catchment, is classified as "highly erodible land" (HEL), which is defined as pasture land with mean land-based erosion of at least 1.0 tonnes per hectare per year. HEL produces about 77% of the *Baseline* 358,000 t/y of the catchment sediment load that originates from land-based sources.

Farm management plans for HEL (Scenario 2) primarily involve planting poplar or willow poles, but excludes stock exclusion (unless combined with riparian fencing, which is Scenario 5).

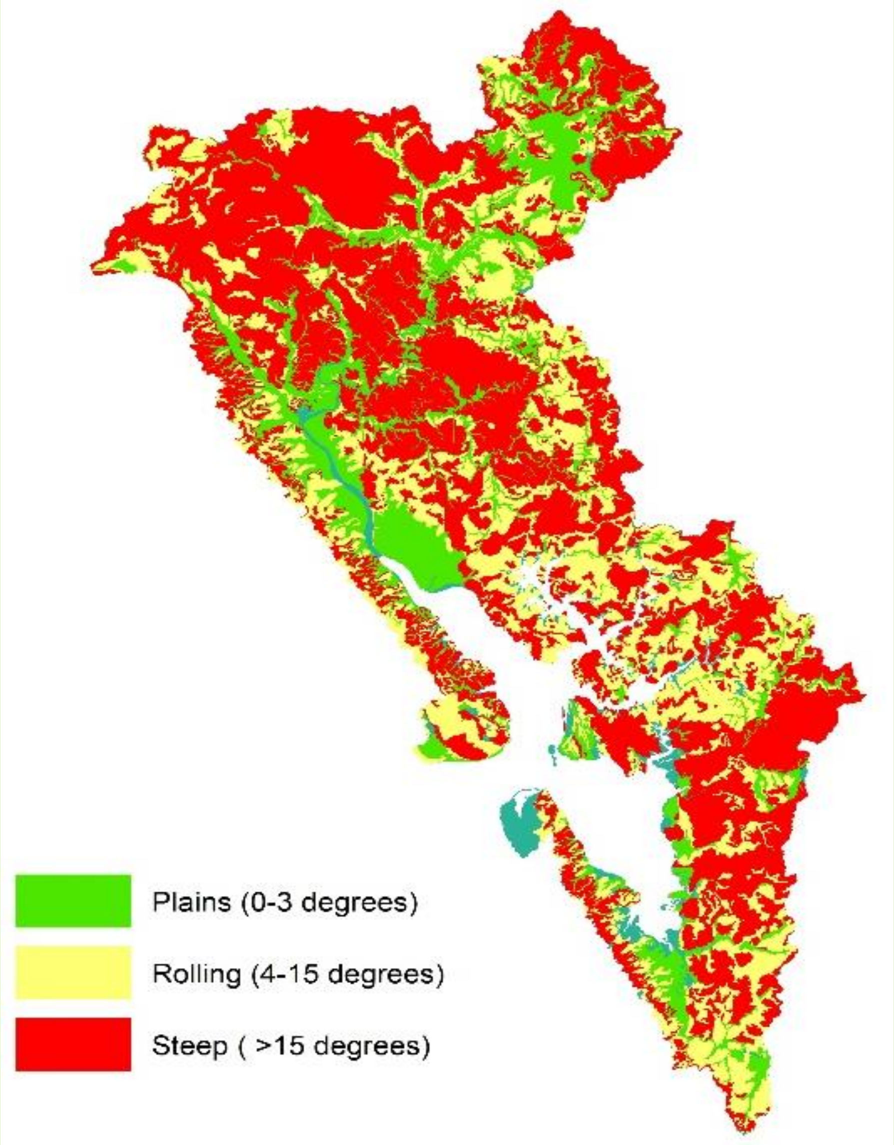


Proposed stock exclusion regulations

NZ Government's proposed stock exclusion regulations[1] would require, by the end of 2017, dairy cattle on milking platforms and farmed pigs to be excluded from all permanently flowing waterways that are at least 1 m wide at any one point. Fencing is not an explicit requirement of the Clean Water stock exclusion rules; however, we have assumed that fencing will be a key element of any on-the-ground implementation of the rules.

Dairy support cattle (including third-party dairy grazing), beef cattle and farmed deer must be excluded from permanently flowing waterways on land that has a slope of between 0 and 15 degrees.

For the scenarios that incorporated these rules (Scenarios 3, 4 and 5), we assumed that all eligible farms had fully implemented their riparian fencing requirements by the end of the model simulation period (i.e., 2030)[2].



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[1] Based on the "Clean Water" consultation document recently released by the New Zealand Government, http://www.mfe.govt.nz/publications/fresh-water/clean-water-90-of-rivers-and-lakes-swimmable-2040.

Explanation of Scenario 9 – the technical details

Scenario 8 constrains the AASR to the component of the *Baseline* AASR that is due to marine sediment **plus** the smaller of (a) the catchment-sediment component of the *Baseline* AASR **or** (b) the catchment-sediment component of the "natural" AASR predicted under Scenario 11 (all non-forest land planted with native bush and pre-human settlement wetlands restored) **plus** 2 mm/year (see Footnote).

Referring to Table 5-2:

- For depositional basins ARIF, TNSF and WHIF, (a) is smaller than (b) and hence no reduction in catchment sediment runoff is required to meet the Scenario 8 target AASR.
- For all the other depositional basins, (a) is greater than (b) and hence reduction in catchment sediment runoff is required to meet the Scenario 8 target AASR.
- Basins KAIF, MAIF and KPIF require the greatest reduction in catchment sediment (relative to the Baseline scenario) to meet the Scenario 8 target AASR.

Table 5-2. Percentage reductions in catchment sediment (relative to *Baseline* scenario) required to meet Scenario 8 target AASR (see text for explanation).

	Baseline			**Scenario 11 "natural"**			**Scenario 8**			
Harbour depositional basin	AASR (mm/y)	Marine sediment component (mm/y)	Catchment sediment component (mm/y)	AASR (mm/y)	Marine sediment component (mm/y)	Catchment sediment component (mm/y)	Marine sediment component (mm/y)	Catchment sediment component (mm/y)	AASR (mm/y)	% reduction in catchment sediment component (relative to *Baseline)* required to achieve target AASR
WAIF	3	0.6	2.4	0.89	0.6	0.29	0.60	2.29	2.89	-5%
ARIF	2	0.2	1.8	0.36	0.2	0.16	0.20	1.80	2.00	0%
OTIF	3	0.6	2.4	0.78	0.6	0.18	0.60	2.18	2.78	-9%
TNSF	1.5	1.2	0.3	1.24	1.2	0.04	1.20	0.30	1.50	0%
WHIF	2	0.2	1.8	0.32	0.2	0.12	0.20	1.80	2.00	0%
ORIF	3	0.6	2.4	0.88	0.6	0.28	0.60	2.28	2.88	-5%
KAIF	6.5	2.6	3.9	3.41	2.6	0.81	2.60	2.81	5.41	-28%
MAIF	4	0.4	3.6	0.90	0.4	0.50	0.40	2.50	2.90	-31%
KPIF	7	0	7	1.18	0	1.18	0.00	3.18	3.18	-55%

Footnote: 2 mm of sediment accumulation per year above the natural sedimentation rate is the adverse-effects threshold proposed by Townsend and Lohrer (2015). The natural sedimentation rate that is factored into the threshold is defined as the rate under native-forested catchment prior to human occupation. The natural sedimentation rate may vary between different estuaries and within different parts of an individual estuary.

5.2 Application of mitigation / landuse change

For each scenario, the catchment sediment load is calculated from the *Baseline* (2014 landuse/no-mitigation) load by applying mitigation options or by changing landuse (afforestation) as needed, as set out in Table 5-3.

Table 5-3. Applicability of sediment-mitigation options and landuse change (afforestation) to specific landuses and erosion processes.

Mitigation Type	Description	Landuse		Erosion Process				
		Pasture	Arable & horticulture	Earth flow	Gully erosion	Land slides	Surface erosion	Bank erosion
Afforestation	Plant non-native land with pine plantations or native bush.	X	X	X	X	X	X	X
Farm Management Plan (e.g. Space-planting)	Predominantly planting poplar or willow poles on pastoral land that averages at least 1.0 tonne of sediment lost (eroded) per hectare per year (Highly Erodible Land). It does not include riparian management.	X		X	X	X		
Riparian fencing	Construct fences along permanent waterways (rivers and streams).	X						X
Riparian fencing + planting	Construct fences along permanent waterways (rivers and streams) and plant 5 m strips of grass or other vegetation.	X	X				X	X
Riparian grass buffer strip	Plant 5 m strips of grass or other vegetation without fencing.	X	X				X	
Wetland construction	Construct or restore wetlands of various sizes.	X	X	X	X	X	X	
Cover crops	Applied to arable or horticultural land.		X				X	
Debris dams	Construct in gully, often along with tree planting.		X		X			
Sediment retention pond	Construct pond on first-order streams to trap sediment .	X	X	X	X	X	X	
Silt fence	Erected to catch urban sediment flow.		X				X	
Wheel track diking	Applied to arable or horticultural land.		X				X	
Wheel track ripping	Applied to arable or horticultural land.		X				X	
Combination	Includes a combination of the practices listed above. Often more effective, albeit at a higher cost.	X	X	X	X	X	X	X

Comments

Many options in the table are assumed to apply only to arable and horticultural enterprises. Less than 1% of the total catchment is in these landuses, which produce about 0.5% of the *Baseline* catchment sediment load. Thus, implementing many of the practices shown in the table will have little to no effect on catchment sediment load.

We did not include any urban mitigation options, which should have only a minimal effect on the results, since urban landuse is a very small percentage of the catchment area and urban sources of sediment are small compared to other (non-urban) sources.

Each mitigation and afforestation option has an assumed cost and efficiency at reducing catchment sediment loss (Table 5-4).

Table 5-4. Mitigation and afforestation costs and efficiencies for key mitigation options implemented in NZFARM for the study. Costs are broken out by initial capital, ongoing and periodic maintenance, and opportunity costs associated with taking land out of production.

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

Annualised costs

Initial capital and periodic maintenance costs are annualised over 25 years using a discount rate of 8%, which is a typical assumption for this type of analysis (e.g., Daigneault and Samarasinghe, 2015; Grintner and White 2016). Annual maintenance and opportunity costs are assumed to accrue on a yearly basis and thus are directly subtracted from the base net revenue.

Comments

Each mitigation and afforestation option has the potential to have different impacts based on farm size, location and net revenue. For example, a large sheep and beef farm next to a large stream will likely face higher absolute costs for the fencing option than for the farm management plan option because the latter consists of a large initial fixed cost ($5,000 or more) that does not vary by farm size. Conversely, a dairy farm that only needs to fence a short length of stream would likely face higher costs for constructing a wetland as this would involve taking some land out of production and thus incurring an opportunity cost.

5.3 Calculation of freshwater sediment attributes

NZFARM predicts the three freshwater sediment attributes under each scenario, which are reported at each of the seven freshwater reporting nodes shown in Figure 4-3.

We assumed that, at each freshwater reporting node, the suspended-sediment-concentration (SSC) percentiles all change exactly proportionately in response to a reduction in catchment sediment load. That is, a 50% reduction in sediment load results in a 50% reduction in the 50th percentile SSC, a 50% reduction in the 80th percentile SSC, and so on.

We then used data to calculate how the visual clarity and euphotic depth change in response to the reduction in SSC at each node. For each node, we derived an equation that relates SSC to visual clarity and to euphotic depth. Note that both visual clarity and euphotic depth are inversely related to SSC – when SSC is high, visual clarity and euphotic depth are both low.

Results

1. For all nodes except Kaihu River at Gorge, a 50% reduction in SSC was found to increase all of the visual clarity percentiles by approximately 70% and the euphotic depth percentiles by approximately 35%. For example, if the 80th percentile visual clarity is 1 m before sediment-load reduction then it will be 1.70 m after a 50% reduction in sediment load, and so on.
2. At Kaihu River at Gorge, a 50% reduction in SSC was found to increase all of the visual clarity percentiles by approximately 35% and the euphotic depth percentiles by approximately 30%.

Catchment size and landuse upstream of each freshwater reporting node vary, as shown in Table 5-5.

Table 5-5. Distribution of landuse (hectares) in the catchments upstream of each freshwater reporting node.

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

Comments

Landuse will have an effect on the way mitigation translates into changes in suspended-sediment concentration, visual clarity and euphotic depth at each of the nodes.

For instance, 46% of the land upstream of Mangakahia River at Titoki is forestry or native bush and thus may not benefit from implementing erosion control practices as much as at, say, Manganui River at Mititai, where only 10% of the upstream land is under forest cover.

5.4 Calculation of harbour sediment attribute

NZFARM predicts the single harbour sediment attribute (annual-average sedimentation rate, or AASR) under each scenario, which is reported for each of the nine depositional basins shown in Figure 4-5. For this, we developed a model for predicting the change in AASR that occurs in response to a reduction in catchment sediment load.

Table 5-6 shows, for each of the nine harbour depositional basins, the catchment sources of sediment, where catchments are shown in Figure 5-1. For example, 40% of the catchment sediment that deposits in harbour depositional basin ARIF originates from catchment WAR, and the remaining 60% originates from catchment ARR.

Table 5-6. Sources of catchment sediment for each of the nine harbour depositional basins shown in Figure 4-5. Catchments are shown in Figure 5-1.

Harbour depositional basin	**Catchment**									
	WAR (Wairoa R)	ARR (Arapaoa R)	OTR (Otamatea R)	WHR (Whakaki R)	ORR (Oruawharo R)	TAR (Tauhoa R)	HOR (Hoteo R)	APR (Araparera R)	MAR (Makarau R)	KKR (Kaipara/ Kaukapakapa R)
WAIF	1	0	0	0	0	0	0	0	0	0
ARIF	0.4	0.6	0	0	0	0	0	0	0	0
OTIF	0.3	0	0.7	0	0	0	0	0	0	0
TNSF	0.95	0	0	0	0	0	0.05	0	0	0
WHIF	0.5	0	0	0.5	0	0	0	0	0	0
ORIF	0.3	0	0	0	0.7	0	0	0	0	0
KAIF	0.1	0	0	0	0	0.1	0.8	0	0	0
MAIF	0	0	0	0	0	0	0.05	0.4	0.55	0
KPIF	0	0	0	0	0	0	0.05	0	0	0.95

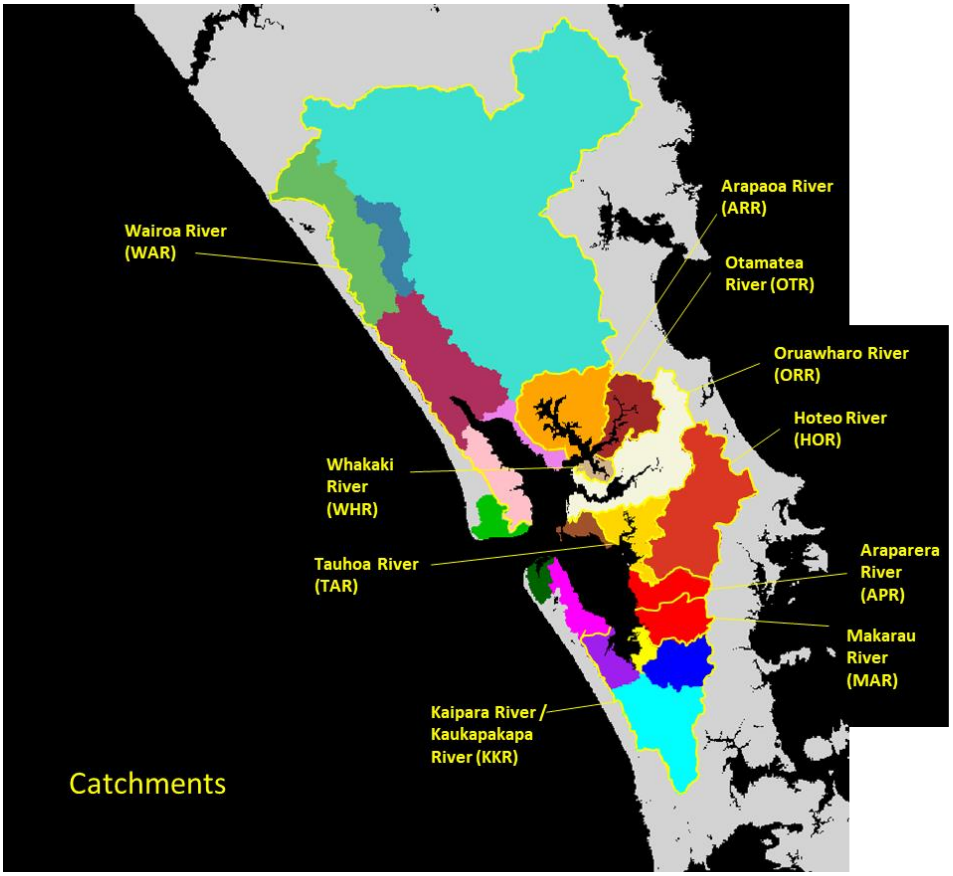

Figure 5-1. Catchments.

Comments

The model accounts for the fact that sediment deposited at any given location in the harbour may originate from any of numerous river catchments that drain into the harbour. For instance, sediment that deposits on the Kakarai (KAIF) intertidal flats at the mouth of the Hoteo River primarily originates from the catchment of the Hoteo River (HOR), but some also originates from further afield, for instance, from the catchment of the Tauhoa River (TAR) and the catchment of the Wairoa River (WAR). This is an important consideration, since mitigation may not be applied uniformly across the whole catchment of the Kaipara Harbour, which has to be accounted for.

The model also accounts for the fact that, in addition to the catchment sediment that deposits in the harbour, sediments of marine origin, washed in from the coastal ocean and dispersed and deposited by waves and currents, and shell hash that is produced *in situ*, may also deposit in any given depositional basin.

The partitioning between catchment and marine sources of sediment will affect the sensitivity of AASR to reductions in catchment sediment load. For instance, AASR in Kaipara (KPIF) depositional basin will be more sensitive to reductions in catchment sediment load due to mitigation since sedimentation in that basin is entirely due to catchment sediment (see Figure 4-4). AASR in Tinopai (TNSF) will be least sensitive, since a large proportion of the sedimentation at that location is due to marine sources of sediment (Figure 4-4), which are not affected by mitigation in the catchment.

6. Results

We repeat here that the *Baseline* scenario, against which the other scenarios are compared, comprises:

- 2014 catchment landuse,
- catchment sediment loads corresponding to 2014 catchment landuse with no mitigation,
- present-day freshwater sediment attribute states at seven locations in the catchment,
- present-day annual-average sedimentation rates in nine harbour depositional basins.

The no-mitigation assumption is significant:

- No mitigation was assumed for the *Baseline* because we were not able to precisely quantify and locate present-day efforts at sediment mitigation in the catchment (e.g., fences to exclude livestock from water bodies, poplar or willow trees planted to stabilise highly erodible pasture, or constructed wetlands).

Because the *Baseline* does not account for present-day mitigation, costs and benefits (e.g., net revenue and reductions in catchment sediment load) that are shown as, for instance, percentage change relative to the *Baseline*, will be overstated.

Caveats on the *Baseline* scenario

Daigneault et al. (2017) discuss caveats associated with the definition of the *Baseline* scenario.

Appendix 6 of Daigneault et al. (2017) explains in detail why a no-mitigation baseline was used instead of a current-mitigation baseline.

6.1 Area of land with effectively-implemented mitigation option

Figure 6-1 shows, for each mitigation option, the total area (hectares) of farms or forests that have the mitigation option effectively implemented on at least a portion of it. It is not the area physically occupied by mitigation. For multiple mitigation options (e.g., "Farm Plan & Fencing") the area represents farms that have more than one mitigation option implemented on the same land block.

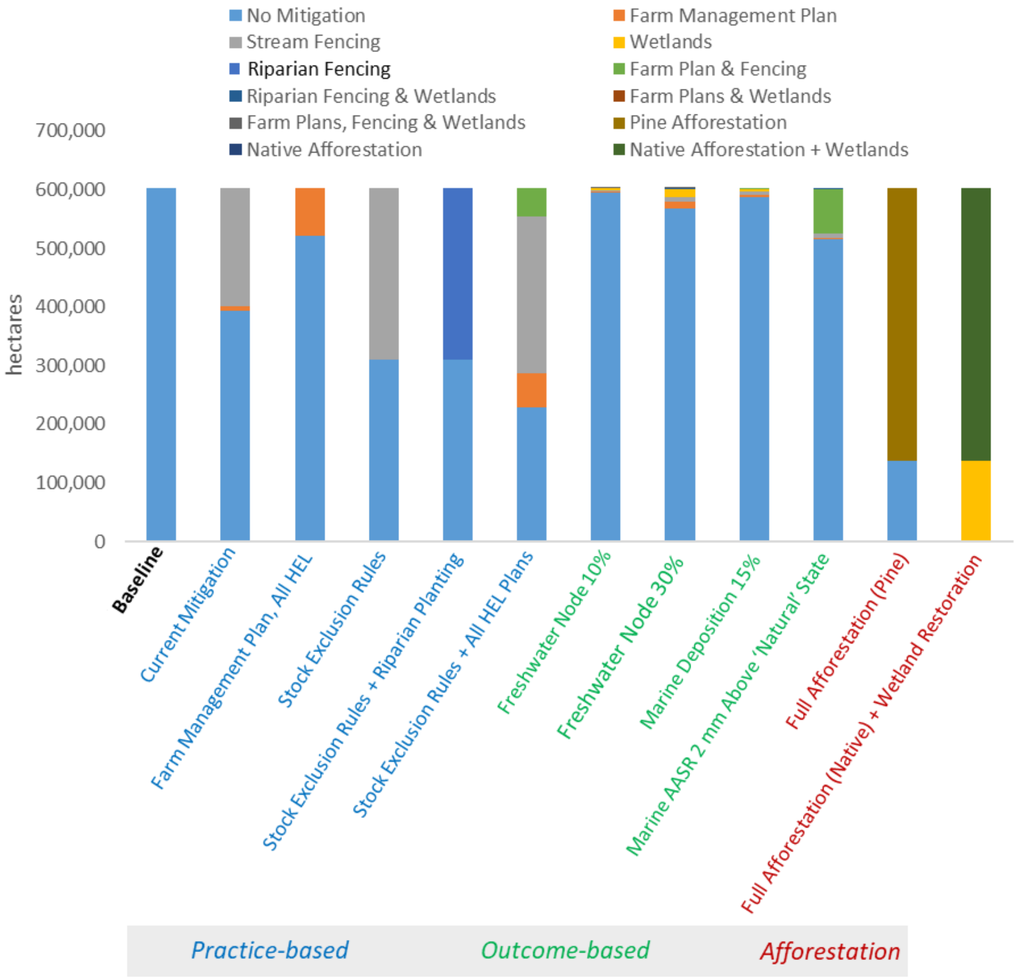

Figure 6-1. Area (ha) of land with effectively-implemented mitigation option by scenario. Data underlying the figure are provided in Appendix 5 (Table A.5.5) of Daigneault et al. (2017).

Results

Nearly all of the mitigation options are estimated to be implemented on what is currently pastoral land. Between 13% and 62% of the total area in the catchment will have some mitigation implemented on a part of the land, depending on scenario.

6.2 Annualised mitigation costs

Table 6-1. Annualised mitigation costs by landuse in $ per hectare per year.

		Landuse									
Scenario number	**Scenario name**	Dairy	Sheep & Beef	Deer	Lifestyle Blocks	Arable & Horticulture	Forestry	Native Bush	Other	**Total area***	**Mitigation area only****
Baseline Scenario											
0	Baseline	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Sediment-Mitigation Scenarios											
Practice-based											
1	Current Mitigation	$10	$17	$18	$17	$0	$0	$0	$0	$11	$32
2	Farm Management Plan, All HEL	$4	$7	$7	$2	$0	$0	$0	$0	$4	$32
3	Stock Exclusion Rules	$12	$29	$34	$35	$0	$0	$0	$0	$17	$36
4	Stock Exclusion Rules + Riparian Planting	$140	$69	$96	$92	$0	$0	$0	$0	$69	$141
5	Stock Exclusion Rules + All HEL Plans	$16	$35	$41	$37	$0	$0	$0	$0	$22	$35
Outcome-based											
6	Freshwater Node 10%	$0.5	$0.4	$0.0	$0.4	$0.0	$0.0	$0.0	$0.0	$0.3	$31.0
7	Freshwater Node 30%	$2.3	$2.8	$1.4	$2.8	$0.0	$0.0	$0.0	$0.0	$1.9	$34.0
8	Marine Deposition 15%	$1.2	$1.2	$28.2	$1.9	$0.0	$0.0	$0.0	$0.0	$1.1	$42.0
9	Marine AASR 2 mm Above 'Natural' State	$3	$19	$419	$99	$5	$0	$0	$0	$14	$101
Landuse-Change Scenarios											
Afforestation											
10	Full Afforestation (Pine)	$1,659	$1	$595	$1	$3,645	$0	$0	$10	$424	$549
11	Full Afforestation (Native) + Wetland Restoration	$2,054	$39	$990	$66	$4,040	$37	$25	$14	$550	$550

* Estimated as total mitigation cost divided by total area for each landuse.

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

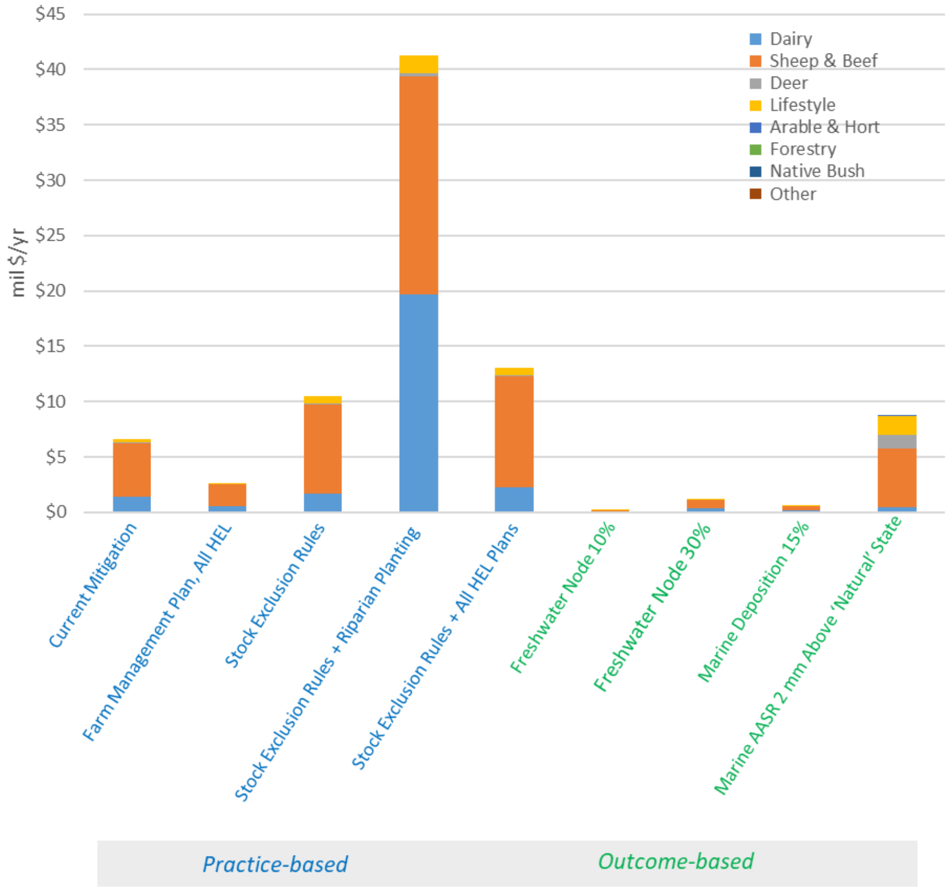

Figure 6-2. Annualised mitigation costs for the practice-based and outcome-based scenarios by landuse. Data underlying the figure are provided in Appendix 5 (Table A.5.6) of Daigneault et al. (2017).

Results

1. Sheep and beef farms face the largest total and per-hectare costs for nearly all scenarios. This is expected, as sheep and beef farms comprise the largest area of productive land and pasture in the catchment, are often located on land with high erosion rates, and have the greatest length of streams running through them.
2. The total costs for scenarios that include fencing and farm management plans as mitigation options may be overstated by as much as $6.6 million/y, as some dairy and sheep and beef farmers have already fenced some or all of their streams.
3. Higher per-hectare costs are generally for the scenarios that account for opportunity costs due to taking some land out of production (e.g., by riparian fencing or wetland construction).
4. Many of the estimates appear cheaper than one may anticipate, because mitigation practices are not necessarily implemented on every parcel of land in the catchment. For example, both the *Stock Exclusion Rules* and *Farm Management Plan, All HEL* scenarios assume that mitigation is only implemented on pastoral farms that meet certain criteria, which are defined by landuse, slope, and annual erosion rate.

6.3 Reduction in total catchment sediment load relative to *Baseline* scenario

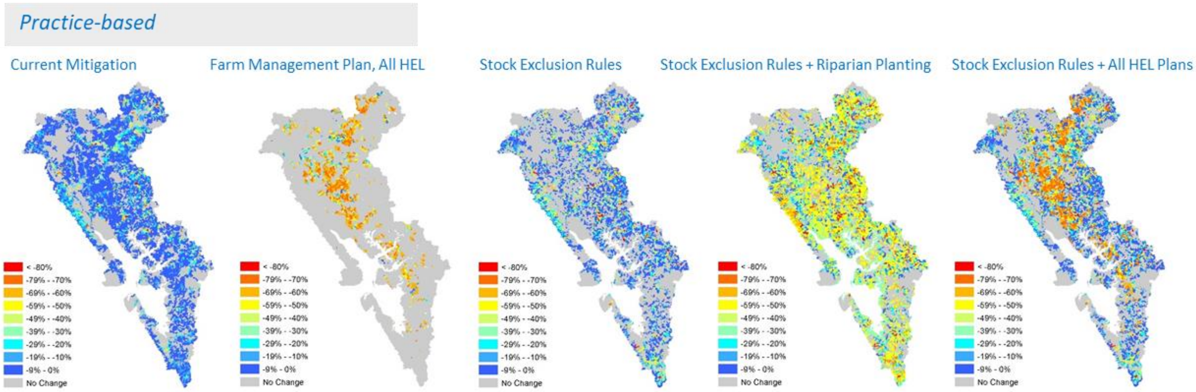

Figure 6-3. Total catchment sediment load (land-based plus streambank sources) as % of *Baseline* scenario – practice-based scenarios. (See Appendix for figure enlargement.)

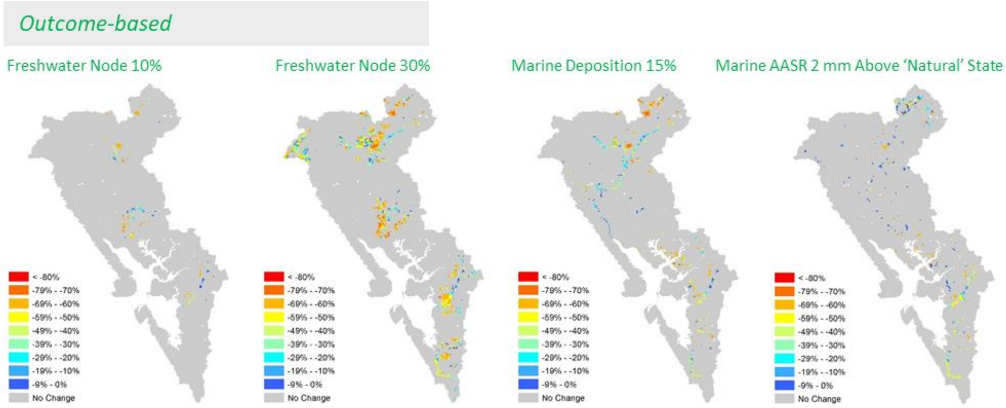

Figure 6-4. Total catchment sediment load (land-based plus streambank sources) as % of *Baseline* scenario – outcome-based scenarios. (See Appendix for figure enlargement.)

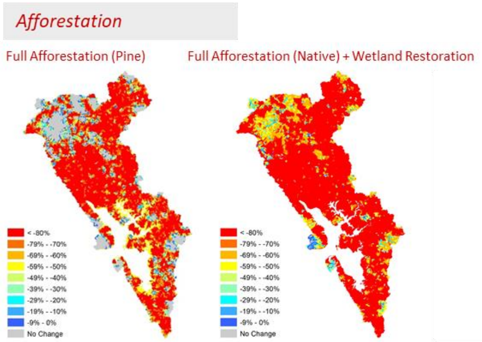

Figure 6-5. Total catchment sediment load (land-based plus streambank sources) as % of *Baseline* scenario – afforestation scenarios. (See Appendix for figure enlargement.)

Results

1. HEL farm management plans primarily are effective at reducing sediment along a northwest to southeast ridge across the middle of the catchment. Fencing and riparian planting are effective across the entire catchment (Figure 6-3).
2. For the outcome-based scenarios (Figure 6-4), the areas where mitigation practices are applied and sediment loads reduced are concentrated in small but specific areas of the catchment. Interestingly, although the two *Freshwater Node* objectives are distinctly different to the *Marine Deposition 15%* objective, the areas where sediment is reduced are similar for all of those scenarios. The most obvious difference is that reductions under *Marine Deposition 15%* tend to be concentrated along major streams in the catchment, but reductions under the two *Freshwater Nodes* scenarios tend to be located in more upland parts of the catchment. This makes sense, since the freshwater nodes themselves tend to be located in upland parts.
3. The two afforestation scenarios (Figure 6-5) indicate that there is potential for significant sediment reductions throughout the catchment. The *Full Afforestation (Native) + Wetland Restoration* scenario shows that additional reductions can be had not only when planting trees on land that is currently pasture, but also when restoring wetlands throughout the catchment, including in areas that are still forested today.

6.4 Net revenue, mitigations costs and catchment sediment loads by scenario

Table 6-2. Net revenue, mitigation costs and catchment sediment loads by scenario.

Scenario number	Scenario name	Net revenue (mil $)	Total mitigation cost (mil $/y)*	Average mitigation cost ($/(t.y)*	Land sources of sediment (t/y)	Streambank erosion sources of sediment (t/y)	Total catchment sediment load (land plus streambank) (t/y)
Baseline Scenario							
0	Baseline	$372.10	$0	$0	358,510	332,982	691,492
	Change from Baseline						
Sediment-Mitigation Scenarios							
	Practice-based						
1	Current Mitigation	–2.0%	$6.6	$81	–5%	–19%	–12%
2	Farm Management Plan, All HEL	–1.0%	$2.6	$13	–54%	0%	–28%
3	Stock Exclusion Rules	–3.0%	$10.5	$118	0%	–27%	-13%
4	Stock Exclusion Rules + Riparian Planting	–11.0%	$41.3	$194	–25%	-37%	–31%
5	Stock Exclusion Rules + All HEL Plans	–3.0%	$13.0	$46	–54%	–27%	–41%
	Outcome-based						
6	Freshwater Node 10%	–0.1%	$0.2	$5	–8%	-3%	–6%
7	Freshwater Node 30%	–0.3%	$1.2	$10	–24%	9%	–17%
8	Marine Deposition 15%	–0.2%	$0.6	$6	–17%	-13%	–15%
9	Marine AASR 2 mm Above 'Natural' State	–2.3%	$8.7	$84	–11%	-5%	–8%
Landuse-Change Scenarios							
	Afforestation						
10	Full Afforestation (Pine)	–69%	$255.3	$543	–66%	-71%	-68%
11	Full Afforestation (Native) + Wetland Restoration	–89%	$330.8	$546	–90%	–85%	–88%

* Costs annualised over 25 years at a discount rate of 8%.

Comments

The *Full Afforestation (Pine)* and *Full Afforestation (Native) + Wetland Restoration* scenarios are unrealistic because they take virtually all land out of production. Nevertheless, they show the upper bounds of what could be achieved in respect of catchment sediment reduction, e.g., 88% reduction of total catchment sediment load under *Full Afforestation (Native) + Wetland Restoration*.

In most cases, land-based sediment (landslide, earthflow, gully erosion) is reduced more than sediment from streambanks. The two main exceptions are the *Current Mitigation* and the *Stock Exclusion Rules* scenario. This is because fencing streams without any other mitigation practices does not have an impact on land-based sediment.

Results – Afforestation scenarios

1. Afforesting the 77% of the catchment that is currently not covered with woody vegetation (both afforestation scenarios) could reduce total catchment sediment load by 68–88%. The cost is between $255 and $331 million per year, much of which is attributed to opportunity cost.
2. The *Full Afforestation (Native) + Wetland Restoration* scenario indicates that total annual-average pre-human settlement catchment sediment loads were approximately 85,000 t/y. This translates into an average, over all 9 harbour depositional basins, AASR of 0.4 mm/y.

Results – Practice-based scenarios

1. Most of the practice-based scenarios require mitigation to be implemented on a much greater area of the catchment (compared to the outcome-based scenarios), yielding average mitigation costs of $46/tonne or more.
2. The exception in the case of the practice-based scenarios is *Farm Management Plan, All HEL*, which targets areas with relatively high erosion rates, resulting in significant reductions in sediment loss at relatively low cost ($2.60 million per year annualised, equivalent to a 1% reduction in net revenue in the catchment compared to the *Baseline* scenario).
3. Implementing the NZ Government's "Clean Water" stock exclusion rules (*Stock Exclusion Rules* scenario) is estimated to cost about $10.5 million per year, which is equivalent to a 3% reduction in net revenue in the catchment compared to the *Baseline* scenario, and which will achieve a 27% reduction in sediment from streambank sources and a 13% reduction in total catchment sediment runoff. The new rules are possibly not as effective as anticipated, as fencing is assumed to reduce streambank erosion by only 50% compared to an unfenced stream (see Table 5-4).
4. Extending the stock exclusion rule to require 5 m stream buffers with riparian planting (*Stock Exclusion Rules + Riparian Planting*) would reduce total catchment sediment load by 31%, at an added cost of $41.0 million per year, which is equivalent to an 11% reduction in net revenue in the catchment compared to the *Baseline* scenario.
5. Combining the stock exclusion rules (with fencing but no riparian planting) with farm management plans on all HEL (*Stock Exclusion Rules + All HEL Plans*) reduces total catchment sediment load by 41% at a cost of about $13.0 million per year (3% reduction in net revenue in the catchment compared to the *Baseline* scenario). This cost is equivalent to about $50 per hectare per year on farms where the mitigation practices are implemented, although actual costs may be less for farms that have already implemented some mitigation practices that were not accounted for in the no-mitigation *Baseline* scenario.

Results – Outcome-based scenarios

1. For three of the four outcome-based scenarios, the average cost of mitigation is between \$5 and \$10 per tonne of sediment mitigated. Costs are generally less than under the practice-based scenarios because the model targets areas with the most cost-effective mitigation potential and hence requires less total area in the catchment to implement mitigation practices.
2. Load-reduction targets under the *Freshwater Node 10%* and *Freshwater Node 30%* scenarios could be achieved at relatively small cost (\$0.2 to \$1.2 million per year). This is because reductions can be achieved by specifically targeting farm plans, stream fencing and wetland construction on 6,000 to 32,000 ha of pastoral land with very high erosion rates and relatively low implementation costs per tonne of sediment mitigated. Total catchment sediment is reduced by 6% and 17%, respectively, relative to the no-mitigation *Baseline* scenario, with these reductions being concentrated in the seven target areas.
3. Reducing by 15% the amount of catchment sediment that reaches all of the harbour depositional basins (*Marine Deposition 15%*) could be achieved for \$0.6 million per year, and could be achieved by targeting about 15,000 ha of farms with a relatively even split of farm plans, stream fencing, and wetland construction (see Figure 6-1). However, this may not have a large effect on annual-average sedimentation rate in the harbour, since marine sediment, which is not reduced by sediment mitigation in the catchment, also contributes to sedimentation.
4. The *Marine AASR 2 mm Above 'Natural' State* scenario has a much higher cost than the other outcome-based scenarios: \$8.7 million per year, equivalent to about a 2.3% decline in net revenue relative to the *Baseline* scenario. This is primarily because three of the nine basins (KAIF, MAIF and KPIF, all in the southern harbour) all require the catchment-sediment component of the AASR to be significantly reduced (by 28%, 31% and 55%, respectively, see Table 5-2) to achieve the AASR target, which requires mitigation having to be implemented over a significant area. The model estimates that most of the mitigation will come in the form of combining farm management plans with fencing of streams, including on many farms with minimal baseline erosion rates.

Comment

Only load-reduction targets (i.e., outcomes) were investigated for freshwater. Both a load-reduction target and an attribute target were investigated for the harbour. Attribute targets were not investigated for freshwater.

7. Benefits inferred from predicted changes in sediment attributes

7.1 Freshwater

Figure 7-1 shows the freshwater sediment attributes predicted under each of the scenarios (including *Baseline*) for each of the seven freshwater reporting nodes.

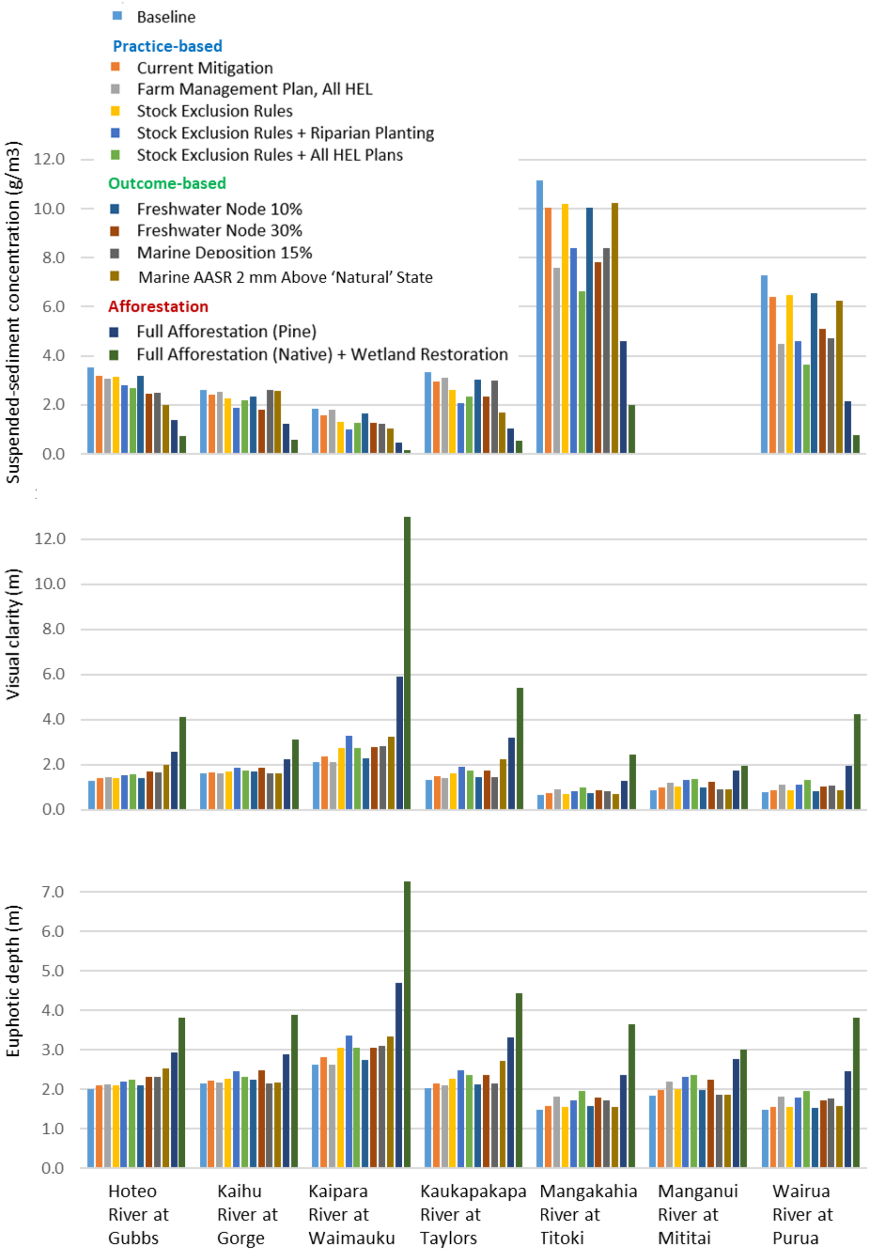

Figure 7-1. Suspended-sediment concentration, visual clarity and euphotic depth at each of the freshwater reporting nodes. Data for suspended-sediment concentration were not available for Manganui River at Mititai. Data underlying the figure are provided in Appendix 5 (Tables A.5.2 to A.5.4) of Daigneault et al. (2017).

Comments

Considered across all scenarios:

- Suspended-sediment concentration was highest in the Mangakahia River, second-highest in the Wairua River, third-highest in the Hoteo, Kaihu and Kaukapakapa Rivers, and lowest in the Kaipara River.
- Clarity and euphotic depth were both higher in the Kaipara River than in all the other rivers.
- Euphotic depth was intermediate in the Hoteo, Kaihu, Kaukapakapa and Manganui Rivers, and lowest in the Wairua and Mangakahia Rivers.

Results (1)

In terms of achieving improvements in the freshwater sediment attributes, only the two full-afforestation scenarios really stand out above the *Baseline* scenario. The improvements in attributes, averaged across all seven freshwater reporting nodes, are shown in Table 7-1 for the two full-afforestation scenarios.

Scenario	Change compared to *Baseline*	Change compared to *Current Mitigation*
	Suspended-sediment concentration	
Full Afforestation (Pine)	↓64%	↓59%
Full Afforestation (Native) + Wetland Restoration	↓84%	↓81%
	Visual clarity	
Full Afforestation (Pine)	↑119%	↑98%
Full Afforestation (Native) + Wetland Restoration	↑294%	↑257%
	Euphotic depth	
Full Afforestation (Pine)	↑58%	↑48%
Full Afforestation (Native) + Wetland Restoration	↑120%	↑106%

Table 7-1. Percentage changes in sediment attributes relative to the *Baseline* and *Current Mitigation* scenarios, averaged across all seven freshwater reporting nodes. A negative change (signified by ↓) in suspended-sediment concentration is an improvement. A positive change (signified by ↑) in visual clarity and euphotic depth is an improvement.

The performance of *Full Afforestation (Pine)* is not much below the maximum attainable under *Full Afforestation (Native) + Wetland Restoration*, which would require considerably more effort without any potential future economic return.

Results (2)

- Both full-afforestation scenarios are predicted to reduce suspended-sediment concentration to less than the lowest values observed in a study of the Pomahaka River (South Otago), which generally were associated with healthy stream invertebrate and fish faunas.
- Native New Zealand fish such as galaxiids are at least partly nocturnal and also use lateral lines to locate their prey. Therefore, achieving improvements in visual clarity may not be necessary for them. Based on a US study, salmonid visual hunting abilities may not be significantly impaired given typical *Baseline* clarity.
- Increases in euphotic depth may not be ecologically relevant given that average (across all seven freshwater nodes) euphotic depth is already almost 2 m under the *Baseline* scenario, although there may be benefits in deeper reaches through increased light causing an increase in primary production, which provides more food for higher trophic levels (e.g., grazing invertebrates and, indirectly, predators feeding on the grazers). On the other hand, stream shading will increase under tall riparian vegetation, thus reducing in-stream light levels, which could negate the increased euphotic depth. More light reaching streams could increase the risk of problem algae. However, this should not be an issue, since nutrient runoff would be greatly reduced under the full- afforestation scenarios.

Notwithstanding the assessment of visual clarity and euphotic depth, we conclude that it is reasonable to expect that stream invertebrate and fish communities would become significantly healthier if one of the full-afforestation scenarios were implemented.

Results (3)

Stock Exclusion + All HEL Plans also has the potential to yield beneficial outcomes.

- *Stock Exclusion + All HEL Plans* is predicted to reduce suspended-sediment concentration compared to *Baseline* by 51% in the Wairua River, 41% in the Mangakahia River, 32% in the Kaukapakapa River and 28% in the Kaipara River. It is also predicted to increase water clarity compared to *Baseline* by about 0.5 m at four of the seven freshwater reporting nodes (Kaipara, Kaukapakapa, Manganui and Wairua Rivers), and euphotic depth by the same amount at three of the seven freshwater reporting nodes (Kaipara, Kaukapakapa and Wairua Rivers).

Results (4)

The predictions for visual clarity under several of the mitigation scenarios that did not involve full afforestation have encouraging implications for human contact recreation in rivers.

- Existing guidelines recommend that visual clarity should be > 1.6 m for contact recreation. Average (over all freshwater nodes) visual clarity under the *Baseline* scenario (1.24 m) and the *Current Mitigation* scenario (1.37 m) are below that threshold. Under four of the sediment-mitigation scenarios, visual clarity is predicted increase to values at or slightly above the 1.6 m guideline. These four scenarios are *Freshwater Node 30%* (1.60 m), *Marine AASR 2 mm Above 'Natural' State* (1.64 m), *Stock Exclusion Rules + All HEL Plans* (1.66 m), and *Stock Exclusion Rules + Riparian Planting* (1.67 m). These increases in visual clarity may be a benefit for those people living in the catchment who would enjoy swimming in rivers.

Comment (1)

Only load-reduction targets (i.e., outcomes) were investigated for freshwater (Scenarios 6 and 7). Attribute targets were not investigated for freshwater.

Comment (2)

Adverse ecological effects of suspended fine sediment in streams and rivers have been much less extensively researched than those of deposited fine sediment, which are known to be far-reaching and include a number of well-documented negative effects on stream invertebrates, fish and ecosystem processes. Deposited sediment alters the physical habitat by clogging interstitial spaces used as refugia by benthic invertebrates and fish, degrades food resources, and reduces the number of sites suitable for egg laying, thus affecting the diversity and composition of biotic communities. Clapcott et al. (2011) predicted that contemporary fine-sediment cover in streams and rivers of Kaipara Harbour catchment varies mainly between 60–100%, whereas the reference fine-sediment cover (in the absence of human landuse) is considerably lower at 20–50%. The very high contemporary fine-sediment cover should be at least partly reversible, with expected positive effects on stream communities, making reducing in-stream deposited fine sediment a worthwhile longer-term goal to aim for.

7.2 Harbour

Table 7-2 and Figure 7-2 show annual-average sedimentation rate (AASR) predicted under each of the scenarios for each of the nine harbour depositional basins. The final column in Table 7-2 is an adverse-effects threshold, which is 2 mm/y on top of the AASR under the *Full Afforestation (Native) + Wetland Restoration* scenario. The green bars in Figure 7-2 show the same adverse-effects threshold.

Table 7-2. Annual-average sedimentation rate (mm/y) in each of the harbour depositional basins under each scenario. Data in the table are from Appendix 5 (Table A.5.1) of Daigneault et al. (2017). The final column is the adverse-effects threshold. Predictions of AASR that exceed the adverse-effects threshold are shown in bold red.

Harbour depositional basin	**Scenario**												**Adverse-effects threshold**
	Baseline	Current Mitigation	Farm Management Plan, All HEL	Stock Exclusion Rules	Stock Exclusion Rules + Riparian Planting	Stock Exclusion Rules + All HEL Plans	Freshwater Node 10%	Freshwater Node 30%	Marine Deposition 15%	Marine AASR 2 mm Above 'Natural' State	Full Afforestation (Pine)	Full Afforestation (Native) +Wetland Restoration	
WAIF	**3.0**	2.7	2.3	2.7	2.2	2.0	2.9	2.6	2.6	2.9	1.4	0.9	2.9
ARIF	2.0	1.8	1.4	1.8	1.5	1.3	2.0	1.9	1.7	1.8	0.7	0.4	2.4
OTIF	**3.0**	2.8	2.1	2.8	1.9	1.9	**3.0**	**2.9**	2.6	2.8	1.3	0.8	2.8
TNSF	1.5	1.5	1.4	1.5	1.4	1.4	1.5	1.4	1.5	1.5	1.3	1.2	3.2
WHIF	2.0	1.8	1.3	1.9	1.0	1.2	1.9	1.8	1.7	1.4	0.7	0.3	2.3
ORIF	**3.0**	2.8	2.2	2.8	2.5	2.0	**3.0**	2.9	2.6	2.9	1.3	0.9	2.9
KAIF	**6.5**	**6.1**	**5.9**	**6.1**	**5.8**	**5.5**	**6.2**	**5.5**	**5.9**	5.1	4.1	3.4	5.4
MAIF	**4.0**	**3.9**	**3.8**	**3.9**	**3.0**	**3.7**	**4.0**	**3.9**	**3.5**	2.9	2.9	0.9	2.9
KPIF	**7.0**	**6.0**	**6.7**	**5.1**	**4.1**	**4.8**	**6.3**	**5.0**	**6.0**	3.2	1.9	1.2	3.2

Adverse-effects threshold

The predictions of annual-average sedimentation rate are assessed against an adverse-effects threshold, developed by Townsend and Lohrer (2015), of 2 mm of sediment accumulation per year above the "natural annual sedimentation rate". The natural annual sedimentation rate that is factored into the threshold is defined as the rate under native-forested catchment prior to human occupation. The natural annual sedimentation rate may vary between different estuaries and within different parts of an individual estuary. We take the natural annual sedimentation rate to be the AASR predicted under the *Full Afforestation (Native) + Wetland Restoration* scenario. Note that AASR, and therefore the natural annual sedimentation rate in the threshold, may include both catchment and marine sources of sediment.

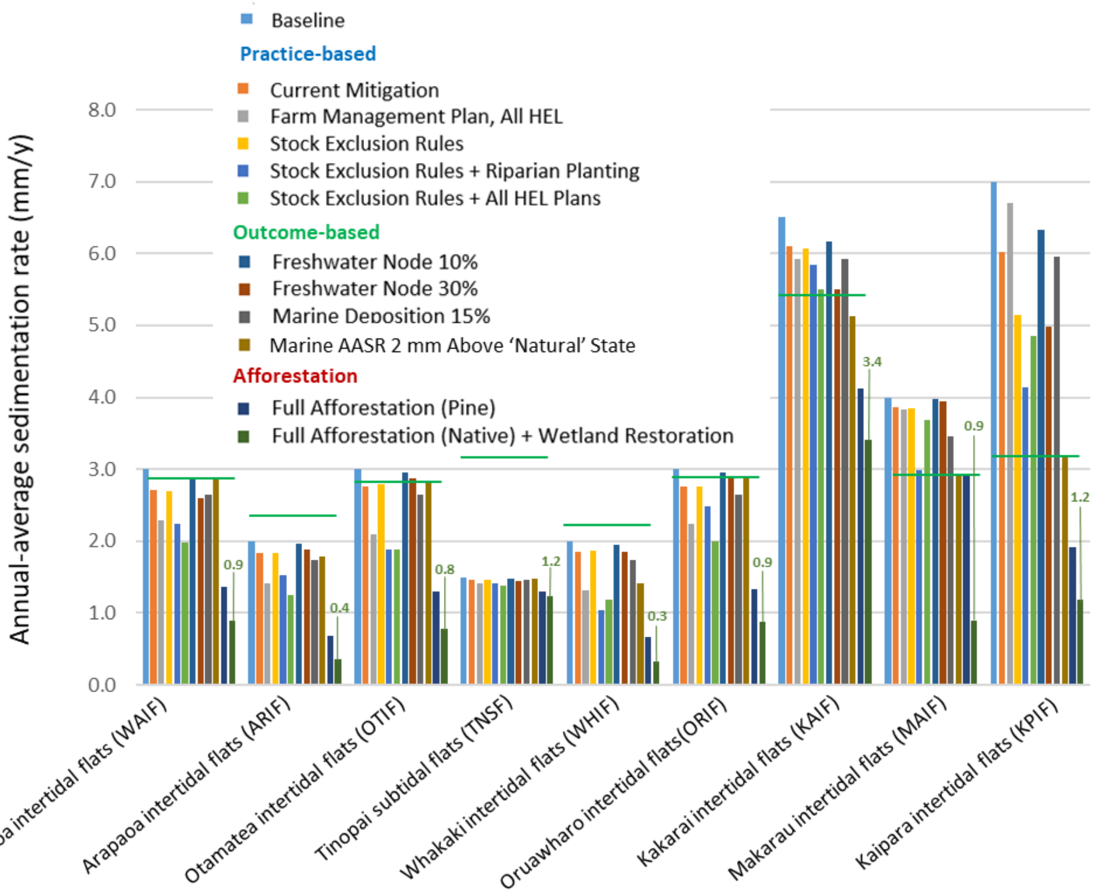

Figure 7-2. Annual-average sedimentation rate (mm/y) in each of the harbour depositional basins under each scenario. Data underlying the figure are provided in Appendix 5 (Table A.5.1) of Daigneault et al. (2017). The green horizontal bar shows the adverse-effects threshold for each depositional basin.

Comments

Sediment mitigation and landuse change in the catchment only reduce the component of the AASR that is due to catchment sources of sediment; it does not reduce marine sources of sediment.

There is wide variation in AASR across basins under the various scenarios. This is because the proportion of land and streambank sediment deposited varies from basin to basin, and thus a mitigation practice that targets one type of erosion may be more effective than another.

Comment

Both a load-reduction target (Scenario 8) and an attribute target (Scenario 9) were investigated for the harbour.

Results (1)

With the exception of both of the afforestation scenarios and the *Marine AASR 2 mm Above 'Natural' State* scenario (which achieves a specific target sedimentation rate), AASR is mostly not predicted to reduce by more than about 1 mm/y in any of the harbour depositional basins. This is because reductions in land and streambank sources of sediment in the areas of the catchment that are sources of sediment to the basins are relatively small.

Results (2)

In five of the depositional basins, all within the northern sector of the harbour, *Baseline* AASR is within a fraction of a millimetre per year of the adverse-effects threshold. These basins are WAIF, ARIF, OTIF, WHIF and ORIF.

- These basins will be experiencing some level of sediment stress and will benefit from management interventions to reduce catchment sediment runoff.
- In addition to the two afforestation scenarios, *Stock exclusions + All HEL plans* is predicted to reduce AASR by more than 1 mm/year in all five zones.

Results (3)

Baseline AASR exceeds the adverse-effects threshold by at least 1 mm/year in three of the depositional basins, all of which are in the southern sector of the harbour. These basins are KAIF, MAIF and KPIF.

Only a few scenarios are predicted to reduce AASR to less than or close to the adverse-effects threshold:

- AASR under both full-afforestation scenarios is predicted to be significantly less than the threshold in KAIF and KPIF. In MAIF, AASR is significantly less than the threshold under *Full Afforestation (Native) + Wetland Restoration* and close to the threshold under *Full Afforestation (Pine)*.
- The *Marine AASR 2 mm Above 'Natural' State* scenario reduces AASR to the threshold in all three basins.
- Both *Freshwater Node 30%* and *Stock Exclusion Rules + All HEL Plans* are predicted to reduce AASR to close to the threshold in KAIF. No other scenario is predicted to reduce AASR to close to the threshold in MAIF or KPIF.

Results (4)

In KAIF, MAIF and KPIF, reducing AASR to less than or close to the adverse-effects threshold should result in benefits to the benthic ecology:

- KAIF. Although the seabed is very muddy close to the mouth of the Hoteo River, there are extensive sandy intertidal flats further offshore with seagrass beds and cockles (*Austrovenus stutchburyi*). Cockles provide an important recreational and cultural food source for humans; are an important prey item for birds, rays and other fish; and are functionally important, for example, nutrient recycling and water filtering. Cockles are sensitive to excessive sediment, and hence stand to benefit from reductions in sediment, boosting the cockle population and the ecosystem functions and services that they provide.
- MAIF. The seabed is muddy, although not uniformly, and mainly dominated by polychaetes. The most abundant bivalve species is *Hiatula siliquens*, followed by the wedge shell *Macomona liliana*. Cockles are present, but low in number. Management interventions to reduce catchment sediment may have positive effects on the densities of shellfish.
- KPIF. The seabed is muddy. There are medium to high densities of shellfish such as *Macomona liliana*. Like cockles, *Macomona* is an important prey item for birds, rays and other fish, and provides important functions such as nutrient recycling and water filtering. Also like cockles, *Macomona* is sensitive to excessive sediment, and therefore stand to benefit from reductions in sediment, with corresponding improvements in associated ecosystem functions and services.
- Intervention in the catchment to reduce sediment runoff will potentially have the greatest effect in KPIF, since all the sediment deposited in that basin is judged to derive from catchment sources (see Figure 4-4).

Results (5)

Bed-sediment muddiness is likely to be a key determinant of the trajectory of any recovery. Specifically, ecological health may improve only slowly with reductions in sedimentation rate at sites where the seabed currently has greater than 20% mud.

- The less muddy seabed at KAIF offshore from the Hoteo River will see faster recovery following any intervention in the catchment.
- The extensively muddy seabed at MAIF and KPIF will hinder improvements and lengthen the time over which any recovery of the benthic ecology will occur.

Annual-average sedimentation rate as a management metric – important caveats

Annual-average sedimentation rate as a metric to guide management does not necessarily fully address the issue of sediment stress, which is a multi-faceted, multiplicative combination of rare but catastrophic sedimentation events, gradual muddying of the seabed, the areal expansion of muddy habitats, and increases in suspended-sediment concentrations. Inferring improvements from reductions in annual-average sedimentation rate alone is therefore challenging and should, at this stage, be viewed as indicative.

This was the first attempt in New Zealand to assess ecological implications from an adverse-effects threshold for annual-average sedimentation rate. Although the threshold was developed by experts and based on information in the scientific literature, the threshold requires more testing and refinement.

Although annual-average sedimentation rate can be treated as indicative of estuarine ecological health and functioning, management actions and strategies still need to be nested within a wider framework that considers different modes of impact by sediments.

The main application of this modelling exercise may be identifying the basins that are most at risk at present and exploring the cost effectiveness and relative benefits of alternative management actions.

8. Uncertainties and limitations

General

Overall, “average” (as opposed to “extreme”) drivers and metrics (e.g., annual-average catchment sediment load, annual-average sedimentation rate, median suspended-sediment concentration) were employed in analyses. These do not capture events that might occur during any given year (for example, during large rainstorms) or variability that might occur from year to year.

Sediment is not the only cause of environmental degradation of freshwater and estuarine ecosystems.

Climate change was not addressed.

NZFARM

NZFARM should be used to provide insight on the relative impacts and trade-offs across a range of policy scenarios, rather than to explicitly model the absolute impacts of a single policy scenario. The NZFARM predictions should be used in conjunction with other decision support tools and information not necessarily included in the model to evaluate the best approach to managing sediment.

NZFARM models “representative farms”; it does not model specific farms in the catchment. Some landowners in the catchment may face higher or lower costs than predicted using representative farms.

For the *Baseline* scenario, NZFARM assumed: (1) 2014 landuse, (2) net farm revenue based on a 5-year average of input costs and output prices over the period 2010–2014), and (3) no landowners were implementing management practices intended to reduce catchment soil erosion. The third assumption is likely to have the greatest impact on model predictions, as Northland Regional Council and Auckland Council have indicated that some farms in the catchment have implemented farm plans and/or fenced streams. Because *Baseline* does not account for present-day mitigation, costs and benefits (e.g., net revenue and reductions in catchment sediment load) that are shown as, for instance, percentage change relative to the *Baseline*, will be overstated.

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

Each management practice included in NZFARM is assumed to have a fixed rate of effectiveness for reducing sediment loads. In reality, the actual effectiveness of any given practice is likely to vary depending on where, when, and how well the practice is implemented. A sensitivity analysis that quantifies the potential effect of adjusting the effectiveness rates for farm management plans, fencing streams, and riparian planting is presented in Appendix 6 of Daigneault et al. (2017).

All landowners are assumed to collectively select the optimal combination of management practices required to achieve specific outcomes related to managing sediment. This is assumed to occur over a period of at least 10 years, as landowners typically need adequate time to make significant changes to their operation. In reality, not all landowners will necessarily select the option that is considered to be optimal, and thus the actual effectiveness of the policy may be overstated.

NZFARM does not monetize the ecosystem services and functions that accrue from improving water quality.

NZFARM does not account for any flow-on effects of changes in landuse and land management beyond the farm gate. Possible flow-on effects include change in regional employment and GDP due to reductions in farm outputs as a result of taking land out of production. There could also be social and cultural impacts.

NZFARM predicts only a subset of possible metrics that could be used to determine best options for managing sediment at the catchment level.

SedNetNZ

SedNetNZ was calibrated against a very limited dataset.

Only the total catchment sediment load was addressed in the calibration; different erosion processes (e.g., gully erosion, streambank erosion) were not individually calibrated.

Freshwater

Sediment attributes were evaluated for only a limited number of freshwater reporting nodes (seven). The freshwater nodes are not necessarily representative or inclusive of all freshwater habitats in the catchment.

That suspended-sediment concentration percentiles all change exactly proportionately in response to a reduction in catchment sediment load is an assumption and is largely untested by data.

The methods for evaluating the freshwater sediment attributes from changes in suspended-sediment concentration are based on limited data.

Adverse ecological effects of deposited fine sediment were not addressed, which are known to be far-reaching and include well-documented negative effects on stream invertebrates, fish and ecosystem processes. It would ultimately be desirable to link catchment sediment loads to in-stream levels of not just suspended fine sediment but also deposited fine sediment. This is a challenge for future research.

Adverse ecological effects of suspended fine sediment in streams and rivers have been much less extensively researched than those of deposited fine sediment.

Only load-reduction targets (i.e., outcomes) were investigated for freshwater. No attribute targets were investigated.

Harbour

Sediment attributes were evaluated for only a limited number of harbour depositional environments (nine). The harbour depositional environments addressed in the analyses are not necessarily representative or inclusive of all depositional environments in the harbour.

Parameters required to evaluate annual-average sedimentation rate in the harbour given annual catchment sediment load were estimated from: a source-tracing study that addressed only a limited number of potential sources, a very limited range of numerical model simulations of harbour sediment transport, and very limited observations (e.g., percentage of bed sediment composed of shell hash).

Present-day annual-average sedimentation rate was estimated by direct measurement in only a few of the nine harbour depositional basins; for the other basins, it was estimated from a variety of indirect information.

An exclusive focus on sedimentation rate as a management metric will not fully address the wider issues of sediment as a stressor in estuarine environments. Sustained sedimentation, even at rates below the adverse-effects threshold used herein, may result in a long-term muddying of the seabed, which can result in one or more of the following: loss of mud-sensitive species from benthic communities, reduced biodiversity, loss of large functionally important species such as cockles. Sustained sedimentation may also result in elevated concentrations of suspended sediment, which may cause adverse effects.

There is little information that specifically links annual-average sedimentation rate to estuarine ecological health and functioning. In the absence of any other information, the adverse-effects threshold was based largely on experiments that found that 3 mm of sediment deposition in the immediate aftermath of a rainstorm was the minimum thickness capable of producing significant shifts in macrobenthic community structure.

The natural sedimentation rate that is factored into the adverse-effects threshold is not a measured value. Instead, we took the natural annual sedimentation rate to be the AASR predicted under the *Full Afforestation (Native) + Wetland Restoration* scenario.

The assessment of harbour ecological health and functioning is based on the annual-average sedimentation rate that arises from the deposition of both catchment- and marine-source sediment. This may over-estimate the extent of adverse effects since the benthic ecology will be stressed principally by just the catchment sediment.

9. Appendix

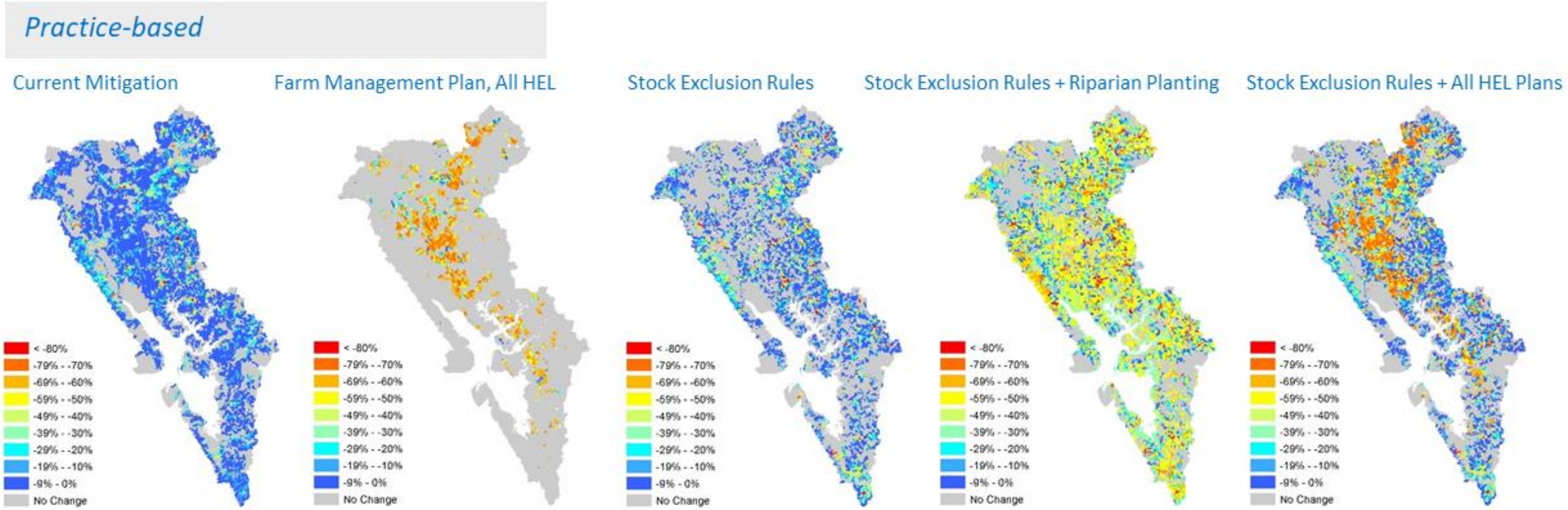

Figure 6-3. Total catchment sediment load (land-based plus streambank sources) as % of *Baseline* scenario – practice-based scenarios.

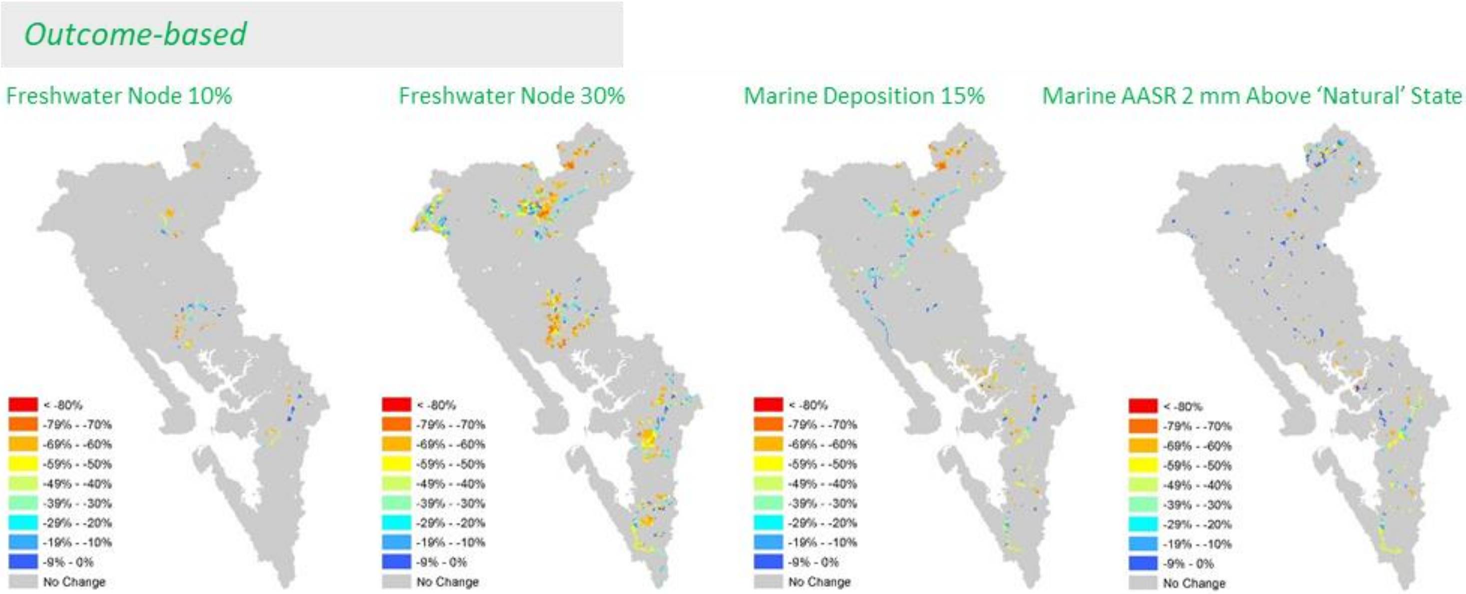

Figure 6-4. Total catchment sediment load (land-based plus streambank sources) as % of *Baseline* scenario – outcome-based scenarios.

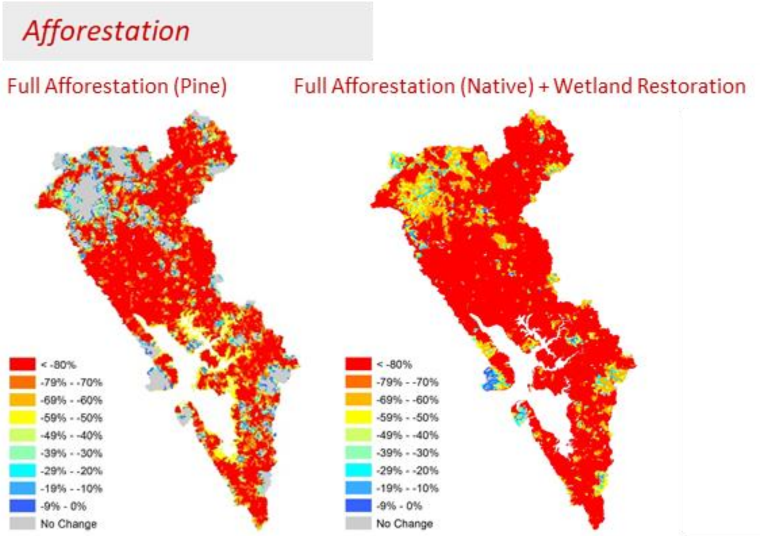

Figure 6-5. Total catchment sediment load (land-based plus streambank sources) as % of *Baseline* scenario – afforestation scenarios.

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