Manaaki Whenua
Landcare Research

National modelling of impacts of proposed sediment attributes: literature review and feasibility study

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Literature review and feasibility study for national modelling of sediment attribute impacts

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Summary

Project and Client

- The Ministry for the Environment (MFE) requires an analysis of the potential impacts (physical and economic) of proposed regulations for the National Objectives Framework (NOF) for managing in-stream sediment levels. Manaaki Whenua has been funded to 1) review knowledge of erosion and sediment mitigation effectiveness in reducing sediment loading, 2) review the costs and co-benefits of mitigations, and 3) undertake a feasibility study to identify at least two approaches to conduct a nationwide cost-benefit assessment for scenarios possible to meet required sediment load reductions

Objectives

- Summarise previous reviews of the effectiveness of erosion and sediment control (ESC) practices and review available data on timeframes for different ESC practices to become effective; the range of effectiveness for different ESC practices, and where possible explanations for the reason's effectiveness may vary; and on the effect of ESC practices on different particle size fractions;
- Describe how the effect of ESC practices has been incorporated into erosion and sediment models to provide estimates of sediment load reductions;
- Review available information on the costs and co-benefits of erosion and sediment mitigations;
- Summarise estimated values of direct costs and describe co-benefits of erosion avoidance and reduced sedimentation;
- Identify literature gaps and recommend parameter values for economic modelling;
- Prepare a feasibility study for a nationwide cost-benefit assessment of mitigations scenarios to meet sediment load reduction requirements necessary to achieve bottom line sediment thresholds, and provide two distinct approaches for developing mitigation scenarios to meet sediment load reduction requirements and for co-benefit calculations.

Methods

- Information on the range of erosion and sediment control practices and their effectiveness was summarised from previous reviews.
- The literature cited in these reviews was re-examined to extract information on the timeframes for different ESC practices to become effective, the range of effectiveness for different ESC practices, the reasons why effectiveness may vary, and the effect of ESC practices on different particle size fractions.
- A summary of approaches to modelling sediment load and incorporating the effects of erosion mitigation in New Zealand was prepared from published papers and reports. It describes how ESC practices are commonly bundled for modelling applications.

- Existing research on costs and co-benefits of ESC practices and sediment reduction in New Zealand was reviewed.
- The review considers the impacts of the ESC practices above and beyond water quality impacts, ways to value sediment and water quality impacts using non-market valuation, summarises values for costs and co-benefits of different mitigation options, and identifies gaps in the literature.
- The review is used to suggest two methods for a feasibility study of the costs and co-benefits of ESC practices for the proposed NOF sediment standards.

Results

- A wide variety of ESC practices are used in New Zealand, depending on the land use and the type of erosion process(es) generating sediment.
- ESC practices for runoff-generated erosion (sheet, rill, gully) can be broadly categorised as (1) water management to control runoff, reduce water velocity and sediment generation, and to separate clean water and dirty water; (2) erosion control to reduce sediment generation; and (3) sediment control to trap sediment before it moves offsite and into water ways. Control of these types of erosion typically involves a combination of biological control (using grass or cover crops for sheet and rill erosion, trees for gully erosion), mulches, geotextiles, and structural measures (such as sediment retention ponds).
- Mass movement erosion (landslides earthflows, slumps) is controlled by practices that influence slope hydrology and/or soil strength and is most often achieved by space-planted trees, afforestation, or reversion. The same ESC practices (especially afforestation) are often used for control of large scale mass movement-gully erosion.
- Streambank erosion is controlled by practices that reduce hydraulic scour, or increase bank strength and resistance to erosion; typically, riparian planting and fencing for stock exclusion are used to mitigate this process.
- Commonly used values for erosion reduction as a result of ESC practices are:
  - Surface erosion: wetlands – 60–80%, sediment retention ponds – 70% (with chemical treatment), 30% (without chemical treatment), silt fences – 99%, grass buffer strips – 40%, wheel track ripping – 90%, cover crops – 40%
  - Landslides, gully erosion: space-planted trees – 70%, afforestation or reversion – 90%,
  - Gully erosion: space-planted trees – 70%, afforestation or reversion – 90%, debris dams – 80%
  - Earthflows: space-planted trees – 70%, afforestation or reversion – 90%
  - Bank erosion: riparian fencing and/or planting – 50%
- There is a wide range for the effectiveness of some ESC practices but there has been little study of the factors affecting variation in performance of either afforestation or space planted trees. It is likely that several factors affect mitigation performance including: underlying susceptibility of the land to erosion, size of rainfall event, metric used for assessing performance, scale of investigation, adequacy of treatment. Variation in performance effectiveness for ESC practices used for earthworks is better

studied and a wide variety of factors influence performance depending on the individual ESC practice.

- Any of the ESC practices involving trees or shrubs (afforestation, space-planting, riparian or gully planting) take a relatively long time to become fully effective: afforestation and reversion – 10 years, space planted trees and gully tree planting – 15 years, riparian retirement with fencing: 2 years. Vegetative practices (e.g. cover crops, re-grassing) used to control surface erosion require development of near complete vegetation cover but the time scales for this are likely to be short (up to a year). Most of the practices that are used for earthworks erosion management are effective immediately.
- Little information is available on variation in the performance of different ESC practices with respect to trapping particles of different sizes but the effects are likely to be significant particularly for surface erosion and for several ESC practices including sediment retention ponds and buffer strips.
- Several models have been used in New Zealand to assess the effects of ESC practices in reducing erosion at site, catchment and national scale by both runoff-generated surface erosion as well as mass movement and gully erosion. The main models used are NZeem®, CLUES, USLE, SedNetNZ, and GLEAMS. Most of the models are long-term steady state models that provide prediction of average annual sediment yields. Typically, modelling involves bundling several different ESC practices into an analysis based on development and implementation of Whole Farm Plans and riparian exclusion of stock. USLE, and GLEAMS are commonly used for modelling the effects of erosion mitigation for urban earthworks with load reduction factors calculated to reflect the performance of several different sediment control practices that are usually used.
- Costs and co-benefits of erosion and sediment mitigation were synthesized from several different sources resulting in a wide variety in some costs.
- On average, ESC practices involving trees or managing erosion processes, including wetland, spaced planting and protection of gully heads, are more effective in reducing erosion but also costlier compared to riparian management practices.
- Co-benefits, in terms of reducing nitrogen, phosphorous, and *E. coli*, for afforestation and wetlands, are quite significant (with low uncertainty); however, high uncertainty has been identified for other range of ESC practices that manage erosion processes, such as swales, sediment ponds and detainment bunds, due to lack of information.
- The proposed feasibility study includes descriptions of possible methods that can be used to analyse costs and co-benefits of introducing sediment mitigation at the national level. For analysing the costs of sediment mitigation at the national level, we describe advantages and disadvantages of two versions of New Zealand Forest and Agriculture Regional Model (NZFARM). Both versions of the model are economic optimisation models that consider the decision-making of land users through profit maximization from land uses subject to land use area and scenarios of sediment reduction levels.
- The first version of NZFARM is a linear economic model that focuses on costs and benefits of adopting mitigations, and does not include the land use change aspect (e.g. change from sheep and beef to dairy or horticulture). The NZFARM linear model makes it possible to capture the specific costs of mitigation options and sediment

reduction scenarios on land uses. The second version of NZFARM is a non-linear model that includes both adoption of mitigation options and land use change. ESC practices can be included as management practices for land uses in both versions of NZFARM, while considering land use area and sediment reduction levels as constraints. The second version of NZFARM requires model calibration, and the land use change modelling might lead to the maintenance of, or even an increase in, economic returns of land uses from implementing sediment reduction scenarios.

- Most studies in New Zealand that value freshwater use stated preference approaches, although avoided cost estimates have been used in some studies.
- A feasibility study summarises an approach to determining which streams and catchments do not meet proposed sediment threshold values (C/D threshold) using results provided by NIWA, and outlines methods available to provide a nationwide estimate of the costs and co-benefits of interventions to meet sediment load reduction requirements. We will use the linear version of NZFARM that restricts land use change to analyse scenarios for erosion mitigation and their costs and co-benefits.

Conclusions

A wide variety of ESC practices are used in New Zealand, depending on the land use and the type of erosion process(es) generating sediment. While performance efficiencies are known for many individual ESC practices often multiple practices are used to achieve a desired performance efficiency (i.e. individual practices are “bundled” into a suite of mitigations). This is especially the case for pastoral soil conservation farm plan implementation, urban erosion and earthworks mitigation, and in modelling studies.

Erosion mitigation effectiveness can vary widely but there has been little detailed study of the factors affecting variation in performance. It is likely that several factors affect mitigation performance including underlying susceptibility of the land to erosion, size of rainfall event, different metrics used for assessing performance, scale of investigation, adequacy of mitigation treatment. Any of the ESC practices involving trees or shrubs (afforestation, space-planting, riparian or gully planting) take time to become fully effective and this is typically 10 to 15 years. Many structural practices are effective immediately. Little information is available on variation in the performance of different ESC practices with respect to trapping particles of different sizes. Several models have been used in New Zealand to assess the effects of ESC practices in reducing erosion at site, catchment and national scale. They have been applied to both runoff-generated surface erosion as well as mass movement and gully erosion and include both empirical models (NZeem®, CLUES, WANSY, USLE) and hybrid empirical – process models (SedNetNZ, GLEAMS). Typically, mitigation practices are bundled to assess performance.

Estimated values for the costs and co-benefits of ESC practices have been derived from empirical research and from simulation modelling. ESC practices have been divided into two groups: (1) riparian management, and (2) managing hillslope erosion processes. The results show that practices within the managing erosion processes group are more expensive than riparian management practices group. Co-benefits in reducing other pollutants (N, P, and *E. coli*) are highest when implementing the managing erosion processes practices with a range of pollutant reduction between 4 and 70%.

New Zealand-based literature on the valuing improved water quality through a reduction in sediment is relatively limited. There are several studies that value changes in water quality, but a much smaller group of studies that value changes in sediment specifically. Typically, studies that value water quality use stated preference approaches; however, most do not directly use sediment in their surveys but rather other measures of water quality or ecosystem health and therefore need a function that links changes in sediment to measures of water quality.

Catchments defined by NIWA where predicted current sediment load exceeds proposed sediment standards can be used as the spatial basis for applying mitigation scenarios and calculating the costs and co-benefits of these scenarios. These catchments cover about 71% of New Zealand and sediment load will need to be reduced by between <1% and 83% of the current sediment load in individual catchments. We propose to use the national scale NZFARM model to analyse scenarios for the costs of implementing erosion mitigation practices to meet sediment reduction targets. We propose to use the linear version of NZFARM that restricts land use change.

Recommendations

- We recommend the use of NZeem® to undertake an analysis of the effect of erosion mitigation in reducing sediment load to meet the sediment thresholds determined by NIWA.
- The NZeem® results can be used with NZFARM to assess the costs and co-benefits of erosion mitigation at national scale.

1 Introduction

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

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

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

Manaaki Whenua – Landcare Research (MWLR) and NIWA responded to the RfP with a joint proposal to complete all four components listed above. Following negotiation with MfE, two contracts have been let:

- NIWA has been funded to complete components 1 and 2 above
- MWLR has been funded to
  - review knowledge of erosion and sediment mitigation effectiveness in reducing sediment loading, and the costs and co-benefits of mitigations
  - complete a feasibility study that identifies at least two approaches to conduct a nationwide cost-benefit assessment for scenarios possible to meet sediment load reduction requirements

  These meet part of the requirements of components 3 and 4, but a decision on whether to complete the nationwide and catchment-based analysis of the costs and benefits of meeting proposed regulatory thresholds will be made following completion of the feasibility study.

This report describes work completed by MWLR to:

1. review the erosion and sediment control literature to synthesise core mitigation characteristics, and also the costs and co-benefits of erosion mitigations;
2. prepare a feasibility study for nationwide cost-benefit assessment of mitigations scenarios to meet sediment load reduction requirements necessary to achieve bottom line sediment attribute thresholds.

2 Background

The National Policy Statement for Freshwater Management (NPS-FM) and National Objectives Framework (NOF) do not currently define attributes for sediment. Over the past 3 years MfE has been leading work to develop sediment attributes to include in the NOF. This has involved the following work streams:

1. a review of (i) the effects of fine sediment on ecosystem health and numerical thresholds for sediment-related environmental state variables (ESVs), and (ii) the relationships (methods, tools, techniques) that relate catchment loads to sediment-related ESVs (Davies-Colley et al. 2015). This identified four proposed ESVs: deposited fine sediment (DS), suspended sediment concentration (SSC), visual clarity (VC), and light penetration (LP).
2. An extensive compilation and analysis of all existing data on suspended sediment loads, SSC, total suspended solids (TSS), sediment rating curves (SRCs) and DS (see Hicks et al. 2016) including:
    - collation of all available data from which SRCs could be defined;
    - development of methods to relate SSC to VC, LP, turbidity (T), DS, and suspended load particle size distribution (PSD);
    - development of models to estimate the parameters defining SRCs for locations without data;
    - analysis of how the parameters of SRCs change in response to changes in catchment sediment loads;
    - characterisation of the relationship between T, VC, SSC and LP;
    - development of methods for predicting T, VC, and LP as functions of SSC;
    - examination of the extent to which sediment PSD changes with change in sediment load and in what circumstances it changes;
    - analysis of relationships between sediment load and streambed DS to determine if an empirical approach could be developed to predict DS.
3. Development of classification systems for “reference state” variation in New Zealand streams to provide a basis for determining natural variation in sediment attributes against which current values and future trends in sediment attributes can be evaluated:
    - Clapcott and Goodwin (2017) analysed all the available data on DS and recommended a two-group classification of New Zealand streams but acknowledged significant data limitations;
    - Depree (2017) developed a classification system that classifies New Zealand rivers according to variation in reference state of TSS, VC and T, quantified the relationship between sediment ESVs and ecological responses, and recommended T be used as the ESV for sediment
4. Results from previous work streams combined with new analyses by Depree et al. (in prep.) and Franklin et al. (in prep.) have been used to develop proposed NOF sediment attribute tables for suspended sediment (represented by median values of VC and T over 2 years) and deposited fine sediment (represented by median values

over 2 years of % fine sediment cover in run habitats determined by the instream visual method – SAM2) in wadeable NZ stream and rivers. The proposed values provide bottom line thresholds for managing sediment impacts on ecosystem health in New Zealand fresh waters.

This work provides the basis for defining sediment attributes, methods for predicting sediment attributes for all stream reaches in New Zealand, and relating changes in sediment load to changes in sediment attribute values. Some of this work has begun to address the issue of how land use or land management affects catchment sediment load and hence sediment attributes (see section 8 of Hicks et al. 2016). MfE have identified observed and predicted exceedances of proposed bottom line sediment thresholds and now want to test the social, cultural, economic, and environmental implications of adding the proposed attributes to the NPS-FM. This requires an analysis of the effect of erosion mitigation on erosion and sediment load, as well as analysis of the costs and co-benefits of the range of available mitigations.

Erosion and sediment control (ESC) practices used in New Zealand have previously been comprehensively reviewed by Basher (2016) and Basher et al. (2016a, b), and covered mitigations used for earthworks on urban and infrastructure projects, horticultural and arable cropping, pastoral farming (dairy, sheep, beef, deer), and forestry. In an earlier review, McDowell et al. (2013) provided a semi-quantitative analysis of farm scale mitigation strategies, focused on pastoral farming and cropping, for sediment as well as phosphorus, nitrogen and *E. coli* and illustrates some of the co-benefits of erosion control. The reviews of Basher (2016) and Basher et al. (2016a, b) focused on New Zealand-based information, but also included relevant international literature, with quantitative assessments of mitigation performance. These reviews covered both the on-site performance and mitigation of off-site effects. This report summarises these reviews and also includes a summary of (1) the timeframes for different ESC practices to become effective, (2) the range of effectiveness for different ESC practices, and where possible explanations for the reasons effectiveness may vary, (3) the effect of ESC practices on different particle size fractions, and (4) description of how the effect of ESC practices has been incorporated into both empirical and process-based erosion and sediment models to provide estimates of sediment load reductions.

This review also uses the results of previous reports on the cost of erosion mitigation (including Daigneault and Samarasinghe 2015, Daigneault et al. 2017, and Doole 2015). Costs of the ESC practices include fixed costs (e.g. implementation costs) and variable costs (e.g. operating cost or opportunity cost of taking land out of production). As these costs are often materialized over several years, discount rates are used to annualize them. Cost may also vary by land use. Previous reports have based their cost estimations on screening national and international literature as well as expert opinion. For instance, Doole (2015) reviewed the costs and co-benefits for a range of ESC practices. In his analysis, several cost components were considered including construction, planting, fencing, maintenance, and lost value from occupied area. Similarly, Daigneault and Samrasinghe (2015) estimated the fixed and variables costs of different ESC practices to assess the potential economic costs of meeting a range of targets for sediment and *E. coli* in the Whangarei Harbour. This review provides the necessary information required for the feasibility study. The cost items as well as the efficacy of different ESC practices in reducing other pollutants (e.g. P, N, and *E. coli*) are one of the key outputs of this review. This information will help in weighing the costs of the ESC practices against the monetary benefits of reducing erosion and other pollutants.

3 Objectives

- Summarise previous reviews of the effectiveness of ESC practices;
- Review available data on timeframes for different ESC practices to become effective; the range of effectiveness for different ESC practices, and where possible explanations for the reason's effectiveness may vary; and on the effect of ESC practices on different particle size fractions;
- Describe how the effect of ESC practices has been incorporated into erosion and sediment models to provide estimates of sediment load reductions;
- Review available information on the costs and co-benefits of erosion and sediment mitigations;
- Summarise estimated values of direct costs and describe co-benefits of erosion avoidance and reduced sedimentation;
- Identify literature gaps and recommend parameter values for economic modelling;
- Prepare a feasibility study for a nationwide cost-benefit assessment of mitigations scenarios to meet sediment load reduction requirements necessary to achieve bottom line sediment thresholds, and provide two distinct approaches for developing mitigation scenarios to meet sediment load reduction requirements and for co-benefit calculations.

4 Methods

Information on the range of erosion and sediment control practices and their effectiveness was summarised from Basher (2016) and Basher et al. (2016a, b), which drew on previous reviews by Hicks (1995), Hicks and Anthony (2001), Phillips et al. (2000, 2008), Parkyn et al. (2000), Parkyn (2004), Basher et al. (2008a, b), and Basher (2013). The literature cited in these reports was re-examined to extract information on (1) timeframes for different ESC practices to become effective; (2) the range of effectiveness for different ESC practices, and explanations of the reason's effectiveness may vary; and (3) the effect of ESC practices on different particle size fractions.

A literature review was undertaken to identify erosion and sediment modelling studies in New Zealand that incorporate analysis of the effect of ESC practices in reducing erosion and sediment load. A summary of approaches to modelling sediment load in New Zealand is given in Elliott and Basher (2011). The focus of the current review was commonly used models, including two empirical models (CLUES – Elliott et al. 2008, 2016; NZeem® – Dymond et al. 2010), and one hybrid empirical-process based model (SedNetNZ –

Dymond et al. 2016). This analysis also considered how ESC practices are commonly bundled[1] for modelling applications.

We reviewed existing research on costs and co-benefits of ESC practices and sediment reduction in New Zealand was evaluated. The review focussed on two main sources of costs and co-benefits. First, the ESC practices themselves have a range of impacts, above and beyond water quality impacts. We identified several studies that evaluate the practices themselves. Second, there are several ways to directly value sediment and water quality impacts using non-market valuation. We summarise here the New Zealand literature in this area, as well as several paramount international studies. This review: (1) provides insights on the range of values for costs and co-benefits of different mitigation options, and (2) identifies key review reports and gaps in the literature. Our review began with several recent key reports including Doole (2015), Daigneault and Samarasinghe (2015), Dorner et al (2018a), and Daigneault et al. (2017). The objective of some of these reports was to review the literature on the costs and (co-) benefits of sediment mitigation practices in order to provide a general overview of the potential impacts while other reports have collected such information in order to use it as inputs for quantitative economic analysis. To explore beyond these recent sources, we also searched the main New Zealand and international non-market valuation databases, including Lincoln University's Non-Market Valuation Database[2] and the Environmental Valuation Reference Inventory[3].

The output of the review of costs and co-benefits of ESC practices in New Zealand is used to suggest two methods for the feasibility study of costs and co-benefits of ESC practices in reducing sediment loads to meet NOF standards. We propose two economic approaches for the study of ESC practices at the national scale. The economic approaches can be the most suitable as they can calculate the costs and benefits of ESC practices, consider resource constraints and behavioural aspects in land use decision making. The feasibility study includes the description of two approaches based on the short review of methods, and accordingly capability of these approaches for analysing the costs and co-benefits of ESC practices. We identify the most suitable approaches for the feasibility study of costs and co-benefits of ESC practices based on the problem statement, reviewing different possible approaches, available data to conduct such analysis, and advantages and disadvantages of the two approaches.

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[1] Erosion and sediment control practices are commonly considered as a suite of complementary practices that achieve an overall effectiveness. For example, on urban earthworks ESC may commonly include a combination of runoff diversion, hay bales, silt fences, geotextiles, and sediment retention ponds that together achieve a desired sediment retention effectiveness.

[2] selfservice.lincoln.ac.nz/nonmarketvaluation/

[3] evri.ca

5 Erosion and sediment mitigation

5.1 Effectiveness of ESC practices

A comprehensive analysis of the scientific basis for use of ESC practices across all land uses in New Zealand, including data on performance efficiency, is given in Basher et al. (2016b). The information compiled in that report forms the basis for the current summary. The full range of ESC practices used in New Zealand are described by Hicks and Anthony (2001) for rural land uses and for urban (including infrastructure) earthworks by Leersnyder et al. (2016).

Basher et al. (2016b) note that a wide variety of ESC practices are used in New Zealand, depending on the land use and the type of erosion process(es) generating sediment. There is a fundamental distinction between ESC practices used for runoff-generated erosion and those for mass movement erosion, as well as a specific set of ESC practices used for bank erosion control. Appendix 1 provides a list of all the ESC practices used, or recommended for use, in New Zealand summarised by land use. Information on performance efficiency is not available for all ESC practices and the focus here is on the commonly used ESC practices. In addition, ESC often involves use of multiple techniques to achieve a desired performance efficiency (i.e. individual practices are 'bundled' into a suite of mitigations – this is especially the case for urban erosion and earthworks mitigation, for pastoral soil conservation farm plan implementation, and in modelling studies).

ESC practices for runoff-generated erosion (sheet, rill, gully) can be broadly categorised as (1) water management to control of runoff, reduce water velocity and sediment generation, and to separate clean water and dirty water; (2) erosion control to reduce sediment generation; and (3) sediment control to trap sediment before it moves offsite and into water ways. Control of these types of erosion typically involves a combination of biological control, geotextiles, structural measures, and management practices. Mass movement erosion (landslides earthflows, slumps) is controlled by practices that influence slope hydrology and/or soil strength. Typically, biological methods of erosion control (space-planted trees, afforestation, reversion) are used to mitigate these processes, although a range of structural practices can also be used (Hicks & Anthony 2001; Basher et al. 2008a). Many of the erosion mitigation practices used for mass movement are also used for gully erosion control because while "classic" gully erosion is a runoff driven process, in New Zealand the worst gully erosion (e.g. Gisborne–East Cape area) involves a significant component of mass movement (see Marden 2012; Marden et al. 2012) Streambank erosion is controlled by practices that reduce hydraulic scour, or increase bank strength and resistance to erosion (Watson & Basher 2006). Again, typically, biological methods of erosion control (space-planted trees) are used to mitigate this process but fencing for stock exclusion is also widely used, and structural methods are used where there are high-value assets to protect.

Key studies that provide data on the performance of different erosion mitigation practices, with an emphasis on New Zealand data and on rural land uses, are summarised in Table 1. A summary of the erosion mitigation alternatives used for different erosion processes and land uses, and the commonly use effectiveness values is given in Table 2.

Space-planted trees (mainly willows and poplars) and afforestation are the most commonly used practices for controlling erosion on pastoral farmland. They can be highly effective in reducing erosion at hillslope scale, especially by shallow landsliding but also for gullying and earthflows. The on-site performance of space-planted trees in reducing erosion, mainly by landsliding, has been examined in a small number of studies using both quantitative and semi-quantitative methods. There are no published studies on their effect on sediment yield. Published reductions in landsliding using space-planted trees from quantitative studies at hillslope scale range from 70 to 95%. However, measured or assessed reductions at larger spatial scales are often less than this because plantings are inadequate. Individual trees influence the amount of landsliding within a radius of c. 10 m.

Afforestation is often used to control widespread and severe erosion. Mature, closed-canopy, indigenous or exotic forest (and scrub) typically reduces landsliding by 90%, and has been used to control severe gully erosion and reduce rates of earthflow movement (by 2–3 orders of magnitude). Trees younger than about 8 years, before canopy closure, are far less effective in reducing erosion. In the Gisborne–East Coast region stabilisation of severe gully erosion by afforestation is highly dependent on gully size and shape at the time of planting, with an 80% chance of success for gullies <1 ha and little chance of success once gullies exceed 10 ha. Comparison of sediment yield from forested and pasture catchments at small catchment scale showed sediment yield reductions of 50–90%.

Earthworks and clearfelled areas of plantation forests have the potential to generate large amounts of sediment by both surface erosion processes and mass movement. Landslides can mobilise logging slash in debris flows and cause severe off-site effects. The effects of forest harvesting on increasing sediment yield, and the consequences of poor road and landing construction and maintenance have characterised in some early studies (e.g. Pearce & Hodgkiss 1987; Fahey & Coker 1989, 1992) but little is known of the performance of modern engineering standards for water control, road and landing construction. In recent years, there has been a major effort by the forest industry to better manage the environmental impacts of forestry, with a strong emphasis on infrastructure engineering for water and sediment control, and careful siting of roads and landings to reduce erosion hazard. ESC practices promoted for forestry listed in regional council guidelines are largely derived from those used for urban earthworks and infrastructure, with the addition of some practices that are forestry specific and aimed at direct harvesting effects. The latter tend to be general guidelines (e.g. haul away from watercourses, safely dispose of slash) and little is known of their effectiveness. Basher et al. (2016b) concluded there have been no New Zealand studies that are forestry specific to test that the ESC design criteria in council guidelines are appropriate. Rather they are based on experience of practitioners.

ESC practices to control water and wind erosion on cropland have not been much studied in New Zealand. In row crops, compacted wheel tracks are recognised as major sources of runoff and erosion. Ripping of wheel tracks reduced erosion by 95% on strongly structured clay soils. Overseas literature suggests this practice would be most effective on silty and clayey textured soils and less effective on sandy soils. Wheel track diking has been shown in New Zealand trials to reduce runoff, but the impact on soil loss has not been characterised. Overseas studies have shown this practice can reduce soil loss by 60 to >92%. Cover crop trials in New Zealand have demonstrated an improvement in aggregate size and stability which by inference should reduce soil erodibility and erosion. At Pukekohe, a cover crop trial produced a relatively small reduction in soil loss (26–38%). In a severe storm in this area in 1999 there was little erosion where cover crops were present. There have been many international studies on the influence of cover crops on erosion rates that show they can reduce erosion by more than 90%. There have been no studies of the effectiveness of grass riparian buffer in cropland New Zealand. Overseas studies show that they can be highly effective in reducing sediment delivery to streams by decreasing the velocity of runoff and allowing particles to settle and infiltrate. Buffers typically retain 40–100% of the sediment mass that enters them but the effectiveness of buffers in removing sediment varies widely depending on buffer width, buffer type, particle size of the sediment, the ability of the vegetation to retard flow, soil infiltration rate, the amount of runoff, slope gradient, and length of contributing slope. There is little information on the performance of sediment retention ponds used for sediment control from arable cropping, either in New Zealand or internationally. One preliminary unpublished study at Pukekohe found annual soil loss was reduced to one third of that where no sediment retention pond was used. A current trial of two different size sediment retention ponds (sized at 0.5 and 1.3% of contributing catchment area) found the average efficiency was up to 99% for bedload but lower for suspended load (the 1.3% pond was 97% and the 0.5% pond was 83%, Andrew Barber, pers. comm.). One overseas study showed ponds can be highly efficient (>65%) in removing sand and silt but were unable to remove clay particles in runoff. Field shelter provided by windbreaks has historically been widely practised to protect cropland from wind erosion in eastern parts of New Zealand but no data are available on their trapping efficiency.

During the plantation forestry cycle earthworks (for roads and landings) and clear-felled areas have the potential to generate large amounts of sediment by both surface erosion processes and mass movement. Landslides can mobilise logging slash in debris flows and cause severe off-site effects. The effects of forest harvesting on increasing sediment yield, and the consequences of poor road and landing construction and maintenance have been well characterised. In recent years, there has been a major effort by the forest industry to better manage the environmental impacts of forestry, with a strong emphasis on infrastructure engineering for water and sediment control, and careful siting of roads and landings to reduce erosion hazard. ESC practices promoted for forestry in regional council and industry guidelines are largely derived from those used for urban earthworks and infrastructure, with the addition of some practices that are forestry specific and aimed at direct harvesting effects. The latter tend to be general guidelines (e.g. haul away from watercourses, safely dispose of slash). There have been no New Zealand forestry-specific studies to test that the ESC design criteria in council guidelines are appropriate. Rather, they are based on experience of practitioners. Reviews of the effectiveness of forestry best management practices in the USA mostly focus on surface erosion and demonstrate the effect of implementing multiple best management practices including silvicultural options, road and track management and stream crossing management. They show that best management practices can minimize erosion and sedimentation (quoted sediment reduction efficiencies of >50%) but implementation rates and quality are critical. Riparian buffers are effective in trapping sediment (efficiencies of 71–99% for sediment in surface runoff) and trapping efficiency is influenced by sediment size and roughness of understorey vegetation. None of the reviews specifically mention management practices aimed at minimising landslides or debris flows which are considered the main contributors to erosion and sediment generation in New Zealand (Phillips et al. 2018).

ESC practices are widely used and can be highly effective in reducing the generation of sediment and its discharge from construction sites (including urban earthworks and large scale roading projects). Performance efficiencies are known for a number of ESC practices (Table 1) and some exceed 90%. Many studies have reported order of magnitude (or even two orders of magnitude) reductions in sediment loads and concentrations from implementation of individual or multiple ESC practices. Most are rarely used in isolation and commonly an overall performance efficiency of 70% is assumed typically up to a 10-year recurrence interval storm. Note that the majority of published studies involve sampling simulated rainfall-runoff from experimental plots to assess the comparative performance of a range of mulching materials and erosion control geotextiles or blankets. Studies of the performance of sediment retention ponds, with and without chemical treatment, show that show that performance efficiencies of 70–>90% can be achieved.

Table 1 Summary of key studies providing information on erosion mitigation treatment performance (derived from Basher et al. 2016b)

Mitigation treatment	Summary	Effectiveness metric	Study location	Erosion type	Land use	Reference
Afforestation (mostly comprises comparison of forested sites with non-forested sites but some directly investigate of effect of afforestation or reforestation)	Landslide density 80% lower under indigenous forest, pines >8 years old or scrub than pasture prior to Cyclone Bola, and increased to c. 90% lower during Cyclone Bola (except for scrub)	Landslide density (number ha^{-1})	New Zealand	Landslides	Pastoral farming	Marden & Rowan (1993)
	Prior to Cyclone Bola landslide densities were 74% lower under pines > 8 years old than pasture, and after Bola increased to 91%	Landslide density (number ha^{-1}) and volume (m^3 ha^{-1})	New Zealand	Landslides	Pastoral farming	Phillips et al. (1990)
	Volumetric landslide rates 87% lower under pines > 8 years old than under pasture, 40% lower for trees between 2 and 8 years old, while trees < 1 year old produced 24% more sediment than did pasture	Landslide volume (m^3 ha^{-1})	New Zealand	Landslides	Pastoral farming	Marden et al. (1991)
	Tall woody vegetation typically produced c. 70% less sediment than pasture over multiple landslide events	Sediment generation rate (t km^{-2})	New Zealand	Landslides	Pastoral farming	Reid & Page (2002)
	Tall woody vegetation produced 50–90% (depending on land type) less sediment than pasture during Cyclone Bola	Landslide density (number ha^{-1}) and sediment generation rate (m^3 ha^{-1})	New Zealand	Landslides	Pastoral farming	Page et al. (1999)
	During Cyclone Bola scrub had 74% less landsliding than pasture. Age and density of scrub affected the amount of landsliding – landsliding reduced by 65% in 10-year-old scrub compared with pasture, and 90% in 20-year-old scrub	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Bergin et al. (1993, 1995)
	Landslide density under pine trees was >80% lower than pasture	% area affected by landslides and landslide density (number ha^{-1})	New Zealand	Landslides	Pastoral farming	Fransen & Brownlie (1995)
	Area affected by landslides in 2004 storm 70–90% lower under closed canopy vegetation than pasture, and 30–75% lower under spaced willows/poplars	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Hancox & Wright (2005)
	Forest generally reduced landsliding by 90% and scrub by 80% in 2004 Manawatu-Wanganui storm	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Dymond et al. (2006)

Mitigation treatment	Summary	Effectiveness metric	Study location	Erosion type	Land use	Reference
Afforestation (cont')	Area of landsliding under forest (pines or indigenous) was c. 70% less than pasture, c. 30–40% less where extensive (space-planted) trees were present, and little different where only scattered trees present	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Hicks & Crippen (2004)
	Area affected by landsliding >90% less under forest and scrub compared with pasture	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Pain & Stephens (1990)
	Surface movement rates on forested earthflows were 2–3 orders of magnitude lower than on grassed earthflows	Movement rate (m month^{-1})	New Zealand	Earthflow	Pastoral farming	Zhang et al. (1993)
	Afforestation used to stabilise gullies in Gisborne-East Coast region. Ability to stabilise gullies with trees is highly dependent on gully size and shape at the time of planting, with an 80% chance of success (i.e. stabilisation over one forest rotation) for gullies <1 ha and little chance of success once gullies exceed 10 ha. Afforestation estimated to have reduced sediment yield by approximately 33% in the Waipaoa catchment and by 16% in the Waiapu catchment from what it would have been without afforestation. No performance efficiency given.	Area of active gullying (ha)	New Zealand	Gully	Pastoral farming	Marden et al. (2005, 2008, 2011, 2012); Herzig et al. (2011)
	In 1992 storm in Manawatu–Wanganui area of landslides c. 35% less under forest (pine or indigenous) than pasture	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Varvaliu (1997)
	In 1992 storm in Manawatu-Wanganui area of landslides 85% less under forest and scrub than pasture	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Hicks et al. (1993)
	For a given storm magnitude forested catchments yield on average 63% less (range 40–78%) sediment than pasture catchments. Mean annual sediment yield of forested catchments typically 50–95% less than pasture catchments	Storm (t km^{-2}) and mean annual sediment yield (t km^{-2} yr^{-1})	New Zealand		Pastoral farming	DM Hicks (1990)
	Small pine forest catchment yielded 82% less sediment than a pasture catchment but an indigenous forest catchment yielded 23% more sediment than the pasture catchment (due to available riparian sediment sources)	Mean annual sediment yield (t km^{-2} yr^{-1})	New Zealand	Landslides, bank erosion, surface erosion	Pastoral farming	Dons (1987)

Mitigation treatment	Summary	Effectiveness metric	Study location	Erosion type	Land use	Reference
Afforestation (cont')	Small catchments with riparian (pine) afforestation had double the sediment yield of a pasture catchment (due to lack of riparian ground cover)	Mean annual sediment yield (t km^{-2} yr^{-1})	New Zealand	Bank erosion, surface erosion	Pastoral farming	Smith (1992)
	Indigenous forest catchment yielded 90% less sediment than a pasture catchment	Mean annual sediment yield (t km^{-2} yr^{-1})	New Zealand	Bank erosion, surface erosion	Pastoral farming	Bargh (1977, 1978)
	Yields in small indigenous forest and mixed vegetation catchments were 68% lower and 166% higher respectively than in a pasture catchment. The high yield from the mixed vegetation catchment was due to a single large landslide	Mean annual sediment yield (t km^{-2} yr^{-1})	New Zealand	Landslides, bank erosion, surface erosion	Pastoral farming	Quinn & Stroud (2002)
	Indigenous forest catchment yielded 38% less sediment than a pasture catchment over a 12-year period, including both before and after erosion mitigation treatment. Differences greater for the largest storm events (yields were c. 70% lower for the indigenous forest catchment during storm events with >5 year ARI).	Mean annual sediment yield (t km^{-2} yr^{-1})	New Zealand	Landslides, bank erosion, surface erosion	Pastoral farming	Hughes et al. (2012)
	Sediment yield measured in adjacent small pasture and pine forest catchments in the erodible sandstone and mudstone hill country of Hawke's Bay from the pre-harvest period through to 6 years post-harvest. Before harvest forest catchment produced 73% less sediment than the pasture catchment. During the harvesting phase the forest catchment producing 44% more sediment than the pasture catchment but the increase in yields only persisted for 2 years. Individual storm-event sediment yields were up to 10 times higher from the harvested catchment. Over the 11 years of the study the forest catchment produced 62% less sediment than the pasture catchment, suggesting that over the full length of a forest rotation a forested catchment would produce c. 70% less sediment than a pasture catchment	Mean annual sediment yield (t km^{-2} yr^{-1})	New Zealand	Landslides, bank erosion, surface erosion	Pastoral farming	Eyles & Fahey (2006)

Mitigation treatment	Summary	Effectiveness metric	Study location	Erosion type	Land use	Reference
Space-planted trees	Influence of trees extends 11 m. If trees had been planted at 10-m spacing with 100% establishment and survival there would have been a reduction in landslide damage of 70%. On the hillslope examined, where the spacing of 14-year-old trees was 20 m and 66% of the planted trees had survived, the actual reduction in landslide damage due to space-planted trees was only 14%	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Hawley & Dymond (1988)
	Examined the effects of small groups (5–10) of mature space-planted trees (dominantly poplar with some willow and Eucalyptus) at 40 sites in the Manawatū and 25 sites in the Wairarapa. The effect of the space-planted trees was compared with landslide occurrence in comparable pasture sites without trees to assess the influence of the trees. Trees reduced landslide occurrence by 95% compared with paired pasture control sites.	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Douglas et al. (2009, 2013)
	Examined the effects of small groups (5–10) of mature space-planted trees (dominantly poplar with some willow and Eucalyptus) at 40 sites in Hawkes Bay. The effect of the space-planted trees was compared with landslide occurrence in comparable pasture sites without trees to assess the influence of the trees. Trees reduced landslide occurrence by 78% compared with paired pasture control sites.	Area affected by landslides	New Zealand	Landslides	Pastoral farming	McIvor et al. (2015)
	Assessed the effect of space-planted trees on erosion in a storm in the Whareama catchment, Wairarapa. Adequately installed soil conservation measures reduced gullying by 50%, streambank erosion by 24%, mass movement of colluvial footslopes by 67% and steep hills by 71% compared with unstable, unplanted slopes. Only about half the soil conservation measures were adequately installed. Suggests catchment sediment supply was 23% less than could have been expected in the absence of soil conservation	Area affected by landslides, gullies; length of bank erosion	New Zealand	Landslides, bank erosion, gully erosion	Pastoral farming	Cameron (1991)

Mitigation treatment	Summary	Effectiveness metric	Study location	Erosion type	Land use	Reference
Space-planted trees (cont')	No performance efficiency given - treatments rated as successful or not successful. Treatments were afforestation, gully wall planting, channel (pair) planting and debris dams. Treatment of erosion successful at 42% of gully sites and 63% of earthflow sites.	Subjective assessment of effectiveness (degree to which land has been returned to state of minimal erosion)	New Zealand	Gully, earthflow	Pastoral farming	Thompson & Luckman (1993)
	No performance efficiency given – treatments rated as successful or not successful. Earthflow – 14 out of 17 earthflow sites successfully treated by space planting trees. Gully – 9 out of 13 gully sites successfully treated by space planting or pair planting trees	Based on Thompson & Luckman (1993)	New Zealand	Earthflow, gully and landslide	Pastoral farming	Phillips et al. (2008)
	Post-Cyclone Bola assessment. Based on measured percentages of area eroded by landslides, earthflows, and gullies and assessment of performance of soil conservation measures on a transect through the Waihora catchment he estimated that erosion was 22% lower (measured as area of damage) than it would have been in the absence of soil conservation measures but could have been reduced by 74% had soil conservation measures been installed everywhere they were needed, and to an adequate standard. Of the soil conservation measures that had been used, only 35% were assessed as adequate.	% area affected by landslides, gullies	New Zealand	Landslides, earthflows, and gullies	Pastoral farming	Hicks (1989a, b, 1992a)
	Landslide area 39% less under space planted trees than pasture in Manawatu 2004 storm	Area affected by landslides	New Zealand	Landslides	Pastoral farming	Hicks & Crippen (2004)
	Land with soil conservation space plantings produced a 22% reduction in sediment generation compared with pasture in Cyclone Bola	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Page et al. (1999)
	In 1992 storm in Manawatu-Wanganui area of landslides c. 35% less with space-planted trees than pasture	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Varvaliu (1997)
	In 1992 storm in Manawatu-Wanganui area of landslides 60% less with extensive space-planting than pasture, and 10% less with scattered trees	% area affected by landslides	New Zealand	Landslides	Pastoral farming	Hicks et al. (1993)

Mitigation treatment	Summary	Effectiveness metric	Study location	Erosion type	Land use	Reference
Space-planted trees (cont')	Riparian planting assessment in the Waihora, Whareama, and Waipa catchments. Where plantings were adequate channel damage was reduced substantially (by >50% in the Waihora), but 40–60% of the plantings were rated as inadequate	% of bank eroded	New Zealand	Bank erosion	Pastoral farming	Hicks (1992b)
Riparian fencing	Suggests bank erosion reductions ranging from 30-90% using data from Line et al. (2000), McKergow et al. (2003), Meals & Hopkins (2002), and Owens et al. (1996)	Sediment load	New Zealand	Bank erosion	Pastoral farming	McKergow et al. (2007)
	30% reduction in bank erosion based on unpublished data from Whatawhata Research Station (site PW3)	Non-storm suspended sediment concentration (g m^{-3})	New Zealand	Bank erosion	Pastoral farming	Monaghan & Quinn (2010)
	Estimated that actively eroding banks reduced from 30 to 4%, 1–7 years after riparian buffers were established and resulted in an 85% reduction in catchment sediment load	% length of eroding banks	New Zealand	Bank erosion	Pastoral farming	Williamson et al. (1996)
	Monthly water quality sampling from Dairy Best-Practice catchments (including riparian fencing) showed 4-11% reduction in SS concentrations; sediment assumed to mainly be derived from bank erosion	Non-storm suspended sediment concentration (g m^{-3})	New Zealand	Bank erosion	Pastoral farming	Wilcock et al. (2013)
Riparian fencing and planting	Assumed 80% bank erosion reduction based on a 'conservative' adjustment of the Australian SedNet model parameter (95%). In the Australian version of SedNet, the 95% value was derived from the assumption that pre-settlement (Australia) river banks had high levels of riparian vegetation.	Assumption	New Zealand	Bank erosion	Pastoral farming	Dymond et al. (2016)
	55–65% reduction in bank erosion (depending on type of planting and buffer width) based on unpublished data) from Whatawhata Research Station (site PW3).	Non-storm suspended sediment concentration	New Zealand	Bank erosion	Pastoral farming	Monaghan & Quinn (2010)

Mitigation treatment	Summary	Effectiveness metric	Study location	Erosion type	Land use	Reference
Riparian fencing and planting (cont')	Small catchment -scale cattle exclusion from riparian areas and extensive riparian planting. No evidence of a progressive reduction in yield in the treated catchment (half afforested, part planted in native trees and shrubs, part space-planted, riparian fencing implemented). This was attributed to the limited pre-intervention data set (2 years) and high natural inter-annual variability in sediment yields	Mean annual sediment yield ($t\ km^{-2}\ yr^{-1}$)	New Zealand	Bank erosion	Pastoral farming	Hughes et al. (2012)
Wetlands	Natural seepage and constructed wetlands estimated to reduce sediment in overland flow by 60% (no measured data), constructed wetlands by 60–80% (1% and 2.5% of catchment area as wetland)	Estimate	New Zealand	Surface erosion	Pastoral farming	McKergow et al. (2007)
	Combination of natural and constructed wetlands predicted to reduce sediment load from 27 to 68% (0.06–4.31% of catchment area as wetland)	Model estimate of % reduction in sediment load	New Zealand	Surface erosion	Pastoral farming	Tanner et al. (2013)
Temporary or permanent seeding	Sediment load reductions >90%	Sediment load ($t\ km^{-2}$)	International	Surface erosion	Urban earthwork s	Fifield (1999)
	Soil loss from established grass estimated to be 50 times less than bare soil (sediment load reduction of 98%)	USLE model prediction	New Zealand	Surface erosion	Urban earthwork s	ARC undated
Mulch	Sediment loads from mulched topsoil and mulched subsoil plots were c.94% and 85% lower than those bare topsoil and bare subsoil plots, respectively	Sediment load ($t\ km^{-2}$)	New Zealand	Surface erosion	Urban earthwork s	ARC 2000
Silt fences	Sediment removal efficiencies of up to 99%, predominantly a function of the settling of sediments in ponded water upstream of a fence rather than a result of filtering by the fence fabric	Sediment load (kg)	International	Surface erosion	Urban earthwork s	Summarised in Basher et al. (2016a)
Sediment retention pond	Overall sediment removal efficiency of a pond over 11 storm events was 90%, with range from 70 to 99% in individual events	Sediment load (kg)	New Zealand	Surface erosion	Urban earthwork s	Winter (1998)

Mitigation treatment	Summary	Effectiveness metric	Study location	Erosion type	Land use	Reference
Sediment retention pond with chemical treatment	Compared sediment retention efficiency of ponds with and without chemical treatment (PAC) over 7 storm events. The treated pond achieved an average sediment removal efficiency of >68% (range 48–92%), while the untreated pond performed well below this level with an average sediment removal efficiency of c. 30% (range 26–91%)	Sediment concentration (g m^{-3}) and load (kg)	New Zealand	Surface erosion	Urban earthworks	Moores & Pattinson (2008)
	Two ponds treated with PAC had overall sediment removal efficiency of c. 99%		New Zealand	Surface erosion	Urban earthworks	Larcombe (2009)
	Several ponds treated with PAC had overall sediment removal efficiency of c. 99%,		New Zealand	Surface erosion	Urban earthworks	Ridley & De Luca (2015)
Decanting earth bund	Sediment removal efficiencies of 23–79% in natural rainfall events, and 47–75% in simulated rainfall events		New Zealand	Surface erosion	Urban earthworks	Babington & Associates (2004)
Wheel track ripping	Reduced erosion by 95% on clay-rich soils at Pukekohe	Sediment load (t ha^{-1})	New Zealand	Surface erosion	Cropping	Basher & Ross (2001)
	Reduced erosion by 98–99% on silty soils and 75–96% on sandy soils	Sediment concentration (g m^{-3}) and load (kg ha^{-1})	International	Surface erosion	Cropping	Deasy et al. (2010); Bailey et al. (2013)
Wheel track diking	Reduced erosion by 60–96%	Sediment load (kg ha^{-1})	International	Surface erosion	Cropping	Xiao et al. (2012); Sui et al. (2016); Truman & Nuti (2009); Rawitz et al. (1983)
Cover crops	Erosion rates on bare, cultivated soil plots 100 times greater than from grass plots	Sediment load (kg ha^{-1})	New Zealand	Surface erosion	Cropping	Basher et al. (1997)

Mitigation treatment	Summary	Effectiveness metric	Study location	Erosion type	Land use	Reference
Cover crops (cont')	At Pukekohe broadcasting wheat on fallow soil reduced soil loss by c .3 8% between May and June, and by c. 26% between June and July	Sediment load (kg ha^{-1})	New Zealand	Surface erosion	Cropping	Johnstone et al. (2011)
	Reductions in erosion rate compared to bare ground of 40–>90%	Sediment load (kg ha^{-1})	International	Surface erosion	Cropping	Summarised in Basher et al. (2016b)
Grassed riparian buffer strips	Buffers typically retain 40–100% of the sediment mass that enters them. The first 3–6 m of buffer plays a dominant role in sediment trapping. They work best on slopes <3° and should not be used on slopes >9°, and should not be used where hillslope contour is concave and concentrates water flow	Sediment load (kg ha^{-1})	International	Surface erosion	Cropping	Summarised in Basher et al. (2016b)
	Suggests treatment efficiencies of 20–30% for permeable soils and channelised flow through buffer strip, 40–80% for permeable soils and non-channelised flow through buffer strip, and 40–50% for permeable soils and non-channelised flow through buffer strip		New Zealand and international	Surface erosion	Pastoral faming	McKergow et al. (2007)
Sediment retention pond	A well-designed pond was estimated to have reduced soil loss to one third of that where no pond was used	Sediment concentration (g m^{-3}) and yield (t ha^{-1} yr^{-1})	New Zealand	Surface erosion	Cropping	Pellow & Barber (2004)
	Sediment retention ponds remove 55–85% of sediment entering them and are more effective on sand and silt sized particles than clay-sized particles	Sediment concentration (g m^{-3}) and yield (t ha^{-1} yr^{-1})	International	Surface erosion	Cropping	Summarised in Basher et al. (2016b)

Table 2 Summary of erosion mitigation alternatives used for different erosion processes and land uses, and the commonly use effectiveness values (derived from Basher et al. 2016b)

Erosion process	Mitigation treatment	Effectiveness (% reduction from baseline erosion)	Land use (s)	Comment
Surface erosion (sheet, rill)	Wetlands (natural or constructed) and sediment traps	60-80	Pasture	Based on estimates in McKergow et al. (2007) and Tanner et al. (2013). Effectiveness depends mostly on size of wetland (as % of catchment area) – 60% for 1% wetland and 80% for 2.5% wetland
	Sediment retention ponds without chemical treatment	30	Urban	Typically, a combination of erosion and sediment control practices are used for urban earthworks. An overall efficiency is usually used based on average efficiency aimed for in using sediment retention ponds with chemical treatment of 70%
		70	Urban	
	Silt fence	99	Urban	
	Sediment retention pond	50	Horticulture	Conservative estimate based on Pukekohe study and limited overseas literature
	Riparian grass buffer strip	40	Horticulture and pasture	Conservative estimate based on McKergow et al. (2007) – can be >80%. Will probably be highly slope dependent
	Wheel track ripping	90	Horticulture	Based on Pukekohe study on clay-rich soils
	Wheel track diking	60	Horticulture	Effectiveness has not been characterised in NZ. Likely to be significantly less than ripping
	Cover crops	40	Horticulture	Limited NZ studies show seasonal reduction in soil loss of c. 30%; international studies show reductions in erosion rate compared with bare ground of 40–>90%
Landslides	Space-planting	70	Pasture	Assumes all area is planted, and all plants survive. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated
	Afforestation	90	Pasture	This also includes reversion to full native scrub or forest cover. Assumes all area is planted. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated. Also assumes trees not harvested – if harvested reduce effectiveness to 80%

Erosion process	Mitigation treatment	Effectiveness (% reduction from baseline erosion)	Land use (s)	Comment
Gully erosion	Space-planting	70	Pasture	Assumes all area is planted, and all plants survive. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated
	Afforestation	90	Pasture	This also includes reversion to full native scrub or forest cover. Assumes all area is planted. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated. Also assumes trees not harvested – if harvested reduce effectiveness to 80%
	Debris dams	80	Pasture	No data available but considered to be highly effective in trapping sediment within gullies so long as gully walls are stabilised with trees. Typically used in combination with vegetation, fencing and control of runoff into gullies to trap sediment within gully systems
Earthflow	Space-planting	70	Pasture	Assumes all area is planted, and all plants survive. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate), effectiveness should be scaled in proportion to area treated
	Afforestation	90	Pasture	Assumes all area is planted. Where only part of an area (polygon) is planted (e.g. area above a given slope threshold or sediment generation rate) then effectiveness should be scaled in proportion to area treated. Also assumes trees not harvested – if harvested reduce effectiveness to 80%
Bank erosion	Riparian fencing	50	Pasture	The 80% used is based on a "conservative" adjustment of the Australian SedNet model parameter (Dymond et al. 2016). The available NZ data suggests the effectiveness is likely to be significantly lower; there is insufficient data to determine whether riparian planting significantly increases effectiveness above simply fencing (to restrict stock access) or to determine effect of width of fencing set back
	Riparian fencing + planting	50	Pasture	

5.2 Variation in ESC performance and factors affecting performance

Data are available on the variation in mitigation effectiveness for some, but not all, ESC practices and is given in Table 1. Afforestation (when the trees are mature) typically produces reductions in erosion ranging from 35 to >90%, and reductions in sediment yield of 50–>90%. Detailed quantitative studies of the on-site performance of space-planted trees in reducing erosion, mainly by landsliding, give values ranging from 70 to 95%. However, wider regional studies often give lower values (30–60%). While there has been little detailed study of the factors affecting variation in performance of either closed canopy forest or space planted trees it is likely that several factors affect mitigation performance including:

- Underlying susceptibility of the land to erosion which is affected by rock type, soils, and slope (e.g. Page et al. (1999) describe the variation in sediment generation rate by landslides in land systems underlain by different rock types in the Waipaoa catchment; Douglas et al. (2013) discuss how site conditions may have affected results of comparison of ‘paired’ tree and pasture sites);
- Size of rainfall event (e.g. Page et al. (1999) document the variation in landslide rate with rainfall magnitude in Cyclone Bola);
- Different metrics used for assessing performance (landslide density (number ha^{-1}), volumetric erosion rate (m^3 ha^{-1}), % area affected by landsliding or gullying, suspended sediment yield (t km^{-2}));
- Different scales of investigation used for assessing performance (individual trees, hillslopes, catchment to regional studies);
- Adequacy of tree survival and planting density at both hillslope and larger scales (e.g. Hawley and Dymond (1988) found that if trees had been planted at 10-m spacing with 100% establishment and survival there would have been a reduction in landslide damage of 70%; the actual reduction was 14% because the spacing of trees was 20 m and only 66% had survived).

More is known about the factors that contribute to the performance of ESC practices for earthworks as there has been far more experimentation, using both natural and simulated rainfall, to improve performance. Moores and Pattinson (2008) provide a detailed analysis of the factors affecting variation in sediment retention pond performance – these included the size of storm event, antecedent moisture, design and performance of the chemical dosing system. Table 3 summarises the factors affecting performance for ESC practices used on earthworks (from Basher et al. 2016b).

Table 3 Factors promoting better performance of ESC practices for earthworks (from Basher et al. 2016b)

ESC practice	Controls on performance
Erosion control using mulches, erosion control geotextiles or blankets	• Potential for displacement – fibrous, interwoven materials are more effective than loose mulches such as straw, which can become displaced by rainfall and runoff • Percentage cover – materials with a higher percentage cover are more effective at reducing soil disturbance by rainsplash • Thickness and associated water-holding capacity – thicker treatments with higher water-holding capacity perform better at reducing overland flow and associated soil loss • Flexibility and weight – flexible, heavier materials that have better contact with the underlying soil surface are better at ponding water, reducing overland flow and associated soil loss • Number of treatments – the use of a combination of treatments has been found to be more effective than single treatments, particularly in relation to the control of fine sediments • Establishment of vegetation – variations in the performance of different materials have been found to become less marked following the establishment and growth of vegetation • Applying mulch to bare subsoil is less effective than applying it to topsoil
Silt fences	• Performance is likely to be higher where the geometry and slope of the site promote upstream ponding • Pore size of the filter fabric influences the extent to which runoff is detained upstream of the fence and the extent to which sediment particles are trapped in the fabric. The trapping of sediment in the fabric matrix further reduces its permeability, contributing to the extended detention of incoming runoff • Soil particle size characteristics – finer soil particles tend to be responsible for the clogging of the filter fabric, reducing permeability and extending detention time. However, where sediment runoff is dominated by finer particles, removal efficiencies are likely to be relatively low because these finer sized particles settle out less readily than the coarser • Silt fences become less effective over time as the build-up of sediments and clogging of the fabric increases the likelihood of overtopping
Sediment retention ponds	• Extended detention time, promoting the settling of finer suspended sediments and increasing the proportion of influent water which is lost via infiltration through the base of the pond • Appropriate sizing with performance increasing as a function of the pond surface area to peak discharge ratio • Greater distance between the pond inlet and outlet, with performance increasing in response to a higher length to width ratio • The presence of permanent ponding, as opposed to fully-drained sediment traps • Pond designs which promote mixing and settling by avoiding dead zones and sheet flow through the upper part of the water column • Protection and stabilization of approach channels, inlets and pond side walls to prevent erosion • The presence of forebays and baffles which reduce velocity and promote sediment settling, but which are not readily overtopped • Outlets that discharge effluent from the pond water surface, rather than from the entire water column • The use of outlet filters, such as gravel or expanded polystyrene envelopes fitted to outlet risers • Chemical treatment (especially with Polyaluminium Chloride) markedly improves the performance of physical devices and is more effective as detention time increases, allowing more time for flocculation and settlement processes to act. PAC treatment makes a greater difference during larger events, when the performance of non-treated ponds is relatively poor.

5.3 Timeframes for ESC sediment removal effectiveness

Any of the ESC practices involving trees or shrubs (afforestation, space-planting, riparian or gully planting) take time to become fully effective. This has rarely been explicitly studied, but rather derived from the observed performance of vegetation of different age in storm event studies (e.g. Cyclone Bola – Marden & Rowan (1993), Phillips et al. (1990)) or from the time to canopy closure (for afforestation and reversion). Dymond et al. (2016) list the following values for 'time to maturity' for biologically based ESC practices:

- afforestation and reversion: 10 years
- space planted trees and gully tree planting: 15 years
- riparian retirement (includes fencing): 2 years

It would be expected that vegetative practices (e.g. cover crops, re-grassing) used to control surface erosion require development of near complete vegetation cover. Similarly grass buffer strips require time to grow sufficiently tall and dense to remove sediment effectively. The time scales for this are likely to be short (up to a year). Practices like wheel track ripping and diking are immediately effective. Riparian fencing for stock exclusion is immediately effective although it may take time for stream banks to stabilise and develop vegetation cover.

Practices that involve trapping of sediment (e.g. debris dams, wetlands) would be expected to be effective as soon as they are constructed. However, as they fill with sediment and have less storage volume their performance efficiency is likely to decline.

Most of the practices that are used for earthworks erosion management are effective immediately (e.g. silt fences, geotextiles, mulches, sediment retention ponds) but the effectiveness of some may change through time. For example:

- Basher et al. (2016b) suggest that silt fence performance may be affected by two factors
  - They may become less effective over time as the build-up of sediments and clogging of the fabric increases the likelihood of overtopping
  - The trapping of sediment in the fabric matrix may reduce its permeability, contributing to the extended detention of incoming runoff and improving performance
- The performance of sediment retention ponds may deteriorate if the pond infills with sediment reducing detention time and settling, and allowing pond overflows in larger storm events.

5.4 ESC performance and particle size effects

Little information is available on variation in the performance of different ESC practices with respect to trapping particles of different sizes. While many studies report the particle size or texture of soils at individual study sites, differences in the particle size of source sediment and sediment delivered to streams are not reported. Some of the more advanced erosion models, particularly those simulating surface erosion, such as WEPP

(Nearing et al. 1989) and Morgan-Morgan-Finney (Morgan et al. 1984), do simulate the transport of different particle size fractions.

Surface erosion which is caused by shallow overland flow is known to preferentially transport finer soil particles. Clay and silt particles are preferentially transported by overland flow (e.g. Parsons et al. 1991; Sutherland et al. 1996; Leguédois & Le Bissonnais 2004). As a result, erosion mitigation that reduces surface erosion (e.g. cover crops, wheel track ripping) is likely to also affect particle of sediment delivered by this process. Similarly, buffer strips that filter water delivered by overland flow are likely to preferentially trap coarser particles and deliver the finer sizes of sediment

Practices for control of mass movement erosion or gully erosion using trees (space-panted trees or afforestation) are likely to have little effect on particle size as the eroded soil moves as a coherent mass with little opportunity for particle size fractionation. Any particle size fractionation is likely to occur once the sediment is delivered to a stream and would be controlled by the capacity of the stream to transport particles of different size.

Practices that involve trapping of sediment, such as sediment retention ponds, debris dams and wetlands, are likely to preferentially trap coarser particles and may pass the finer particles in overflows from the ponds, dams or wetlands. Moores and Pattinson (2008) provide analysis of differences in particle size between inflow and outflow sediment in treated and untreated sediment retention ponds used in urban earthworks. They found sediment size in inflow samples was typically coarser than outflow samples (although in one storm flocculated aggregates were discharged), samples collected at the outlets of the chemically treated and untreated ponds generally had similar particle size characteristics, and there was considerable variation within and between different storm events. They also suggested that some of the results may have been influenced by the variation in the type and location of earthworks activities being undertaken at the time of each storm.

5.5 Assessment of the effects of ESC practices in erosion and sediment models

Several models have been used in New Zealand to assess the effects of ESC practices in reducing erosion at site, catchment and national scale. They have been applied to both runoff-generated surface erosion as well as mass movement and gully erosion. This includes both empirical models (NZeem®, CLUES, WANSY, USLE) and hybrid empirical–process models (SedNetNZ, GLEAMS). This section summarises how ESC practices, including land cover changes, are incorporated into erosion and sediment models used in New Zealand. Most of the models are long-term steady-state models that provide prediction of average annual sediment yields. More detail on the modelling approaches and examples of their use are given in Basher et al. (2016b).

The New Zealand Empirical Erosion Model (NZeem®) was developed to address the effects of soil conservation and land use scenarios on erosion and sediment yield by Dymond et al. (2010). It was derived as a regression relationship between measured catchment sediment yields and catchment attributes. Erosion is modelled as:

$$\mathrm{E} = aCR^{b}$$

where E = long-term average annual erosion rate (t km^{-2} a^{-1})
R = mean annual rainfall (mm a^{-1})
C = a vegetation factor
a = an erosion terrain[4] coefficient
$b = 2$

NZeem® assumes a factor-of-10 reduction in erosion rates for land covered in trees (i.e. $C = 1$ for tall, closed canopy woody vegetation, $C = 10$ for non-woody vegetation). The spatial structure of NZeem® is based on a DEM with 15-m grid resolution. NZeem® was used by Dymond et al. (2010) to assess the effects of different strategies for implementing on-farm sediment control measures on sediment loads in the Manawatū River catchment. The analysis assumed that a fully implemented Whole Farm Plan (WFP) would reduce erosion by 70%. This was based on earlier work by Douglas et al. (2008) that documented an approach to estimating the effects of conservation works on farm sediment export that considered the type of erosion mitigation practice as well as the time it took for erosion control works to mature and become fully effective (Table 4). NZeem® does not distinguish the contribution from different erosion processes and thus far has not been used to evaluate the effect of individual erosion mitigation practices. However, recently Monaghan et al. (in prep.) used NZeem® to assess the impact of soil conservation practices implemented between 1995 and 2015 on the national sediment load. They distinguished the contribution of hillslope and bank erosion by making assumptions about the relative contribution of the two sediment sources.

Table 4 Effectiveness of erosion control works in reducing soil erosion at maturity and the required time to reach maturity (from Douglas et al. 2008)

Erosion control treatment	Maturity (years)	Effectiveness
Afforestation	20	90%
Reversion	5	90%
Space-planted trees	15	70%

A similar approach has also been implemented using the sediment budget model SedNetNZ to assess the effect of implementation of WFPs and riparian retirement on sediment loads in the Manawatū catchment (Dymond et al. 2016) and Hawke's Bay region (Palmer et al. 2014, 2016; Spiekermann et al. 2017). Dymond et al. (2016) used factors for effectiveness and maturity that varied with the type of work implemented and had slightly different values to Douglas et al. (2008) (see Table 5). The analysis using SedNetNZ also provided information on the effect of WFPs on different erosion processes (surface

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

erosion, landslides, earthflows, gully erosion, bank erosion) allowing better targeting of different mitigation practices used for different erosion processes. The spatial basis of most of the modelling in SedNetNZ is a 15-m DEM but the erosion data for each process is summarised, as in CLUES, by River Environment Classification (REC) subcatchment.

Table 5 Effectiveness of erosion control works in reducing soil erosion at maturity and the required time to reach maturity (from Dymond et al. 2016)

Soil conservation work	Maturity (yrs)	Effectiveness (%)
Afforestation	10	90
Bush retirement	10	90
Riparian retirement	2	80
Space-planted trees	15	70
Gully tree planting	15	70
Sediment traps	1	70
Drains	1	70

The CLUES (Catchment Land Use for Environmental Sustainability) model predicts the effects of land use on water quality and its economic implications (Elliott et al. 2016). As with NZeem®, it was derived by empirical regression relationships between measured sediment yield and catchment attributes (Elliott et al. 2008). The catchment attributes included are erosion terrain, rainfall, slope, and land cover class. Hence it can be used to assess the influence of land cover changes on sediment load. The spatial structure of CLUES is based on the REC with a mean catchment size of 0.46 km^2. Semadeni-Davies and May (2014) used CLUES in the Kaipara Harbour to assess the effect of stock exclusion and WFPs on sediment loads into the harbour to support catchment planning using similar mitigation practices and load reduction factors as outlined for NZeem®.

NZeem® and CLUES are both empirical erosion models based on national datasets of suspended sediment yield for model calibration. A regional empirical erosion model (WANSY) is available for the northern North Island (Haddadchi & Hicks 2016) that predicts sediment yield on a 1-ha-grid basis. It is based on a similar regression approach to NZeem® and CLUES but uses improved regional suspended sediment data to calibrate the model. It includes as source terms rainfall, slope, land cover (fraction of catchment area in pasture (or other non-forest land cover), fraction of exotic forest, fraction of native forest or scrub), and lithology. Not surprisingly, Haddadchi and Hicks (2016) found that it out-performed NZeem®, CLUES and SedNetNZ in terms of predicting sediment yield. Because it includes land cover as a source term it could be used to evaluate the effect of land cover change on sediment load.

Two approaches (the USLE or RUSLE and GLEAMS) have commonly been adopted in New Zealand for modelling sediment loads associated with urban development and infrastructure (roading) projects (Basher et al. 2016b). The Universal Soil Loss Equation (USLE) is a widely used method in New Zealand for estimating sediment losses associated with urban development and road construction projects. Developed in the USA from the results of extensive plot-scale experiments (Wischmeier & Smith 1978), the equation estimates the average annual soil loss per unit area (A) as the product of five factors:

$$A = R.K.LS.C.P$$

where: R is the erosivity factor, a function of rainfall intensity;
K is the soil erodibility factor;
LS is the slope length and steepness factor;
C is the cover management factor; and
P is the supporting practices factor.

Values for each factor are calculated from formulae or obtained from look-up tables. In applying the USLE or RUSLE for the estimation of sediment losses from earthworks projects, erosion control practices are partly taken account of through the C and P factors. For bare earth in the absence of erosion and sediment control measures, both C and P take a value of 1 (or higher where the surface of the soil has been modified, and erosion rates are increased). As the effectiveness of measures increases, the values of C and/or P reduce, resulting in a reduction in the estimate of sediment loss. The C factor is used to represent the performance of mulching, grass cover and other forms of erosion control (e.g. erosion control blankets). The P factor was designed as a way of reflecting the influence of various conservation cropping practices on soil loss from agriculture, but in the context of construction earthworks it can be used to represent the influence of surface on sediment generation. Basher et al. (2016b) suggest the USLE does not explicitly take account of sediment control practices. Instead, load reduction factors (LRFs) are typically determined and applied to the untreated sediment load calculations to reflect the performance of different sediment control practices that are applied. A Sediment Delivery Ratio is also applied to represent the proportion of sediment generated on a site that will be transported to sediment control devices. Basher et al. (2016b) provide examples of the typical LRFs used in New Zealand applications.

A number of studies to assess sediment generation associated with major New Zealand construction projects have used the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model, including the Waterview Connection and Puhoi-to-Warkworth state highway projects, both in the Auckland region (Basher et al. 2016b). GLEAMS is a physically based mathematical model developed for continuous simulation (at a daily time step) of surface runoff and sediment losses from the land on a field scale (Knisel 1993). The procedure for deriving sediment loads using GLEAMS field-scale predictions involves dividing a given study area (usually a catchment) into a number of land 'cells', each assumed to be of uniform land-cover, slope and soil type. The GLEAMS model uses a long-term climate record (rainfall, temperature and solar radiation) together with parameter values reflecting land-cover, slope and soil type to calculate a daily series of surface runoff and sediment yields for each cell. The results are then aggregated for the study area as a whole. Earthworks sites are modelled as one of a number of 'bare earth' land-cover classes. These classes have parameter values representing the absence of vegetation or other cover protection, resulting in the generation of markedly higher sediment yields than vegetated (or impervious) covers, holding all else equal. Stabilization of areas of bare earth is represented in GLEAMS by the selection of cover classes reflecting the post-construction land cover, such as grassland or impervious covers. Two approaches for modelling the influence of erosion and sediment control practices in GLEAMS studies have been adopted. The first of these involves the calculation of a treated sediment load by applying an LRF to the untreated load calculated by GLEAMS, in the same way as described above in relation to the USLE. The second approach is the application of a GLEAMS post-processing module simulating a sediment retention pond. The untreated sediment loads estimated by GLEAMS are partitioned into ten particle size classes according to soil type. The model calculates the proportion of the influent sediments that are removed by the pond according to their distribution among the different size classes and the respective settling speeds. Holding all else equal, a pond is modelled to remove a higher proportion of the load of a relatively coarse-grained soil than a relatively fine-grained soil. Where a sediment pond is chemically treated, the settling speeds of the smaller sediment particles entering the pond can be adjusted (increased), to reflect their aggregation as a result of flocculation.

6 Costs and co-benefits of erosion and sediment mitigation

6.1 ESC Practices

Based on a review of published research, the estimated values for the costs and co-benefits of ESC practices are given in Table 6. It is important to recognise that the estimated values of the costs and co-benefits are synthesized from different sources of which some are derived from empirical research and others from simulation modelling. As such, the assumptions underpinning these estimated values should be explicitly listed when utilized in future reports. The values for effectiveness quoted in Table 6 are those used in the reports cited and do not entirely match those quoted in section 5.1.

Doole (2015) has provided a summary review on the costs and effectiveness of a range of practices that mitigate nitrogen, phosphorous, sediment, and *E. coli*. This review was sourced from literature and expert opinion. As there was a wide range of costs and effectiveness for these practices, the report included a sensitivity analysis to examine the impact of uncertainty in these values on producer profit. The results showed that there were no significant changes in profits as a result of changes in costs and efficacy of ESC practices. Similarly, Daigneault and Samarashinghe (2015) used the NZFARM model to estimate possible reduction of producer profits in the Whangarei catchment in order to meet the proposed limits in sediment and *E. coli*. To conduct this analysis, information on producer profits as well as sediment and *E. coli*. was collected for a range of land uses. The analysis assessed a range of practices including fencing streams for stock exclusion, afforestation, wetlands restoration, farm plans, and outcome-based approaches. A recent review by Dorner et al. (2018a) has provided a description of potential practices that can be used to mitigate erosion, their effectiveness, and barriers of uptake. Daigneault et al. (2017a) have assessed the cost and effectiveness of several ESC practices in Kaipara Harbour catchment. The practices used in this study included stock exclusion, farm plans, afforestation, wetland restoration and outcome-based approaches. Similarly to the Whangarei catchment study, the NZFARM model was used to assess the impacts of these practices on profits and sediment loads.

Table 6 categorizes ESC practices into two groups: (1) riparian management, and (2) managing hillslope erosion processes. The results show that, on average, the practices within the managing erosion processes group are more expensive than riparian management practices group. The cost of practices within the managing erosion processes group has a wide range estimated between ~$33 and $9,000 per hectare. For instance, a quite expensive option such as afforestation in combination with fencing streams could lead to a cost of $1,000–2,000 per hectare plus ongoing maintenance costs. The practice of creating new wetlands could cost around $8,940 per hectare, including planting and fencing plus $300 per wetland for operating costs. Swales, soak holes, sediment ponds could cost between $255 and $1,300 per hectare, while detainment bunds cost between $300 and $500 per hectare. The least cost options in the managing erosion processes group are managing risk from contouring and landscaping estimated at $82 per hectare, wheel track ripping/diking estimated at $33–35 per hectare, and spaced planting of poplars or willows on steep erodible land estimated at $34 per hectare. On the other hand, the cost of implementing riparian management was estimated between $142 and $601 per hectare. Fencing was estimated at a cost of $7.10–$34.60 per meter, fencing plus planting was estimated at $255 per hectare, and stock water reticulation away from surface waterbodies was estimated at $145–$613 per hectare.

Co-benefits in terms of reducing other pollutants such as nitrogen, phosphorous, and *E. coli* are highest when implementing one of the managing erosion processes practices with a range of pollutant reduction between 4 and 70%. Afforestation has the ability to reduce nitrogen leaching by 4% and phosphorous loss by 15%. Creation of new wetlands can reduce nitrogen loss by 40% and phosphorous loss by 70%. Some practices within the managing erosion processes group have a range of pollutants reduction between 0 and 20%; however, high uncertainty has been identified for this range due to a lack of information. In comparison, riparian management has the potential to reduce other pollutants by 5–35% from the baseline. In particular, riparian fencing and planting as well as stock water reticulation away from surface water bodies could reduce nitrogen loss between 5 and 15%, phosphorous loss between 5 and 10%, and *E. coli* between 25 and 35%.

Table 6 Summary of the costs and co-benefits of ESC practices

Management area	Mitigations	Expected reductions from baseline Sediment / Erosion	N loss	P loss	*E. Coli*	Relative cost	Nominal cost	Additional details	References
Riparian management	Riparian fencing	40%	Uncertain	Uncertain	Uncertain	Medium	\$7.10/m – \$34.60/m[1]	Fencing estimated at \$7.10/m to fence out cattle (and provide water supply). Fencing out all stock estimated at \$34.60/m	Daigneault et al. (2017a)
	Riparian fencing and planted buffer around water bodies	40–50%	15% for dairy; 5% for drystock	10% for dairy; 5% for drystock	25–35%	Medium to high	\$255/ha[2]	A minimum of \$255/ha, subject to the opportunity cost of buffer, its width and range of waterbodies are excluded.	Doole (2015); Dymond et al. (2016); Keenan (2013); Monaghan & Quinn (2010)
	Stock water reticulation away from surface waterbodies	40%	15% for dairy; 5% for drystock	10% for dairy; 5% for drystock	25–35%	Medium	\$142–601/ha (capital cost) and \$3.13–12.56/ha (operating cost)[3]	Results in good medium-term payback, but some benefit may be extracted through higher carrying capacity, which may increase N losses	Doole (2015); Journeaux & Van Reenen (2017)
Managing hillslope erosion processes	Swales, soak holes, sediment ponds	Swales reduce by 40%; Sediment ponds by 50%	None	0–20% from swales	None	Medium to high	\$255–\$1,300/ha[4]	Swales cost \$255/ha; sediment ponds cost \$750–1,300/ha	Keenan (2013)
	Detainment bunds	Variable	None	Variable	Uncertain	Medium	\$300–500/ha of catchment	Detention bunds appear to be effective at catching particulate P in overland flow, but what this actually equates to on a farm or catchment scale is not fully understood. Not modelled in OVERSEER.	Clarke et al. (2013)

Management area	Mitigations	Expected reductions from baseline				Relative cost	Nominal cost	Additional details	References
		Sediment / Erosion	**N loss**	**P loss**	***E. Coli***				
Managing hillslope erosion processes (cont’)	Complete protection of gully heads	70-90%	None	None	Uncertain	High	$1,000–1,650/ha plus ongoing maintenance	Considering protection using afforestation	Daigneault et al. (2017a)
	Manage risk from contouring/ landscaping	40%	Uncertain	Uncertain	None	Low	$82/ha cropped	Implemented on cropped area	Keenan (2013)
	Wheel track ripping/diking	60-90%	Uncertain	Uncertain	Uncertain	Low	$33-35/ha		Daigneault et al. (2017a)
	Spaced planting of poplars or willows on land use capability class 4–6 (steep erodible) land	70%	None	20%	None	Low to Medium	$1650/ha[5]		Daigneault & Samarasinghe (2015)
	Afforestation or reversion (Land use capability (LUC) class 6, 7 and 8 land that is currently in pasture converted into forestry/mānuka and fenced)	80%	4%	15%	Uncertain	Medium (steep land) to High (easy contoured land)	$1,000–2,000/ha plus ongoing maintenance cost	Opportunity cost is 100% of profits from the area occupied by trees but generates income from trees over time. Average income from Manuka is between $112-$680 per ha per year.	Daigneault et al. (2017a); Doole (2015); Edlin & Duncan (2013)

Management area	Mitigations	Expected reductions from baseline				Relative cost	Nominal cost	Additional details	References
		Sediment / Erosion	N loss	P loss	*E. Coli*				
Managing hillslope erosion processes (cont')	Creation of new wetlands (assumes 1% of farm area)	80%	40%	70%	Up to 50% but recent NIWA work indicates more complexity in this issue	High	$8,940/ha of wetland, including planting and fencing plus $300/wetland for operating cost	One wetland can cover 400 ha of area	Daigneault & Samarasinghe (2015); Doole (2015)

[1] Cost of riparian fencing for dairy is estimated at $7.5 per metre while for sheep and beef is estimated at $35 per meter (Daigneault & Samarasinghe 2015). Other estimates of fencing 5-wire electric fence with electrified wires, 2 plain wires, 2.5-mm wire, number 2 posts and 5-m spacing for dairy farms was at $5 per meter (Doole 2015). However, costs of fencing 5-wire electric fence with electrified wires, 2 plain wires, 2.5-mm wire, number 2 posts and 5-m spacing for sheep and beef farms was at $35 per metre (Doole 2015).

[2] The cost of one plantation around $11.10 (Daigneault & Samarasinghe 2015). Doole (2015) estimated the cost of riparian buffer strip for horticulture land use at $175 per hectare. Chris Keenan (2013) estimated the cost of riparian grass buffer strip for pasture and horticulture land uses at $225 per hectare.

[3] Depends on type of wetland. Lowest cost estimated for natural wetland $200/ha for dairy and $600/ha for sheep and beef (Daigneault & Samarasinghe 2015).

[4] Chris Keenan (2013) estimated the cost of riparian grass buffer strip for horticulture land uses at $750–1300 per hectare treated.

[5] Costs of space planting for pasture farms estimated at $20/stem at 11-m spacing (82 stems/ha). This cost would reduce to $1200 at 13-m spacing (59 stems/ha) and $900 (44 stems/ha) at 15-m spacing.

6.2 Wider Impacts

The previous table and discussion focussed primarily on the ESC practices and their costs and impacts. There is also a wide international literature on the valuation of the endpoints that they produce, such as improved water quality through a reduction in sediment. The New Zealand-based literature in this area is still growing. There are several studies that value changes in water quality, but a much smaller group of studies that value changes in sediment specifically. Several recent New Zealand-based papers contain reviews of this literature, including Marsh and Mkwara (2013), Cullen et al. (2006), Kerr et al. (2004), and Tait et al. (2016).

To appropriately value improvements in sediment, it is important to be mindful of double counting. For instance, consider a policy that uses riparian buffers and other methods to reduce sediment. The riparian buffers themselves can produce aesthetic, biodiversity, and carbon benefits as well as sediment reductions. A cost-benefit analysis of that policy might monetise the overall reduction in sediment using stated preference estimates, and monetise the co-benefits of riparian buffers. However, it is important to exclude the riparian buffers’ sediment benefits since they would already be counted in the overall reduction.

The majority of papers in New Zealand that value freshwater use stated preference approaches. Baskaran et al. (2009), for instance, use a choice experiment to value changes in nitrate leaching. Marsh et al. (2011) use measures of the suitability of waterbodies for swimming and ecological health in a choice experiment aimed at estimating the value of freshwater improvements. There are also several other recent freshwater water quality valuation surveys, including Kerr and Sharp (2008), Tait et al. (2016), Marsh and Phillips (2012), Phillips (2014), Ambrey et al. (2017), and Kerr and Swaffield (2012). However, these papers do not directly use sediment in their surveys, instead using other measures of water quality or ecosystem health. To properly use those studies for benefit transfer, one would first need a function that links changes in sediment to the measure of water quality used.

Another approach to valuing the impacts of sedimentation in New Zealand is to use avoided cost estimates. Jones et al. (2008) focus on the economic costs or erosion and review several notable avoided costs associated with sedimentation. They review several methods for this, including flood damage costs resulting from sedimentation, drinking water treatment costs, lost agricultural productivity, and damages associated with landslides. In an older study, Krause et al. (2001) estimated that the costs of sedimentation are $27.4 million (2001 dollars), which included water storage, drinking water treatment costs, navigation, dredging, and damage from flooding. These avoided costs need to be used with caution, however, as they are frequently overestimates of actual welfare impacts.

In the international literature, a common approach for valuing the non-use values of sediments in benefit cost analysis is through the water quality index (WQI) (Brown et al (1970), which translates changes in several water quality parameters into an overall value. The WQI has been used in several stated preference studies (e.g. Johnston et al. 2005) to calculate non-market values, and sediment (Total Suspended Solids) is one of the main parameters of the WQI. In this approach, commonly used at the US EPA (US EPA, 2009), the impact of sediment on the overall WQI is first modelled. Changes in the WQI can then be monetised using a benefit transfer of stated preference estimates. Some of the early benefit transfers of this approach used Mitchell and Carson (1986) as the main source of values. In more recent applications, a meta-analysis is first performed on values from the literature, with the resulting function employed as a benefit transfer function (US EPA 2015).

7 Feasibility study

The purpose of the feasibility study is to outline the approach to determining which streams and catchments do not meet proposed sediment threshold values (C/D threshold) using results provided by NIWA, and outline methods available to provide a nationwide estimate of the costs and co-benefits of interventions to meet sediment load reduction requirements identified in the analysis from NIWA.

7.1 Defining the streams and catchments that do not meet proposed sediment standards

NIWA (Hicks et al. in prep) have undertaken an analysis for every stream segment in the REC stream network to:

- calculate sediment load,
- use the sediment load data to predict clarity and turbidity,
- compare the predicted present values of clarity and turbidity with proposed sediment threshold values,
- calculate the % load reduction required to meet proposed sediment threshold values and determine whether the maximum load reduction required was for clarity or turbidity (this was defined as a parameter Rmax).

The results of this analysis are illustrated in Figure 1. This shows that of the 593,548 stream segments in the REC stream network 145,397 (25%) do not meet the proposed sediment standards. The load reduction requirements range from <1% to 96.5 % of the current sediment load.

The mitigation analysis cannot be undertaken at stream segment level because it must account for sediment load contributed by the upstream catchment area to any stream link. Therefore, NIWA defined which catchments exceed the proposed sediment standards, and by how much sediment load needs to be reduced, by:

- identifying the farthest downstream stream segment in any catchment that exceeds the proposed sediment standards,
- using this as the pour point to define the upstream contributing catchment,
- calculating the catchment sediment reduction requirement from the average of all non-zero values of Rmax in the contributing catchment.

This resulted in 733 catchments that do not meet proposed sediment standards. These range in size from to 0.3 km^2 to >20,000 km^2, with sediment reduction requirements ranging from <1% to 83.2 % of the current sediment load. They cover about 71% of New Zealand. The results of this analysis are illustrated in Figure 2.

We propose to use the catchments defined by this analysis as the spatial basis for applying mitigation scenarios and calculating the costs and co-benefits of these scenarios.

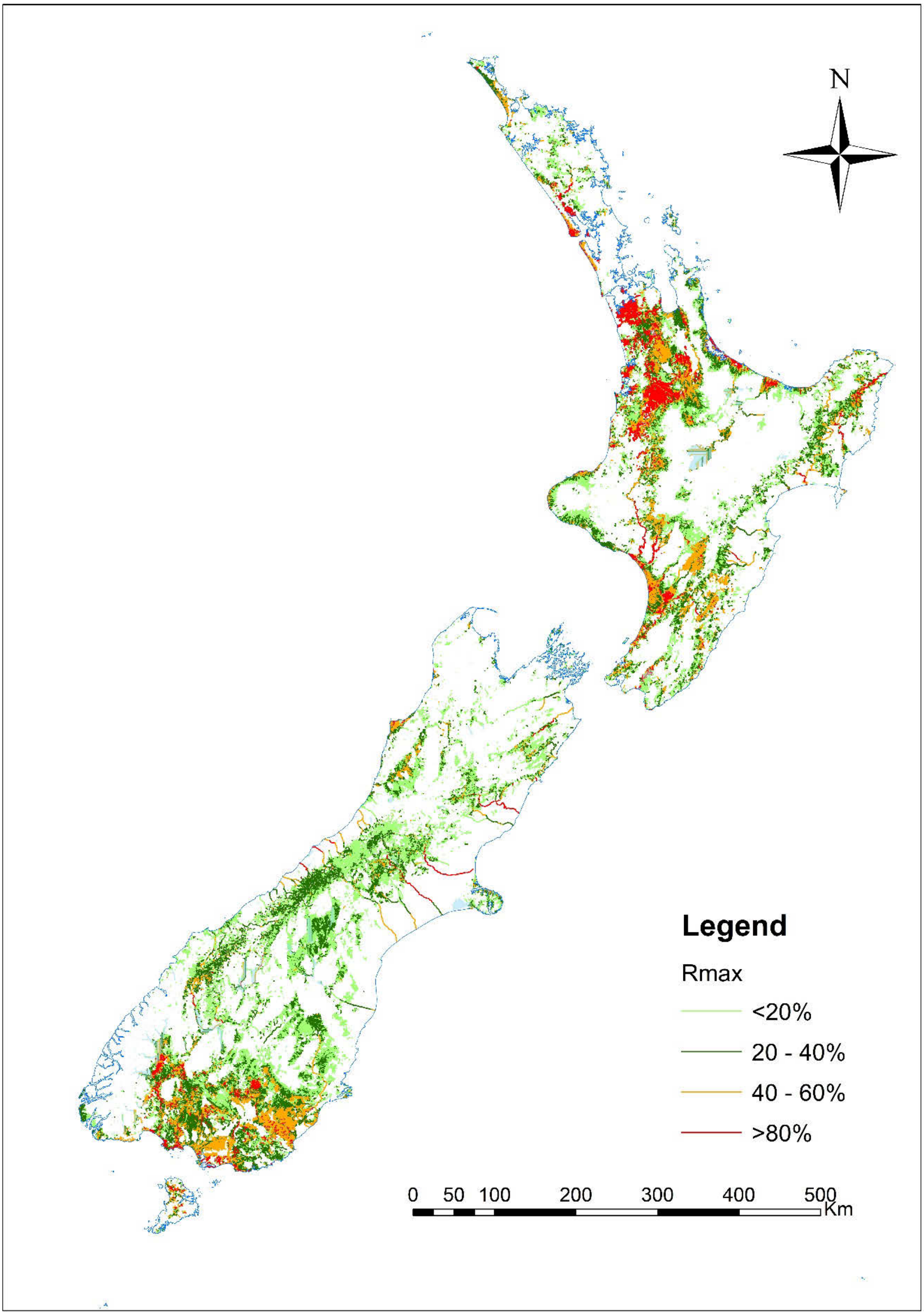

Figure 1 Percentage sediment load reductions required at REC stream segment level. Rmax is the maximum value of load reduction required to meet either the turbidity or clarity standard.

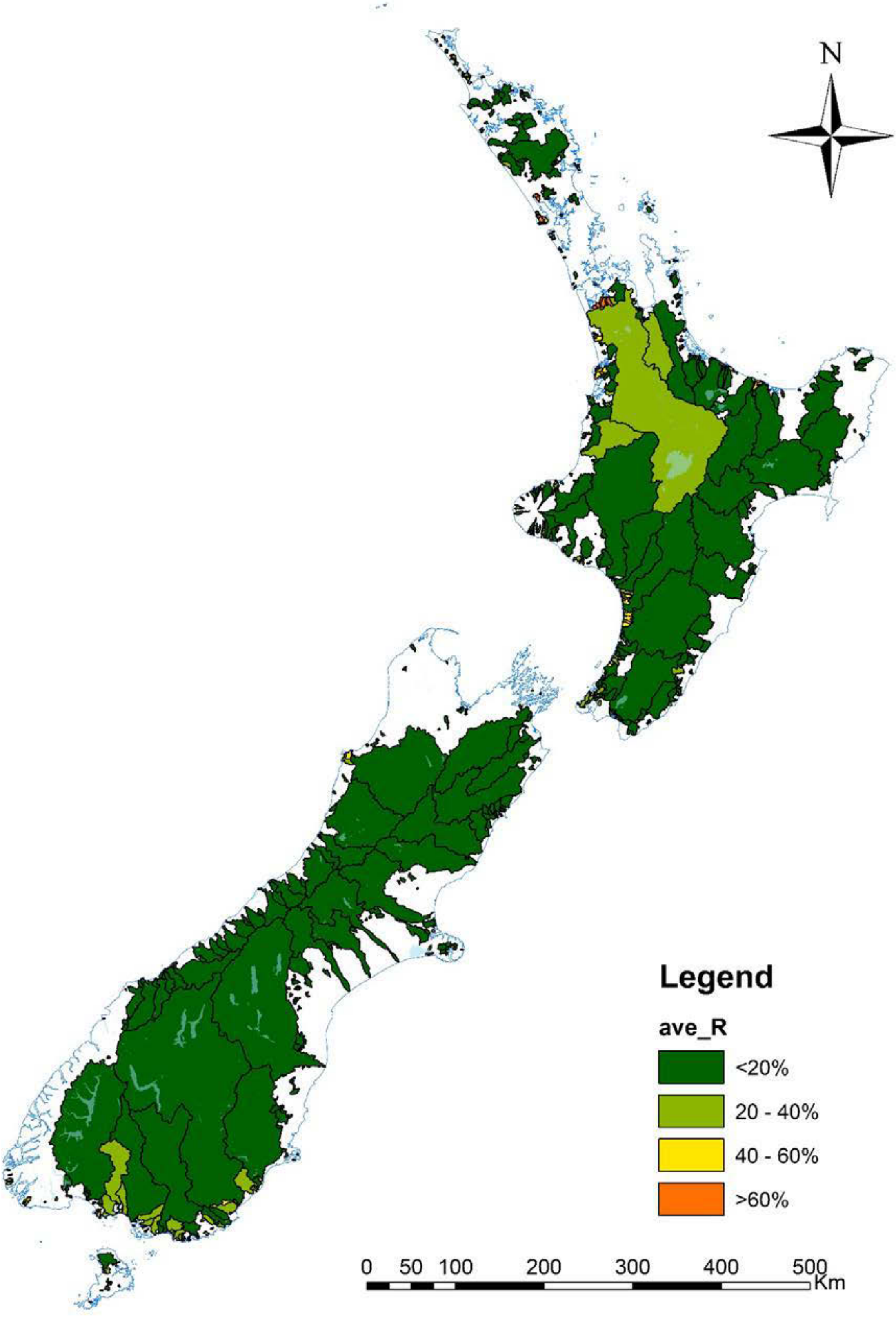

Figure 2 Delineation of catchments that do not meet proposed sediment standards and percentage sediment load reductions required at catchment scale.

7.2 Assessing costs of sediment reduction

Overall description of the approach

For analysing the costs of implementing the ESC practices the ex-ante economic simulation models (hereafter economic models) are the most suitable approaches, because they allow evaluation of the effects of introducing new technologies and policies (Hazell & Norton 1986). Several economic modelling approaches that are often used for assessing at the national scale the costs of ESC practices are identified in section 6. The type of models differs depending on the problem to be addressed and scale of the model. Computable General Equilibrium models analyse the economy-wide effects and consider the inter-sectoral linkages of introducing technological, practice and policy changes (Bandara et al. 2001). In addition, partial equilibrium models look at the effects at the single sector, (e.g. impacts of implementing ESC practices in agriculture and forestry sectors) and considers the change in commodity demand, supply and prices. However, these types of models are usually aggregated to the larger scale such as whole economy or sector, and do not consider site- or region-specific details, and might miss the location and practice specific effects of ESC. Also, these models require extensive data on different sectors of the economy, and their interlinkages and elasticities. Another approach is the farm-level economic modelling analysis of ESC practices that considers in detail farm characteristics such as behaviour, different resources available, agro-ecological conditions and management practices. Yet, this approach is restricted to analyse farm-level effects and thus necessitates data on each single farm, which would lead to extensive data collection for performing the national scale analysis. In contrast, the land use allocation economic model at the national scale can be less data intensive and still captures some degree of the characteristics relevant to land users.

We propose to use the national scale New Zealand Forestry and Agricultural Regional Model (NZFARM). NZFARM is an agri-environmental economic land use allocation optimization model and has been used to assess climate and water policy scenarios across New Zealand (e.g. Daigneault et al. 2012; Djanibekov et al. 2018). NZFARM is a comparative static model that maximizes the profits from agricultural/forestry production subject to feasible land use areas and imposed resource, environmental or other constraints (Fig. 3). The model accounts for all major land use enterprises and land use types in New Zealand. The model estimates costs from introducing sediment mitigation measures on agricultural/forestry production subject to feasible land use, policy and environmental constraints such as limiting the sediment output from land uses. Performance indicators tracked within NZFARM include economic, environmental (such as sediment and greenhouse gas emissions) and agronomic variables. The model is flexible and can be used at a range of scales, including national and catchment scales. Adding new land uses, practices and, technologies requires the financial budgets and environmental impacts (e.g. sediment reduction) to be known and added to the NZFARM land use enterprise input file.

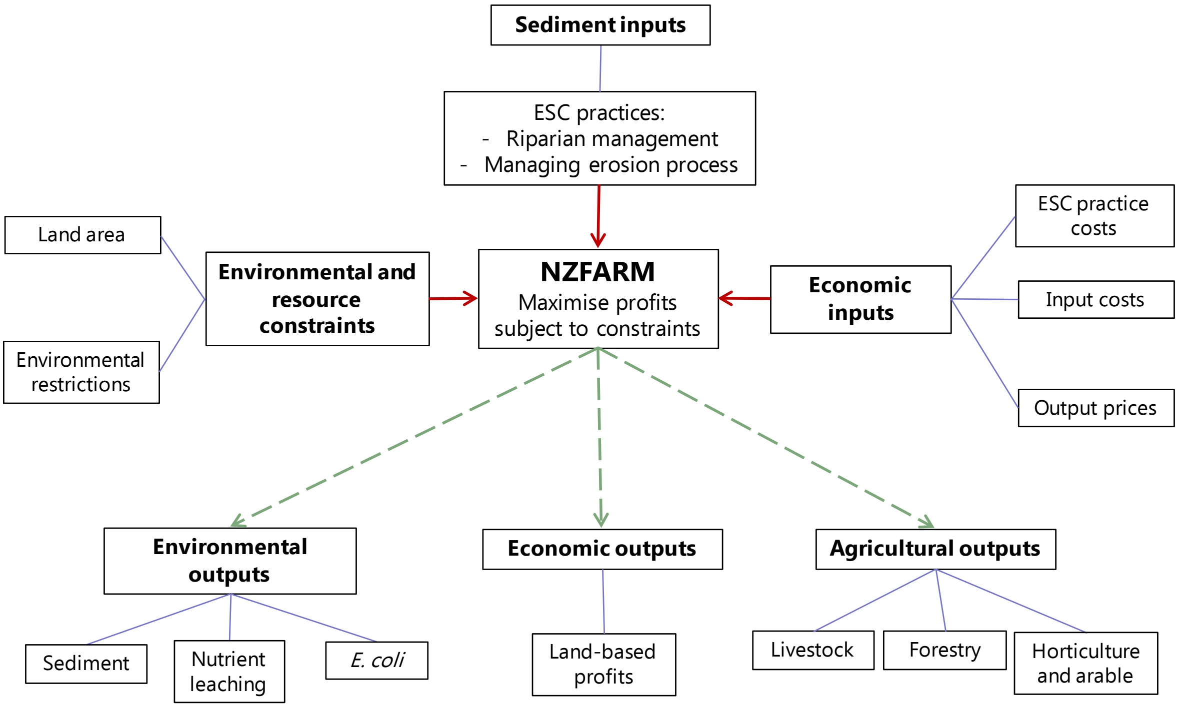

Figure 3 Schematic view of the NZFARM model (adapted from Daigneault et al. (2017a) and Djanibekov et al. (2018)).

Performance indicators tracked within NZFARM include economic (e.g. production and earnings before interest and taxes (EBIT)) and environmental (e.g. sediment, nutrient leaching) variables. Environmental performance indicators within NZFARM show physical values as they currently do not have monetary value and thus are not reflected in cost-benefit structure of land uses. To monetise environmental indicators, we will use valuation approaches (see section 7.2). Economic and environmental performance indicators can be presented at the catchment, regional or national scales.

The model includes land uses such as dairy, sheep and beef, deer, other pasture, arable, forestry, horticulture (e.g. berries, pipfruit, vegetables, viticulture, kiwi fruit), native, and other type of land uses (e.g. conservation, urban land area). Dairy includes various systems distributed across New Zealand. For the sheep and beef sector, we consider six types classified according to topology and management practices. Forestry can be used for carbon sequestration and for timber harvest. The flexible model structure of NZFARM facilitates the addition of new land use systems and/or management practices. Adding new land uses and/or management practices requires the financial budgets and environmental impacts to be known and added to the NZFARM land use enterprise input file. No structural changes to the model are needed.

When calibrating the model, we will ensure the estimated national land use area figures of the baseline reflect those observed in AgriBase and LCDBv4. This will ensure land use area pattern consistency between the model and observed data. The scenarios and mitigation options that will be modelled in NZFARM will be agreed with MfE as it might require considerable time to prepare the data, parametrize and calibrate the model.

Scale of analysis

NZFARM model can run simulations at the national or catchment scales. At national scale, NZFARM optimises the model for all New Zealand, but also disaggregates for 16 regions. The results can be shown at the national level or for each of the 16 regions of New Zealand. The national scale analysis allows the results to be represented for each region and investigate the regions that are most affected by introduction of ESC practices. Analysis at this scale will be aggregated per each region and will not include spatially detailed information at the grid level (based on grids developed by Geographic Information System analysis). This is because the economic (agricultural output and profit) and nutrient leaching relevant data are not available at the grid level.

The catchment scale of NZFARM model analyses the impacts of mitigation options and sediment reduction scenarios in a single case study catchment. The model is simulated at highly detailed scale using the data at the grid level (based on grids developed by Geographic Information System analysis). The results of the catchment scale analysis can be represented on maps by showing information for each land use allocated to the grid. The limitation of this scale of analysis is that the impacts of the single catchment might be irrelevant for other catchments of New Zealand. The effects of mitigation options and sediment reduction scenarios might substantially differ from one catchment to another catchment, and thus the catchment scale analysis will not be representative for the entire New Zealand.

Mitigation options

The NZFARM model can include different mitigation options as reviewed in sections 5.1 and 6.1 and Tables 2 and 6. We propose that the analysis will bundle erosion mitigations into two groups – management of hillslope erosion processes through implementation of WFPs or afforestation, and management of bank erosion through riparian exclusion and/or planting. This approach, similar to that used by Dymond et al. (2016, 2017a), Daigneault et al. (2017a), and Monaghan et al. (in prep.), allows mitigation options and effectiveness to be associated with farm/land use boundaries, or stream reaches and avoids the need to specify spatially exactly where erosion mitigations are implemented. The latter would require far more spatial detail on where individual mitigations would be located and is not feasible at national or large catchment scale.

The financial costs and benefits of mitigations will be included into the profit value (earnings before interest and tax) of land uses, and environmental output in constraint equations of the model.

Scenarios

NZFARM facilitates 'what if' scenario analysis by showing how changes in environmental policy could affect the uptake of ESC practices and any subsequent spill-over effects on a group of performance indicators important to decision-makers and stakeholders. The what if scenario analyses are performed by solving for a baseline, or status quo, economic optimal condition, then imposing specific policy or other changes on the system and solving the model again to compute a new economic optimal condition consistent with the scenario changes. NZFARM facilitates what if scenario analysis by showing how different approaches to achieving the required sediment reduction affect the costs of achieving that reduction. The NZFARM analysis at national scale for the identified catchments will require:

- A baseline scenario with the present pattern of land use (from Agribase) and sediment generation. The sediment generation scenario will utilise data from the NZeem® model which is available for all NZ and incorporates erosion mitigation implemented to 2015 (WFPs, afforestation and riparian exclusion);
- Mitigation measure scenarios will consider land users implementing erosion and sediment control practices and land use change to reduce sediment. These sediment reduction measures will be bundled together as mitigation options (at least WFPs, afforestation, riparian exclusion, as well as practices suitable for arable and horticultural land). The number and type of practices and technologies used for the model will depend on availability of data and will rely on output from the reviews of ESC practices and costs of mitigations. The model will include target (limit) level reductions of sediment for each catchment. A sediment reduction level will be included in the model as a constraint on sediment outputs from land uses and will limit the sediment output from land uses in each catchment. In modelled scenarios, a sediment reduction level will be reduced with respect to the baseline sediment levels by implementing appropriate mitigations.

We can use two approaches for implementation of NZFARM model at the national and catchment scales. These options differ in their ability to assess the effect of sediment reduction measures on sediment output, land use allocation, economic costs, and agricultural production.

Data sources

The key to this analysis is the data used in the NZFARM model. Currently, there are data deficiencies, which means there is no ‘perfect’ dataset that covers all the parameters required for this analysis. There is no nationally consistent dataset that includes up-to-date land use budgets with associated alternative management practices and corresponding environmental impact files (e.g. OVERSEER). Therefore, the data we propose to use for this analysis will come with some caveats in terms of comparability of data between sectors.

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

We propose to use the data compiled for the 2018 Biological Emissions Reference Group project (BERG; Djanibekov et al. 2018) and 2012 national land use data. These data cover a range of agricultural (pastoral, arable and horticulture) and forestry land uses for New Zealand.

We will use 2017 land use budgets for dairy sourced from DairyNZ (DairyNZ Economic Group 2017, 2018). This dataset includes a range of land use management practices as well as the corresponding EBIT, and nutrient losses estimated using Overseer version 6.2.3 and FARMAX. Nutrient losses for dairy are only available for certain types of management practices (mitigation options). 2017 farm budgets for sheep and beef systems were sourced from Beef+Lamb New Zealand economic data. The horticultural budgets are from Horticulture New Zealand. Profit and environmental outputs for land uses that were not obtained from industry will be based on Daigneault et al. (2017a). The sediment input data will come from NZeem® model outputs.

In addition, the national version of NZFARM uses a 2012 national land use map based on AgriBase and LCDBv4 as its baseline land use. This map covers a range of agricultural (pastoral, arable and horticulture) and forestry land uses for New Zealand. The model will be disaggregated by different land uses for each of the catchments identified by NIWA (see Fig. 2). We will use NZeem® outputs to model sediment reduction following approaches outlined in Dymond et al. (2010).

Option 1: NZFARM with mitigation options

This version of NZFARM modelling allows the comparison of two different outcomes: (1) before and (2) after the sediment reduction measures are implemented. The model estimates cost directly from erosion control measures. The baseline scenario (without new sediment policy) will incorporate erosion mitigation measures up to 2015. That scenario will be compared to a scenario that has the policy measures in place (where sediment reduction measures are used to meet targets).

Option 1 uses a linear programming model and restricts the analysis to investigate the adoption rate of sediment mitigation options. This approach optimises the mitigation adoption levels for different land uses to have the maximum economic returns under different sediment reduction scenarios. A limitation of this approach is that it does not consider land use change (e.g. shift of sheep and beef farm to dairy, or shift from pasture to horticultural land uses). This restriction allows the direct capture of the mitigation costs and of sediment reduction scenarios, because they lead to lower economic returns for land users. In contrast, modelling land use changes might lead to the same level or even increase of economic returns from the baseline. This is because the model will optimise land use allocation for achieving the maximum economic returns by replacing the less profitable land uses with the more profitable ones. It would be much more difficult to directly identify the impacts of the mitigations if land uses are changing.

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

Option 2: NZFARM with mitigation options and land use change

This option addresses the land use change and adoption rate of mitigation measures using nonlinear equations, such as constant elasticities of transformation. Nonlinear equations allow the analysis to avoid unreasonable changes in land use allocation and mitigation adoption. For example, land use changes occur in some areas and farmers do not adopt mitigation measures on large (or all) areas, preferring to keep some of their present land uses and practices. These can be due to external factors that limit large land use change (e.g. skills with different land uses, undeveloped infrastructure, or lack of technology). The nonlinear version of the NZFARM model will optimise the land use allocation to achieve the maximum economic returns from land uses. The approach considers mitigation adoption and is subject to constraints on land use area availability and different sediment reduction scenarios. For instance, in this model, we will analyse the change from sheep and beef areas to horticulture, while using constraints to consider the adoption area of sediment mitigations under different sediment reduction scenarios.

The limitation of this version of the model is that the optimisation objective of the model might lead to land use change becoming the prevalent mitigation measure for sediment reduction. This will be because land uses have different erosion rates and sediment mitigation practices that result in lower monetary returns than land uses without such practices. Modelling of land use change might lead to an increase in economic returns (e.g. shift from sheep and beef to more profitable land use), even with the sediment reduction scenarios. Hence, it might not be possible to directly observe the effects of sediment reduction scenarios on adoption of mitigation options and subsequently on costs of land uses. In addition, in contrast to the linear version of the NZFARM model, the nonlinear version requires model calibration, which leads to additional data collection and development of model assumptions.

7.3 Assessing co-benefits of sediment reduction

Summarising the overall benefits and costs of the proposed policy options will bring together the outputs of the NZeem® and NZFARM modelling and data analysis. The central goal of the benefit cost analysis is to evaluate the overall change in economic and social welfare from proposed policies on sediment reduction. The theory and application behind these measures of welfare are drawn from the established literature on welfare economics (Freeman 2003).

In an ideal cost-benefit analysis all of the major impacts would be monetised to facilitate direct comparison of policy scenarios. In practice, there can be a large gap between things that should be monetised and things that can be monetised within time and budget constraints.

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

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

For this study, benefit transfer must be used in the cost benefit analysis. There are several potential ways to do this, which depend on data inputs and external choices. We will present several potential options for this valuation. It is first important, however, to review some of the market and non-market impacts of the chosen policy option. In this case, we differentiate these impacts from the more direct impacts of the implementation practices themselves, contained in Table 6. It is more straightforward to calculate the costs of installing riparian buffers (including the costs of tree planting and land), for instance, than to estimate the downstream benefits of water quality. Table 7 contains a summary of many of these central impacts. For each item, the final column contains some recommendations for how the impact might be quantified or monetised. In a full cost-benefit analysis, the middle two columns would be filled in based on resources and time available.

Table 7 Benefits and costs of sediment

Effect of Sediment	Quantify	Monetise	Description
Impacts on Navigational waterways			The accumulation of sediment in navigational channels and harbours can affect transport, shipping, fishing, and other uses. This can be monetised using an avoided cost approach, employing the cost to dredge the waterbody. See EPA (2009).
Reservoir impacts			Reservoirs and other water storage facilities provide drinking water, flood control, and other benefits. Sediment accumulation affects these abilities. An avoided cost approach could be used to monetise these effects, using the dredging costs as a proxy for the full effect.
Drinking water treatment			Sediment in the water can diminish water quality and hence increase the treatment costs to turn it into drinking water. These treatment costs could be used to estimate the impacts of improved water quality, and are an avoided cost.
Agricultural water uses			If irrigation water is pulled from waterbodies with high sediment content, it can harm crops and reduce agricultural productivity.
Commercial fishing			Sediment in the water can have a negative impact on fish populations through impacts on aquatic habitat. This can affect commercial harvests. Quantification of this effect requires analysis of fishing harvest and sediment inputs.

Effect of Sediment	Quantify	Monetise	Description
Recreational fishing			Sediment-related reductions in water quality can affect the demand for recreational fishing, as well as the experience of recreational fishing. Recreation demand models could be used to monetise these impacts.
Flood damage			Accumulating sediment in rivers and streams can increase the frequency and severity of floods. If a relationship could be established between floods and sediment, the reduced flood damages could be used to estimate impact.
Water-based recreation			Sediment can reduce the quality of water-based recreation. Stated preference surveys could be used to monetise these impacts.
Reduced aesthetics			Sediment-related water pollution can make rivers and streams less aesthetically appealing. Stated preference surveys could be used to monetise these impacts.
Water-related non-use impacts			People who do not directly recreate in the water may still hold values for clean water. They may value bequeathing good water to future generations, or simply value clean water or a healthy environment. Stated preference surveys could be used to monetise these impacts.
Biodiversity-related impacts			Water quality has a range of impacts on aquatic animal populations. People may hold non-use values for the preservation of species. Stated preference surveys could be used to monetise these impacts.
Hydroelectric facility impacts			Sediment can impose additional treatment costs on hydroelectric facilities. These avoided costs could be used to measure impacts.
Carbon impacts from ESC practices			The mix of ESC practices chosen for the policy option will cause changes in carbon. For example, riparian buffers or afforestation will deploy trees widely, which will reduce carbon.
Carbon impacts from changes in production			The sediment policy may change the distribution and composition of producers, which can affect carbon emissions.

Overall Evaluation Approach

The goal of a regulatory cost benefit analysis is to evaluate the impacts of a proposed policy change in order to inform decision making (US EPA 2014). The main focus is on monetising impacts where possible, so that different policy options can be compared with each other. However, there are many instances where impacts cannot be monetised. In those cases, they can be quantified or described to better assist the comparison.

The analysis proposed in this report uses an effect-by-effect approach, whereby the major effects of a policy are analysed individually, and then the results are summarised at the end (US EPA 2014).[5] This approach to cost benefit analysis requires two main scenarios: a

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

baseline and at least one policy scenario. The cost benefit analysis explores the differences between these two options. The baseline depicts the state of the world in the absence of the policy, and its specification can have a significant impact on the results of the analysis. It is important to note that the baseline measures the state of the world across the timeline of concern, not just the state of the world at the time of the policy formulation. For instance, if the policy effects are projected to occur over 50 years, the baseline must characterise that period in the absence of the policy.

The proposed policy options and baseline will be developed in coordination with MfE. The modelling and environmental outputs described in sections 4–6 above will be used to establish the environmental impacts, economic impacts, and regulatory options. This feasibility study also assumes that an appropriate timeline of effects will be established in collaboration with MFE. An overall depiction of the cost-benefit analysis approach appears in Figure 4.

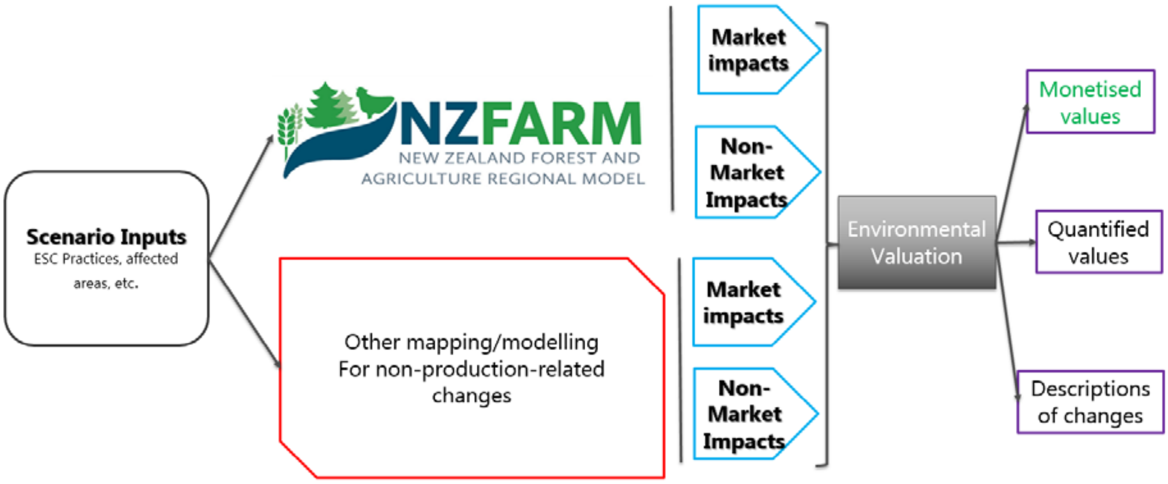

Figure 4 Cost-benefit analysis approach.

Costs

The policy option(s) agreed upon with MfE will specify a particular set of ESC practices that will be used to calculate the costs of regulation. In most cases, the appropriate measure of costs is the social costs of the regulation, defined as the total opportunity costs caused by the regulation (US EPA 2014). In the context of this work, these costs will be considered in a partial equilibrium analysis, where the focus is limited to a particular set of industries or sectors. A full wide-economy computable general equilibrium analysis (CGE) that includes all sectors is beyond the scope of this work.

Table 6 contains a set of cost estimates for these practices that can be applied to the regulatory options to obtain an estimate. Where possible, these costs will be tailored to the particular setting. For instance, if we expect the cost of tree plantings to vary across the country, a set of correction factors will be applied.

The cost analysis will also include the outputs from the NZFARM runs described above. They include costs to the agricultural industry as a result of the new policy. Important changes in land use and net revenues can be identified by that model. Those changes represent important opportunity costs to be included in this model.

Benefits

As identified in Table 7, there are a range of potential benefits arising from sediment reductions. Where possible, the proposed analysis will calculate the monetised benefit of several categories and summarise those benefits across the identified timeline. Discount rates of 3% and 6% will be used to calculate the net present value of the stream of benefits across time[6].

Ideally, all the benefits of sediment would be monetised or quantified. However, due to time, budget, and methodological constraints, the analysis proposed here would use benefits transfer to calculate several main benefits categories. The full breadth of categories depends on available data from several of the main effects. Where possible, other benefit categories will be quantified and described.

One of the main benefits categories identified is the use and non-use value residents hold for water quality improvements. This is likely one of the larger categories of benefits, based on other previous benefit cost-analyses of sediment in other countries (US EPA 2009). Several New Zealand-based studies have attempted to estimate people’s willingness to pay for improvements in water quality. We have identified two options, explained below, that might suitably be used to estimate some of the benefits of sediment reductions. To calculate monetised benefits, both these options would use a benefits transfer that involves the use of existing non-market values estimated in past studies. In the benefits transfer, it is important to match the ‘study case’ (the setting of the past studies from which the estimates come) with the ‘policy case’ (the setting of the current regulation). This typically involves several important trade-offs, so it is important to be transparent about differences and attempt to correct for them in the benefits transfer.

We propose two options for benefits transfer, based on existing New Zealand studies. These studies differ in the water quality parameter that they focus on, as well as the setting of the surveys. One approach uses nitrogen, while the other approach uses clarity. In both cases, we propose to control for local differences in income during the benefits transfer.

Water Quality Valuation Option 1

The first option for valuing water quality is through Baskaran et al. (2009). This paper used a stated preference survey to place a value on nutrient reductions. To value a reduction in sediment, we would first need to estimate a relationship between sediment and nutrients. Using that relationship, a benefit function transfer would be used to value the change in sediment, following the approach demonstrated in Walsh et al. (2017). Since Baskaran et

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[6] Current discount rates from Treasury are found here: https://treasury.govt.nz/information-and-services/state-sector-leadership/guidance/financial-reporting-policies-and-guidance/discount-rates

al. (2009) controlled for income in their survey, we could adjust the results of the benefits transfer to control for local income using census data from Statistics New Zealand.

Water Quality Valuation Option 2

The second option for estimating the value of water quality in a benefit transfer would employ either Tait et al. (2016) or Phillips (2014), both of whom use water clarity in stated preference choice experiments that elicit people's willingness to pay. This approach would require the estimation of a relationship between sediment and clarity. Data from the NIWA analysis will be used to estimate that relationship, which would then be used to transfer values from the stated preference survey. In recent conversations with MFE, an existing relationship between sediment and clarity was identified that could be used to augment this benefits transfer. Changes in sediment from the policy simulations would be translated into clarity. These would be assessed against water clarity standards and then valued using the results of either Tait et al. (2016) or Phillips (2014). Corrections would be made for differences in income between the study site and the policy site.

Other Monetised Estimates

We will also attempt to monetise several other benefit categories. Based on the carbon emission estimates from NZFARM, we will value changes in carbon. MfE has specified two preferred carbon prices for this exercise, at $20 and $25, to reflect recent prices in the ETS market. To capture uncertainty in the carbon price, and reflect potential future increases, we will also calculate benefits under an international estimate of the social cost of carbon.

Where data and budget allow, we will also attempt to calculate the monetised benefits of other categories mentioned in Table 7. The avoided costs of dredging and hydropower plant maintenance, for instance, represent other potential areas that might be monetised. For the 2009 Construction and Development Rule, the US EPA used US-based estimates to value changes in those factors. If the data are available, we will update using New Zealand-based values.

Impact Estimate

After calculating the monetised impacts where possible, quantifying things that cannot be monetised, and describing other impacts, results will be aggregated into several final estimates. Where possible, sensitivity analyses will be presented to explore the sensitivity of the results to particular assumptions, such as the discount rate or social cost of carbon. The results will be presented in tables that will transparently evaluate the different components of the analysis. Where possible, key assumptions will be identified and explained.

8 Conclusions

A wide variety of ESC practices are used in New Zealand, depending on the land use and the type of erosion process(es) generating sediment. While performance efficiencies are known for many individual ESC practices multiple practices are often used to achieve a desired performance efficiency (i.e. individual practices are 'bundled' into a suite of mitigations). This is especially the case for pastoral soil conservation farm plan implementation, urban erosion and earthworks mitigation, and in modelling studies.

Erosion mitigation effectiveness can vary widely (e.g. space-planted trees reduce erosion, mainly by landsliding, by 30–95% in individual studies). There has been little detailed study of the factors affecting variation in performance but it is likely that several factors affect mitigation performance, including underlying susceptibility of the land to erosion, size of rainfall event, different metrics used to assess performance, scale of investigation, and adequacy of mitigation treatment. Any of the ESC practices involving trees or shrubs (afforestation, space-planting, riparian or gully planting) take time to become fully effective, typically 10–15 years, while many structural practices are effective immediately. Little information is available on variation in the performance of different ESC practices when trapping particles of different sizes. Differences in the particle size of source sediment and sediment delivered to streams are generally not reported. Surface erosion caused by shallow overland flow is known to preferentially transport finer soil particles, but practices for control of mass movement erosion or gully erosion using trees are likely to have little effect on particle size as the eroded soil tends to move as a coherent mass. Several models have been used in New Zealand to assess the effects of ESC practices in reducing erosion at site, catchment, and national scale. They have been applied both to runoff-generated surface erosion as well as to mass movement and gully erosion, and include both empirical models (NZeem®, CLUES, WANSY, USLE) and hybrid empirical-process models (SedNetNZ, GLEAMS). Typically, mitigation practices are bundled to assess performance.

Estimated values for the costs and co-benefits of ESC practices have been derived from empirical research and from simulation modelling. ESC practices have been divided into two groups: (1) riparian management, and (2) managing hillslope erosion processes. The results show that practices within the managing erosion processes group are more expensive than in the riparian management practices group. Co-benefits in reducing other pollutants (N, P, and *E. coli*) are highest when implementing the managing erosion processes practices with a range of pollutant reduction between 4% and 70%.

New Zealand-based literature on valuing improved water quality through a reduction in sediment is relatively limited. There are several studies that value changes in water quality, but a much smaller group of studies that specifically value changes in sediment. Typically, studies that value water quality use stated preference approaches; however, most do not directly use sediment in their surveys but rather use other measures of water quality or ecosystem health and therefore need a function that links changes in sediment to measures of water quality.

Catchments defined by NIWA where predicted current sediment load exceeds proposed sediment standards can be used as the spatial basis for applying mitigation scenarios and calculating the costs and co-benefits of these scenarios. These catchments cover about 71% of New Zealand and sediment load will need to be reduced by between <1% and 83% of the current sediment load in individual catchments. We propose to use the national-scale NZFARM model to analyse scenarios for the costs of implementing erosion mitigation practices to meet sediment reduction targets. We propose to use the linear version of NZFARM (option 1) that considers the adoption of mitigation options and restricts land use change.

9 Recommendations

- We recommend the use of NZeem® to undertake an analysis of the effect of erosion mitigation on reducing sediment load to meet the sediment thresholds determined by NIWA.
- The NZeem® results can be used with NZFARM to assess the costs and co-benefits of erosion mitigation at national scale.

10 Acknowledgements

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Appendix 1 – List of erosion and sediment control practices used in New Zealand

Table 8 List of erosion and sediment control practices used for urban earthworks and infrastructure (from Basher et al. 2016b)

	Description of method
Erosion and sediment control plan	Not an ESC practice *per se*, but a framework within which to plan ESC management
	Runoff control
Check dams	Small dams constructed across a swale or channel to act as grade control structures and reduce velocity of runoff
Contour drains and cutoffs	Temporary excavated channels or ridges constructed slightly off the slope contour to reduce slope length and runoff velocity
Diversion channels and bunds	Non-erodible channels and/or bunds for the conveyance of runoff (either clean or dirty water) that are constructed for a specific design storm to intercept and convey runoff to stable outlets or sediment retention ponds at non-erosive velocities
Pipe drop structure and flume	Temporary pipe structures or constructed flumes placed from the top of a slope to the bottom of a slope to convey clean or dirty runoff without causing erosion
Level spreader	A non-erosive outlet for concentrated runoff constructed to disperse flows uniformly across a stabilised slope. Often used in combination with sediment retention ponds
Hay bale barriers	Temporary barriers of hay bales used to intercept and direct surface runoff from small areas
Water table drains and culverts	A channel excavated parallel to a road or track to provide permanent drainage of the carriageway and/or to provide a conveyance channel for stormwater. Culvert connects the drain to a stable outfall
	Erosion control
Stabilised entranceway	Stabilised pad of aggregate on a woven geotextile base located at any entry or exit point of a construction site to reduce erosion in heavily trafficked area. Can include shaker ramp and vehicle wash
Surface roughening	Roughening an unstabilised bare surface with horizontal grooves across the slope or by tracking with construction equipment to increase infiltration, surface roughness, detention storage and entrapment of sediment
Benched slopes	Grading of sloped areas to form reverse sloping benches with diversion channels on a slope to minimise erosion by limiting volume and velocity of runoff
Topsoiling and grass seeding	Planting and establishment of quick growing and/or perennial grass to provide temporary and/or permanent stabilisation on exposed areas, often undertaken in conjunction with the placement of topsoil. Reduces raindrop impact, runoff volume and velocity

	Description of method
Hydroseeding	Application of seed, fertiliser and paper or wood pulp in a slurry sprayed over an area to provide rapid re-vegetation. Reduces raindrop impact, runoff volume and velocity. Applied to critical or difficult areas
Mulching	Application of a protective layer of straw or other material (bark, wood residue, wood pulp) to the soil surface to stabilise soil surface and reduce raindrop impact and runoff, prevent soil crusting, and conserve moisture. Can be used in combination with regrassing and may need crimping or binders
Turfing	Establishment and permanent stabilisation of disturbed areas with a continuous cover of grass turf to provide rapid stabilisation. Reduces raindrop impact, runoff volume, and velocity
Geotextiles, plastic covers, erosion control blankets, geo binders	Placement of a variety of erosion control products to stabilise disturbed soil areas and protect soils from erosion by wind or water. Applied to critical or difficult areas or other areas where there is inadequate space to install sediment controls. Includes temporary biodegradable geotextiles (jute, straw blanket, wood fibre blanket, coconut fire blanket or mesh), permanent non-degradable geotextiles (plastic netting or mesh, synthetic fibre with netting, bonded synthetic fibres) and combination synthetic and biodegradable rolled erosion control products
Soil binders and chemical treatment	Organic or chemical soil-stabilising agents that penetrate the soil and bind particles together to form protective crust which reduces windblown dust generation and raindrop impact
	Sediment control
Sediment retention pond (including flocculation systems)	Temporary pond formed by excavation into natural ground or by the construction of an embankment, with a decanting device to dewater the pond at a rate that will allow the majority of suspended sediment to settle out
Decanting earth bunds	Temporary bund or ridge of compacted earth to intercept sediment-laden runoff and reduce the amount of sediment leaving the site with a decanting device to dewater the decanting earth bund at a rate that will allow suspended sediment to settle out. Used on smaller areas or where a sediment retention pond cannot be installed
Silt fences	Temporary barrier of woven geotextile fabric used to capture sediments carried in sheet flow
Super silt fences	Temporary barrier of woven geotextile fabric over a chain link fence used to capture predominantly coarse sediments carried in sheet flow
Filter socks	A mesh tube filled with a filter material (e.g. compost, sawdust, straw) used to intercept and filter runoff and reduce the velocity of runoff
Flocculation including FlocSocks	Added to sediment retention pond inflows via a rainfall-activated system to accelerate coagulation and settlement of fine colloidal particles
Dewatering	Removal of water from excavations, trenches and sediment control devices by pumping
Stormwater inlet protection	Barrier across or around a stormwater inlet to intercept and filter sediment-laden runoff before it enters a reticulated stormwater system (includes silt fence, geotextile fabric, filter sock, check dam, proprietary products)

	Description of method
Sediment sump	Temporary pit constructed to trap and filter water before it is pumped to a suitable discharge area
Vegetative buffer zones and turf filter strips	Areas of existing grass cover which are retained at appropriate locations to remove small volumes of sediment from shallow sheet flows.
Soakage system	Temporary soak pits to dispose of clean run-on water and sediment-laden site runoff into the ground where infiltration rates and groundwater levels allow
Sediment curtain	Temporary floating geotextile fabric barriers suspended vertically within a water body (stream) to separate contaminated and uncontaminated water to isolate the work area and allow sediments to settle out of suspension
	Streamworks
Temporary watercourse crossings	A bridge, ford or temporary structure installed across a watercourse for short term use by construction vehicles to cross watercourses without moving sediment into the watercourse, or damaging the bed or channel
Permanent watercourse crossings	Bridge, culvert or ford installed across a watercourse where permanent access is required across a small watercourse
Dam (with pumping or diverting)	Temporary practices used to convey surface water from above a construction activity to downstream of that activity
Temporary waterway diversions	A short-term watercourse diversion that allows work to occur within the main watercourse channel under dry conditions. Diverts all flow via a stabilised system around the area of works and discharge it back into the channel below the works to avoid scour of the channel bed and banks
Instream and near stream works	Temporary structures built (from rock, sand bags, wood or a filled geotextile material) within the banks or channel of a waterway to enclose a construction area and reduce sediment delivery from work in or immediately adjacent to the waterway
Rock outlet protection	Rock (rip-rap or gabion baskets) placed at the outfall of channels or culverts

Table 9 List of erosion and sediment control practices used for forestry

	Description of method
Harvest plan	Not an ESC practice *per se*, but outlines the requirements for erosion and sediment control
	Runoff control
Diversion channels and bunds	Permanent non-erodible channels and/or bunds to convey clean runoff to stable outlet.
Contour drains and cutoffs	Temporary (usually) excavated channels or ridges constructed slightly off the slope contour to reduce slope length and runoff velocity and deliver runoff to stable outlet
Broad-based dips	A dip and reverse slope in a road surface with an out-slope in the dip for natural cross drainage, to provide cross-drainage on in-slope roads and prevent build-up of runoff and erosion
Rolling dip	A dip and reverse slope in a road surface with an out-slope in the dip for natural cross drainage to provide cross drainage on in-slope roads and prevent build-up of runoff and erosion; used on roads that are too steep for broad-based dips
Flumes and outfalls	Mechanical conveyance system that transports water from one area to another via a stable outlet without causing erosion. Usually associated with culverts
Check dams	Small dams constructed across a swale or channel to act as grade control structures and reduce velocity of runoff
Water table drains, culverts and sumps	A channel excavated parallel to a road or track to provide permanent drainage and control runoff and/or to provide a conveyance channel for stormwater. Culvert connects drain to a stable outfall and sump at upstream end of culvert can be included to trap coarse sediment
	Erosion control
Surface roughening	Roughening of a bare surface to create horizontal grooves that will reduce the concentration of runoff, aid infiltration, trap sediment and aid vegetation establishment
Log corduroying	Placement of logs to provide a solid working platform, usually in wet processing areas or on access roads to minimise sediment generation
Slash and mulch placement	Application of a protective layer of hay/straw mulch or slash to the soil surface to reduce raindrop impact and prevent sheet erosion
Grassing and hydroseeding	Sowing of seed to establish a vegetative cover over exposed soil and reduce raindrop impact and sheet/rill erosion. Hydroseeding allows revegetation of steep or critical areas that cannot be stabilised by conventional sowing methods.
Rock lining of channels	Protection of bare drains and roadside water tables in erosion prone soils against erosion
Geotextiles	Fabrics used to protect soil surfaces against raindrop impact and sheet/rill erosion particularly in spillways and diversion channels
Benched slopes	Benches constructed on the outside of roads/tracks to place stable fill

	Description of method
Slash management	Placement of slash to avoid mobilisation in water bodies and off landings
	Sediment control
Haybale barriers	Temporary sediment retention devices to intercept and divert runoff for very small catchments
Earth bund	Ridge of compacted earth (preferably compacted subsoil) built on the contour to detain runoff and trap sediment
Slash bund	Temporary bunds of slash for very small catchments to trap the initial 'pulse' of coarse sediment
Earth bund	Temporary bund or ridge of compacted earth to detain runoff long enough to allow sediment to drop out of suspension prior to discharge from catchments <0.1.ha. Typically, a continuous bund constructed on the contour (e.g. around the toe of a landing) or a 'horseshoe' shape incorporating a natural depression
Silt fence	Temporary barrier of woven geotextile fabric used to capture sediment carried in sheet flow from small areas
Super silt fence (debris dam)	Temporary barrier of woven geotextile fabric over a chain link fence used to capture predominantly coarse sediments carried in sheet flow often constructed in areas of active erosion
Silt trap	Temporary small sediment retention pond system
Sediment retention pond (including flocculation systems)	Temporary pond formed by excavation into natural ground or by the construction of an embankment, with a decanting device to dewater the pond at a rate that will allow the majority of suspended sediment to settle out
Sediment trap/soak hole/sump	Constructed hole in porous soils used to control runoff from roads/tracks and trap sediment
	Streamworks
Harvesting operations	Planning of harvesting operations to minimise impacts on stream channels
Dry stream crossings	Temporary crossings of ephemeral channels protected by log corduroying
Permanent watercourse crossings	Bridge, culvert or ford installed across a watercourse where permanent access is required across a small watercourse
Dam (with pumping or diverting)	Temporary practices used to convey surface water from above a construction activity (e.g. culvert installation) to downstream of that activity
Temporary waterway diversion	A short-term watercourse diversion that allows work to occur within the main watercourse channel under dry conditions. Diverts all flow via a stabilised system around the area of works and discharges it back into the channel below the works to avoid scour of the channel bed and banks

Table 10 List of erosion and sediment control practices used for horticulture and arable cropping

	Description of method
Erosion management plan	Not an ESC practice *per se*, but a framework within which to plan ESC management
	Runoff control
Interception drains	Drains to intercept and control runoff from above. If gradient steep then requires check dams
Culverts	In drains to pass paddock entranceways
Benched headlands	Used to direct runoff to paddock edge or drain (stable outlet). May be grassed to trap sediment
Diversion bund	Earth bund used to divert runoff away from vulnerable paddock or to prevent water discharging directly from a paddock
Contour drains	Temporary excavated channels or ridges constructed slightly off the slope contour to reduce slope length and runoff velocity and deliver runoff to stable outlet
Grassed swale (within-paddock)	Grass-covered surface drain formed used to direct clean water runoff along the swale, following its natural course, to a stable outlet
Stabilised (raised) access ways and discharge points	Metalled access point used to control runoff and direct to a stable outlet or other ESC measure
	Erosion control
Cover crops	Crop planted to protect the soil from raindrop impact and sheet/rill/wind erosion between rotations, and ploughed into the soil before planting of a new crop
Wheel track ripping	Shallow cultivation of compacted wheel tracks in row crops to increase infiltration and reduce erosion
Wheel track diking	Use of an implement to create series of closely-spaced soil dams in compacted wheel tracks
Paddock length	Used to break up long paddocks, control runoff and erosion
Cultivation practices	Used to manage soil structure and organic matter, increase infiltration and reduce runoff and erosion. Includes minimum tillage, no-tillage and stubble retention
Strip cropping	Strips of permanent vegetation retained between crops to break up slope length and reduce water and wind erosion
	Sediment control
Vegetated buffers and riparian margins	Grass or hedge areas adjacent to waterways or at paddock boundaries to reduce runoff velocity and filter sediment
Silt/Super Silt fences	Temporary barrier of woven geotextile fabric (incorporating a chain link fence – Super Silt fence) used to capture sediments carried in sheet flow from small catchments
Decanting earth bund	Shallow bund or ridge of compacted earth installed at bottom of paddock to pond runoff, with a decanting device to dewater the bund at a rate that will allow suspended sediment to settle out. Used on smaller areas or where a sediment retention pond cannot be installed
Silt trap	Sediment retention pond formed by excavation into natural ground or by the construction of an embankment, with a decanting device to dewater the pond at a rate that will allow the majority of suspended sediment to settle out

Table 11 List of erosion and sediment control practices used for pastoral farming

	Description of method
Farm plan	Not an ESC practice *per se*, but a framework within which to plan ESC management
	Surface erosion
Pasture management	Maintenance of high level of ground cover to reduce sheet/rill/wind erosion
Contour furrows	Furrow constructed with slight gradient to break up slope to control runoff
	Mass movement (shallow landslides, slumps, earthflows)
Spaced planting	Planting of spaced poles to reduce soil water content, increase soil strength and reduce erosion
Afforestation	Blanket planting of closely spaced trees to reduce soil water content, increase soil strength and reduce erosion
Reversion	Removing stock and fencing erosion-prone areas to encourage reversion to woody vegetation to reduce erosion
Surface drainage	Use of surface ditches, cutoff drains and graded banks to reduce infiltration and dewater ponding areas on slumps and earthflows
Sub-surface drainage	Horizontal boring to reduce subsurface water content of earthflows and slumps
Surface recontouring	Smoothing the land surface to enhance runoff, reduce ponding and soil water content
	Gully erosion
Spaced planting	Planting of spaced poles to stabilise the sides and floors of gullies.
Afforestation	Blanket planting of closely spaced trees to reduce soil water content, increase soil strength and reduce erosion
Graded banks	Series of earth banks formed on long slopes to control surface runoff and divert to a stable outlet
Flumes and chutes	Structures to discharge water across/away from gully heads or sidewalls to a stable outlet further down the gully. Mainly used to control migration of gully headcuts
Pipe drop structures	Pipes used to discharge water across from gully heads or sidewalls to the gully floor. Often used where flow is small
Sump	Constructed hole in porous soils used to control runoff and trap sediment. Typically used in highly porous volcanic soils
Diversion banks	Earth bank used to divert runoff away from gully head to stable outlet
Grassed waterway	Grassed waterway used to divert runoff away from gully head to stable outlet
Drop structures	Spillway constructed of concrete, geotextiles, rock, sheet piling used to safely convey runoff over gully head

	Description of method
Debris dams	Structures constructed of a variety of materials (e.g. timber, pole and netting, brush, logs, iron) to control the grade, reduce channel slope and water velocity, trap debris and stabilise the gully floor
	Streambank erosion
Tree planting	Planting of spaced poles or dense vegetation (shrubs and trees) to stabilise streambanks. Can include tying together of the vegetation to enhance survival
Vegetation lopping and layering	Felling of existing vegetation and layering to stabilise stream banks
Engineering works (rip rap, groynes, gabion baskets, etc.)	Rock and netting structures used to control severe bank erosion. Can be used in combination with biological control
Debris traps	Low dams on the bed of small streams, constructed from netting and posts, to stabilise channels, reduce bank erosion and trap sediment
Gravel extraction	Removal of gravel to take pressure off outside of bends and reduce bank erosion
Bank shaping	Battering of streambanks to reduce potential for bank erosion
Channel diversion/realignment	Realignment of channel away from actively eroding banks to reduce bank erosion
Riparian fencing	Permanent fencing of streambanks to exclude grazing and reduce damage to stream banks by stock
Controlled grazing	Temporary fencing of streambanks to allow infrequent grazing and reduce damage to stream banks by stock