Biophysical performance of erosion and sediment control techniques in New Zealand: a review

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Summary

Project and client

- This report forms part of the deliverables for the MBIE programme 'Smarter targeting of erosion control' (STEC), specifically Milestone 1.2.1-1.

Objectives

- To review the use of erosion and sediment control (ESC) methods in New Zealand.
- To establish the biophysical performance of commonly used measures for controlling erosion and reducing sediment delivery to waterways.
- To review the available information on ESC performance (percentage removal) on sediment quality (e.g. particle size).
- To produce a report to meet Critical Step Milestone 1.2.1-1 of the STEC programme.

Methods

- We reviewed previous work, including recent reviews and updated information.
- We have taken an approach that considers the types of erosion present in New Zealand, presents current ESC practices and techniques used in New Zealand, outlines what we mean by 'effectiveness' and 'performance' (definitions), and then focuses on the methods used to assess effectiveness for the different erosion processes.
- In line with our definition of effectiveness, we show the expected performance range for the various ESC techniques.

Results – key findings

- New Zealand has a relatively short history of ESC compared to many other countries, especially given that it has high erosion rates by global standards.
- A wide variety of ESC practices are used in New Zealand, depending on the land use and the type of erosion process(es) being targeted.
- 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 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 or detainment bunds).
- Mass movement erosion (landslides, earthflows, slumps) is controlled by practices that influence slope hydrology and/or soil strength, which are most often achieved by space-planted trees, afforestation, or reversion. The same ESC practices (especially afforestation) are often used to control 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.
- We define ESC *effectiveness* as the extent to which the soil conservation treatment or ESC practice achieves the desired outcome. Consistent and repeatable methodologies are required to assess effectiveness and enable comparisons. ESC *performance*, while related to effectiveness, is the actual measure of sediment reduction, and it is usually expressed as a percentage relative to a control situation.
- There is a wide range in the performance of some ESC practices, but there has been little work done on the factors affecting this variation. For example, for wide-spaced 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, and adequacy of treatment. Variation in the performance effectiveness of ESC practices used for earthworks has been 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 the development of near-complete vegetation cover, but the time scales for this are likely to be shorter (up to a year). Most of the practices that are used for earthworks erosion management are effective immediately.
- Little information is available on the variation in the performance of different ESC practices with respect to trapping particles of different sizes (i.e. sediment quality), 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 on reducing erosion at the 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 predictions of average annual sediment yields.
- Typically, modelling involves bundling several different ESC practices into an analysis based on the 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.
- Commonly used performance 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%.

Research gaps and needs

Gaps include:

- data on the treatment performance of individual ESC practices
- information on ESC treatment performance across a range of event sizes
- the performance of ESC practices under the full range of soil and rainfall characteristics and land uses in New Zealand
- how to address scale issues, particularly in models (i.e. scaling up from understanding the performance of individual measures to understanding the overall effectiveness of these measures at the farm scale and catchment scale).

Conclusions

- A wide variety of ESC practices are used in New Zealand, depending on the land use and the type of erosion process(es) being targeted.
- While performance efficiencies are known for many individual ESC practices, often multiple practices are used to achieve a desired level of effectiveness (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.
- ESC treatment performance values can vary widely, but there has been little detailed study of the factors affecting this variation. 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, and adequacy of mitigation treatment for the problem being addressed.
- 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 the variation in the performance of different ESC practices with respect to trapping particles of different sizes (i.e. in relation to 'sediment quality').

1 Introduction

New Zealand has a natural environment and history of land management that predisposes the country to soil erosion (Basher 2013a). Erosion processes are naturally very active as a result of a dominance of steep slopes, weak rocks, high rainfall, and common high-intensity rainstorms (e.g. McSaveney 1978; Soons & Selby 1992; DM Hicks et al. 2011; Basher 2013a). Deforestation of much of the country has been relatively recent and extensive, while the introduction of large numbers of grazing animals and intensive land use in some areas has accelerated rates of erosion (e.g. Page et al. 2000; Basher & Ross 2002; Glade 2003). Regional patterns of soil erosion are distinctive, reflecting both natural environmental variation and land management practices (e.g. Cumberland 1944; Eyles 1983).

Erosion and sedimentation are thus natural processes, driven largely by climate and geology, which have been accelerated by human activities. Erosion is also a key national environmental issue, with land use affecting soil loss and sediment polluting waterways (MfE & Stats NZ 2019). For example, the first national estimate of the economic cost of soil erosion and sedimentation was $126.7 million per annum (Krausse et al. 2001), and this number is still used in more recent studies (e.g. Jones et al. 2008).

Manaaki Whenua – Landcare Research has received funding from MBIE for a research programme called ‘Smarter targeting of erosion control’ (STEC). The programme aims to enable a breakthrough in erosion and sediment control (ESC), which is crucial for meeting proposed national water quality targets (MfE 2019a, b). The programme is directed at both the physical performance of ESC measures (the right treatment in the right place with enduring effectiveness) and their cost effectiveness.

Focusing on intensively monitored regional catchments, this programme will apply emerging geospatial technologies to characterise sediment sources, fluxes and particle properties to support the development of new models and tools. The resulting models and data sets will be used to:

- quantify explicit links between erosion sources and sediment-related water quality
- determine the performance of ESC measures
- develop a framework for a national-scale assessment of erosion and sediment redistribution, and their economic impacts.

This will improve soil erosion prediction, reduce the impacts of sediment in fresh and coastal water bodies, and determine how erosion and sediment are best managed to achieve water quality objectives in a cost-effective way.

To meet national freshwater objectives for catchment management (contaminant loss from land to water), regional councils and land managers need higher-resolution data on catchment erosion and sediment delivery to streams, and new tools and models that provide information at the appropriate scale, but particularly at larger spatial scales. These are essential in order to implement national freshwater policy and to justify investment in erosion and sediment control, and also for planning for the predicted increased storminess and erosion as a result of climate change (e.g. Crozier 2010; Basher et al. 2012; Manderson et al. 2015).

In general terms, information and knowledge at the hillslope and small catchment scale is reasonable, but at larger spatial scales New Zealand lacks the quantitative data to ensure erosion control is targeted appropriately. This includes addressing the question 'are trees being planted in the right places and do they survive to provide an effective erosion control treatment?'. Answering this question means

- identifying which parts of the landscape are most susceptible to erosion ('hot spots')
- determining their responses to treatment
- identifying consequent downstream effects.

Accurate identification of these hot spots is essential for:

- understanding the key processes contributing to sediment generation
- designing appropriate erosion control measures
- evaluating the effectiveness of erosion control measures across the range of event magnitudes
- understanding the lag time between erosion control and downstream water quality at different spatial scales.

Within the STEC programme there are several key areas of innovation to improve understanding and management of erosion and sediment in New Zealand. These include:

- improved spatial and temporal resolution of data
- characterisation of sediment quality
- linking erosion source to sediment quality
- enabling a leap in erosion modelling and prediction of the effects of erosion control at scales from hillslope to large catchments.

One research aim (RA1.2) is focused on assessing the biophysical performance of erosion mitigation measures to provide confidence in their use by land managers and in erosion models. A secondary aim is to link the biophysical performance to an assessment of the benefit–cost of measures to reduce sediment in water to improve catchment management to meet catchment water quality targets when they are introduced. It is not the specific aim of this report to cover the economic aspects here, as a parallel work stream within STEC is focused on the economic impacts of erosion and the benefits of mitigation.

This review aims to bring together information (scientific understanding, practical user experience and knowledge, and best practice) to establish guidance at both the regional and national scales for erosion and sediment control in New Zealand. It forms part of the deliverables for STEC, specifically Milestone 1.2.1-1, and is aimed primarily at regional councils and those involved in managing land to deliver freshwater outcomes in New Zealand.

2 Objectives

- To review the use of ESC methods in New Zealand.
- To establish the biophysical performance of commonly used measures for controlling erosion and reducing sediment delivery to waterways.
- To review the available information on ESC performance (percentage removal) on sediment quality (e.g. particle size).
- To produce a report to meet Critical Step Milestone 1.2.1-1 of the STEC programme.

3 Background

3.1 History of erosion control in New Zealand

New Zealand has a natural environment and history of land management that predisposes the country to soil erosion (Basher 2013a). Erosion rates in New Zealand are naturally high by world standards, with about 200 megatonnes of soil/sediment delivered to the ocean each year (DM Hicks et al. 2011). Erosion processes are naturally very active as a result of a dominance of steep slopes, weak rocks, high rainfall, and common, high-intensity rainstorms (e.g. McSaveney 1978; Soons & Selby 1992; DM Hicks et al. 2011; Basher 2013a). Deforestation of much of the country has been relatively recent and extensive, while the introduction of large numbers of grazing animals, and intensive land use in some areas has also accelerated rates of erosion (e.g. Page et al. 2000; Basher & Ross 2002; Glade 2003). Regional patterns of soil erosion are distinctive, reflecting both the natural environmental variation and land management practices (e.g. Cumberland 1944; Eyles 1983).

Erosion and sedimentation are thus natural processes driven largely by climate and geology, which have been accelerated by human activities. Erosion control is a key ecosystem service in New Zealand because of the widespread occurrence of many different forms of erosion (Basher 2013a). As a result, the methods for mitigating erosion and decreasing sediment loss to water bodies must consider both natural and anthropogenic causes of variability in erosion rates (McDowell et al. 2013) and define what is manageable.

In the last two decades a number of reviews have highlighted knowledge of erosion processes and erosion mitigation, including biological erosion control (Phillips et al. 2000, 2008; Basher et al. 2013a,b; Douglas et al. 2008; Mackay et al. 2012; McDowell et al. 2013); farm planning as a tool for reducing the impacts of erosion (and other contaminants) on surface and groundwater (Blaschke & Ngapo 2003; Mackay 2007; Basher, Manderson et al. 2016); riparian management (Collins et al. 2014; McKergow et al. 2014); climate change impacts on erosion and sediment yield (Manderson et al. 2007; Basher et al. 2012, 2020); the social aspects of hill country erosion management (Basher, Botha, Dodd et al. 2008; Basher, Botha, Douglas et al. 2008); and methods to manage sediment and their economic assessment (Dorner et al. 2018).

Historically, awareness of soil erosion and the need for soil conservation had become a matter of national concern by the 1940s following storm events in North Island hill country, and the apparent human-induced degradation of large tracts of the South Island mountainlands (Committee of Enquiry 1939; Gibbs & Raeside 1945; McCaskill 1973; Roche 1994). This resulted in the passing of the 1941 Soil Conservation and Rivers Control Act, the establishment of the Soil Conservation and Rivers Control Council (SCRCC), and catchment boards to manage erosion and sedimentation problems.

In addition, central government agencies (Department of Agriculture, Department of Lands, Ministry of Works) and catchment boards began the development of a wide variety of techniques for controlling erosion (McCaskill 1973; Roche 1994). The initial focus was on controlling extensive gully and earthflow erosion in the North Island, revegetating extensive areas of bare ground in the South Island, and river control in both islands. Techniques were developed through trial and error and experimentation, and included spaced tree planting, graded banks and terraces, contour cultivation, conservation fencing, contour drains, debris dams, drop structures, farm plans, and the identification of land for retirement. The SCRCC undertook research and surveys to underpin the development of soil conservation practice, published bulletins describing the techniques and their application, ran training courses to facilitate practical application, and established experimental farms to experiment with and demonstrate soil conservation techniques (McCaskill 1973; Roche 1994).

Although a wide range of methods are used for erosion control in New Zealand, biological methods are by far the most common (Basher 2013a). A large range of vegetation types and species have been used, including herbaceous, shrub and tree species, mainly exotic species, with more limited use of indigenous species. In rural New Zealand there has been strong emphasis on biological erosion control (either through space-planted trees or blanket afforestation) because of its relatively low cost and its effectiveness, particularly in reducing rainfall-triggered shallow landslides (Douglas et al. 2013; Phillips & Marden 2005). In the case of space-planted trees, pastoral farming was less affected than by afforestation, allowing continued grazing but still affording a level of erosion control, particularly against shallow landslides. Thus, there is a long history of planting trees to control erosion and using farm plans with a narrow soil conservation focus. More recently, whole-farm plans (WFPs) and farm environment plans (FEPs) have been developed by regional councils and other industry groups to reduce soil erosion, but also to take a broader view of land management and integrate soil conservation strategies with farming operations.

With increasing urbanisation and population growth, development associated with urban and roading development also emerged as a major source of sediment generation (Hicks 1994; Auckland Regional Council 1996). This is now widely understood, and almost all councils have tight controls on ESC associated with earthworks (Auckland Regional Council 1996; Auckland Council 2016). Since the 1940s erosion and sediment control techniques have been refined, experimental work has provided better information on treatment performance, there has been better documentation of the application of ESC techniques, and there has been increasing emphasis on ESC for earthworks in urban environments, infrastructure projects, and forestry. The growth of ESC for earthworks in urban environments has been driven by extensive land development, particularly in the main centres, or where there is the potential for severe effects in receiving environments adjacent to developing cities, such as in Auckland (Hicks 1994; Auckland Regional Council 1996).

In the 1970s and 1980s large areas of erodible, soft-rock hill country in the North Island were converted from pasture to *Pinus radiata* forests to control erosion. Subsequently, as a result of changes in government policy, many of these forests have become production forests. Many have been or are currently being harvested, and the erosion problems that were evident under pasture are reoccurring, particularly in the period following harvesting and before the new trees are fully established (Marden 2004; Phillips et al. 2012).

3.2 Erosion processes

The most widespread and active type of erosion is rainfall-triggered shallow landslides, but other mass movements (earthflows and slumps), gully, surface (sheet, rill, wind) and streambank erosion are locally significant. Large tracts of pastoral farmland in New Zealand are located on erodible hill country. In these areas, steep slopes, highly erodible rocks, generally high rainfall, and common, high-intensity rainstorms all contribute to naturally high rates of erosion, which have been exacerbated by recent deforestation and conversion to pastoral farmland (Basher 2013a).

Eyles (1983) provides a summary of the occurrence of erosion in New Zealand using data collected during the surveys that resulted in the New Zealand Land Resource Inventory (NZLRI) (Figure 1). An overview of the main erosion processes in New Zealand is given by Basher (2013a), some of which has been extracted and repeated below.

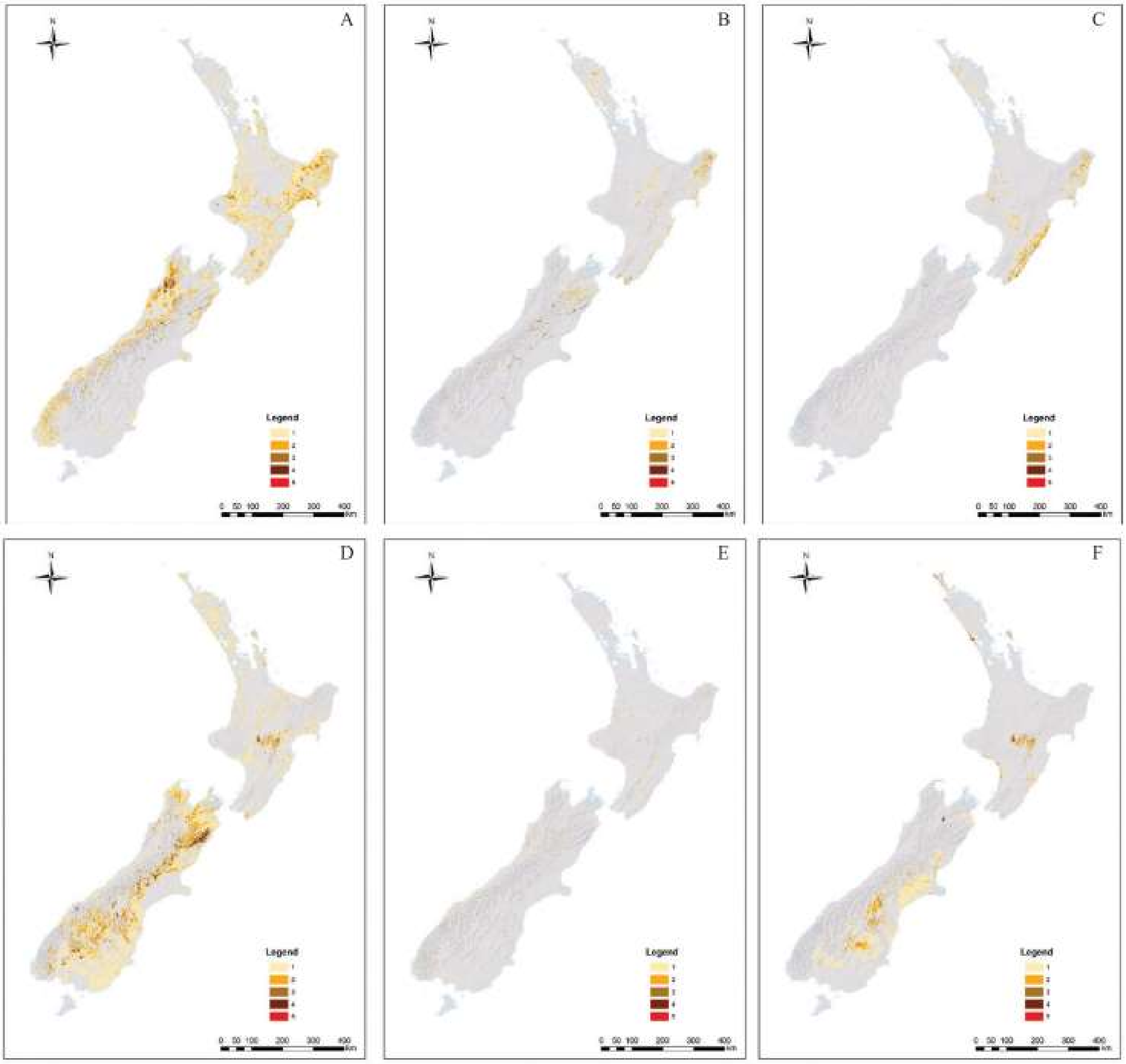

Figure 1. Distribution and severity of the main forms of erosion in New Zealand, derived from the New Zealand Land Resource Inventory: (A) shallow landslides, (B) gully erosion, (C) deep mass movement erosion, (D) sheet and rill erosion, (E) bank erosion, (F) wind erosion.

3.2.1 Surface erosion

This includes splash, sheet and rill erosion. Sheet erosion is widely distributed and typically occurs on bare ground, such as cultivated slopes, forestry cutovers, unsealed roads and tracks, stock tracks, and earthworks associated with urban development, farming, forestry or other land uses (Figure 2). It also occurs on erosion features such as on landslide scars and tails and gullies. In addition to the presence of bare ground, factors that influence surface erosion include slope angle and length, aspect, soil texture, compaction, and rainfall, especially rainfall intensity and duration (Basher 2013a).

Figure 2. Example of surface erosion in loess on the Port Hills, Christchurch (left), and under market gardening at Pukekohe (right).

3.2.2 Mass movement erosion

Because of the dominance of hilly and mountainous terrain in New Zealand, the most widespread type of erosion is mass movement (landslides, earthflows, slumps), especially rainfall-triggered shallow landslides (Figure 3). A wide variety of landslide types occur in the New Zealand landscape (some of these are expanded on below), ranging from small, shallow, rapid failures, to large, deep, creeping rock failures. The most common types are shallow, rapid slides and flows involving soil and regolith, which occur during rainstorms (Glade 1998; Crozier 2005). They are typically characterised by small scars and long, narrow debris tails, where much of the landslide debris is redeposited downslope. This type of landslide can be triggered by small rainfall events after prolonged wet periods, leading to high antecedent soil moisture conditions, or by individual storm cells with high intensity.

Slumps, earthslips, and large-scale failures in regolith and bedrock are deeper failures and are also common in the New Zealand landscape (e.g. Eyles 1983, 1985; Crozier et al. 1995; Hancox & Perrin 2009), but they have a very restricted distribution (see Figure 1).

Figure 3. An example of mass movements: shallow landslides in Hawke's Bay.

3.2.3 Earthflow erosion

Earthflow erosion is the slow movement of soil and associated regolith along basal and marginal shear planes, and with internal deformation of the moving mass (Eyles 1983, 1985; Lynn et al. 2009) (Figure 4). Earthflows range from shallow (<1–2 m) to deep-seated (>10 m, and typically 3–5 m). Deep-seated earthflows typically occur on slopes between 10° and 20° and can cover large areas of a hillslope, while shallow earthflows are more common on slopes >20° and are smaller in area (Lynn et al. 2009). Earthflow erosion occurs mostly in the North Island and is most extensive on crushed mudstone and argillite in the Gisborne – East Coast area, Wairarapa and southern Hawke's Bay.

Figure 4. An example of an earthflow near Gisborne.

3.2.4 Gully erosion

Gully erosion has two main forms in New Zealand: linear features cut by channelised runoff, and large, complex, mass-movement–fluvial-erosion features that are typically amphitheatre-shaped (Marden et al. 2012) (Figure 5). It is most common in the soft-rock hill country of the East Coast of the North Island, on crushed argillite and mudstone, and in the North and South Island mountainlands. It also occurs in Northland and the Volcanic Plateau (Eyles 1983, 1985).

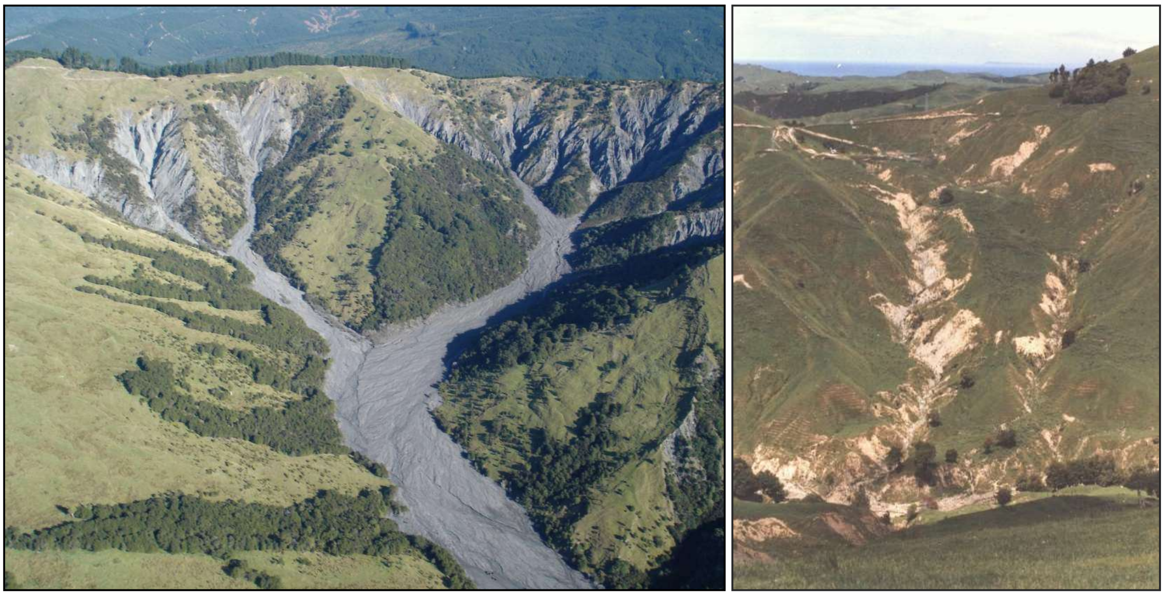

Figure 5. Examples of a large amphitheatre-shaped gully (left), and linear gully erosion (right), East Coast, North Island.

3.2.5 Streambank erosion

Streambank erosion is one of the least understood erosion processes in New Zealand (Watson & Basher 2006; Hughes 2016; Smith et al. 2019). A wide variety of fluvial and mass movement processes contribute to bank erosion (Watson & Basher 2006) and result in a wide range of styles of bank erosion, ranging from small banks to cliffs (Figure 6). It is common along rivers and streams throughout New Zealand

Figure 6. Examples of streambank erosion.

3.2.6 Wind erosion

Wind erosion has long been a concern in New Zealand, with dust clouds commonly observed blowing off cultivated paddocks (Figure 7). The extent and significance of wind erosion was reviewed by Basher and Painter (1997). The most severe wind erosion is mapped on small areas of coastal sand dunes of both islands, and in the Volcanic Plateau in the central North Island. Salter (1984) suggests that 27% of New Zealand is susceptible to moderate to extreme wind erosion.

Figure 7. An example of wind erosion. (Source: RST Solutions limited)

4 Methods and approach

We have taken an approach that considers the types of erosion present in New Zealand, presents current ESC practices and techniques used here, outlines what we mean by effectiveness (in definitions), and then focuses on the methods used to assess *effectiveness* for the different erosion processes. In line with our definition of effectiveness, we show the expected *performance* range for the various ESC techniques. ESC methods may also be classified according to their scale of operation as being local (usually in an urban setting), farm scale, or catchment scale.

Information on erosion and sediment control practices used in New Zealand was primarily derived from published sources, including regional council and industry ESC guidelines, and the *Soil Conservation Technical Handbook*, and from several reviews (e.g. Hicks 1994; Phillips et al. 2000, 2008; Parkyn et al. 2000; Parkyn 2004; Basher, Botha, Dodd et al. 2008; Basher, Botha, Douglas et al. 2008; Basher 2013a; Basher, Manderson et al. 2016; Basher, Moores et al. 2016; Basher et al. 2019) (see section 5).

A comprehensive analysis of the scientific basis for the use of ESC practices across all land uses in New Zealand, including data on performance efficiency, is given in Basher, Moores et al. 2016. The information compiled in this and more recent reports cited above forms the basis for the current report.

This report provides a list of ESC practices used in New Zealand and reviews the science available to assess the effectiveness of these different ESC practices, though, unlike Basher, Moores et al. 2016, we base the current review on erosion process type rather than land use.

Relevant international literature will be assessed in the second stage of this project (CS 1.2.2-1), which will involve the STEC programme's international collaborators, who will contribute to a benchmarking of New Zealand approaches and their effectiveness in the wider international context.

5 Erosion and sediment control: practice, plans and guidance

5.1 Overview of erosion and sediment control practices used in New Zealand

A wide variety of ESC practices are used in New Zealand, depending on the land use and the type of erosion process(es) that are present or active (Table 1). Many of these practices are included in 'plans' as part of voluntary or regulatory requirements (see next sections; 5.1.1 and 5.1.2).

In general terms, many techniques/approaches follow those developed in other countries. However, in New Zealand, largely because of its recent colonial history and development, which included the removal of much of the indigenous forest and low population base, biological methods of erosion control (outside of urban areas) are the most widely used, with a large range of vegetation types and species used throughout New Zealand (e.g. Pollock 1986; van Kraayenoord & Hathaway 1986a, b; Hicks & Anthony 2001; Basher et al. 2008a; Fernandez 2017).

Basher, Manderson et al. (2016), Basher, Moores et al. (2016) and Basher et al. (2019) provide significantly more detail on ESC practices by land use (Appendix 1).

Table 1. Techniques commonly used to control erosion in New Zealand (source: Luckman & Thompson 1993; DL Hicks 1995; Hicks & Anthony 2001; Basher, Manderson et al. 2016; Basher, Moores et al. 2016)

Erosion type	Soil conservation principle	Erosion control practice
Sheet and rill (i.e. surface erosion)	• Maintain ground cover • Maintain soil structure and health	• Water control • Improving drainage • Conservation tillage (contour cultivation, minimum tillage, direct drilling, herbicides) • Wheel-track ripping • Stubble and other mulches • Rotational and strip cropping • Use of low ground pressure to avoid risk • Matching crop and pasture species to site conditions • Surface roughening • Soil binders and chemical treatment • Contour drains, cutoffs, benched slopes, culverts, flumes, diversion channels • Silt fences

Erosion type	Soil conservation principle	Erosion control practice
Shallow mass movement (landslides, debris avalanche, earthflow)	• Maintain root strength contribution to slope stability • Reduce soil water	• Space-planted trees • Reversion to scrub • Afforestation • Adjusting grazing pressure and fencing • Drainage control • Debris dams • Control at toe (earthflows) • Spring taps
Deep-seated mass movement (landslides, slumps, earth and rock flow)	• Maintain root strength contribution to slope stability • Reduce soil water	• Space-planted trees • Reversion to scrub • Afforestation • Adjusting grazing pressure and fencing • Drainage control • Debris dams • Control at toe
Gully	• Control runoff • Avoid exposure of bare ground in overland flow paths • Reduce peak flood flows	• Water control (diversions, flumes, pipes, drop structures) • Space-planted trees • Gully wall and channel (pair) planting • Reversion to scrub • Afforestation • Debris dams • Ground recontouring
Tunnel gully	• Control runoff • Manage ground cover	• Water control • Manage ground cover in overland flow paths • Space-planted trees • Ground recontouring
Wind	• Maintain ground cover • Maintain soil structure and health to reduce erodibility • Maintain surface soil moisture	• Maintain ground cover • Maintain soil structure and health to reduce erodibility • Maintain surface soil moisture
Stream bank	• Maintain riparian vegetation • Reduce bank undercutting and lateral migration	• Tree planting of banks and riparian buffers • Structural control (rock riprap, gabions, groynes, geotextiles) • River diversion • Bank regrading • Vegetation lopping/layering • Reseeding stream banks • Control stock access by fencing • Subsurface drainage at seepage sites

Practices for runoff-generated erosion or surface erosion (sheet, rill, gully) can be broadly categorised into:

- water management – runoff control to reduce water velocity and sediment generation, and to separate clean water from dirty water
- erosion control – to reduce sediment generation

- sediment control – trapping sediment before it moves off-site and into waterways.

Sediment control practices for managing sediment discharges are primarily aimed at intercepting or retaining generated sediment before it reaches a waterway. These include the use of detention ponds, temporary measures such as silt fences, and vegetated buffers.

Runoff control or water management practices are largely aimed at reducing water velocity and sediment generation, and in the case of construction help separate clean and dirty water. These practices include check dams, contour drains and cutoffs, diversion channels and bunds, flumes and pipe structures, level spreaders, hay bale barriers, and water table drains and culverts.

Mass movement erosion is controlled by practices that influence slope hydrology and/or soil strength, which in turn influence slope stability. Biological methods of erosion control are the most widely used, with a large range of vegetation types and species used to control erosion throughout New Zealand (Hicks & Anthony 2001; Basher et al. 2008a). For rural New Zealand, in particular, there has been a strong emphasis on biological erosion control (either through space-planted trees or blanket afforestation) because of its relatively low cost and its effectiveness (Douglas et al. 2013; Phillips & Marden 2005). For widespread and severe erosion, afforestation, typically using conifers such as *Pinus radiata* or Douglas fir (*Pseudotsuga menziesii*), or scrub and native forest reversion, is used.

Bank erosion can be an important source of sediment because it delivers sediment directly into stream channels, and there is substantial legacy sediment in many New Zealand valleys because of recent deforestation and large storms. Streambank erosion is controlled by practices that reduce hydraulic scour or increase bank strength and resistance to erosion. In New Zealand a combination of 'soft' biological erosion control and 'hard' engineering works is used to control bank erosion, and stock exclusion is also used to improve bank stability (see Davies-Colley & Parkyn 2001).

Wind erosion is controlled by practices that reduce soil erodibility, increase soil moisture content, or reduce wind erosivity. In horticulture and arable cropping, practices include limiting the time the soil is bare (by maintaining a vegetative cover or surface residue) and has a dry surface (e.g. by irrigating, use of mulches), terracing, and reducing wind velocity through increased surface roughness (using stubble mulching, ridge-till, coarse seedbeds) or windbreaks and strip cropping.

Erosion and sediment control practices by land-use type (forestry, horticulture, and arable, pastoral farming) are listed in more detail in Appendix 1 (after Basher, Manderson et al. 2016; Basher, Moores et al. 2016). In these tables the design criteria are not exhaustively listed (see the references for more detail) but include some factors that are relevant to thinking about how to design for different environmental conditions and assessing the performance of ESC practices.

5.1.1 Erosion and sediment control (ESC) plans

An integral component of any activity on land that could cause an increase in erosion or generation of sediment is the production of a plan that describes what is being done and how the environmental effects are to be mitigated. Such plans and approaches are either voluntary (e.g. Sustainable Land Use Initiative (SLUI) farm plans) or mandatory as part of regulations (e.g. as part of the National Environmental Standards for Plantation Forestry (NES-PF) or proposed freshwater regulations, or to meet resource consent conditions).

An ESC plan or a farm plan is not an ESC practice *per se*, but forms a framework within which to plan ESC (e.g. selection of practices, design of individual practices, location). These are generally required for urban earthworks and construction activities associated with forestry. They may also be considered as part of consent requirements for a forest harvest plan.

5.1.2 Farm plans

Farm plans have been described as the cornerstone of soil erosion work programmes in New Zealand. For example, in Wairarapa they have been used for many years to plan and implement soil conservation (Cameron 2011), and some of New Zealand's earliest farm plans were piloted here.

However, soil conservation was radically changed following the 1980s state sector reforms. National organisation and administration was abolished (National Water and Soil Conservation Control Authority (NWASCA), Ministry of Works), new regional councils were formed (replacing catchment boards), and new legislation was introduced regarding resource management. Responsibility for dealing with soil erosion was devolved from a national to a regional level, and it was up to individual regional councils to decide how soil conservation was to be managed in their respective regions. Limited resources and competing environmental priorities often resulted in the complete abandonment of previous farm plan programmes and catchment schemes.

Today, farm plans or farm environment plans (FEPs) tend to be focused on a wider range of contaminants than just sediment (nitrogen, phosphorus, sediment, faecal bacteria, etc.) compared to an ESC plan. Increasingly, FEPs are required by regulatory agencies to meet requirements under the Resource Management Act.

Farm plans range from paper-based to digital plans and can be focused on anything from soil conservation to providing ways to improve water quality and farm profitability. For example, NIWA worked with Greater Wellington Regional Council to develop a computer-based framework named FOCUS for maximising the effectiveness of farm plans (McKergow et al. 2014; McKergow 2015). The framework formalises the link between catchment land-use activities and farm water-quality planning undertaken by land management officers (LMOs).

FOCUS is a tool designed to help optimise resource use by prioritising where on-farm works should take place within a catchment and to allow the net effect of farm plan implementation to be assessed. It contains four modules (catchment prioritisation, LMO training, farmer-led planning and implementation, and catchment outcomes), and can be used for sediment as well as other pollutants (nitrogen, phosphorus, and faecal microbes). It is designed to link existing databases (e.g. New Zealand Land Resource Inventory and S-map) and tools or models (e.g. CLUES, Overseer®, NZeem®), and to allow water-quality concerns identified at a catchment scale to be addressed through targeted on-farm advice. The FOCUS farm plan template was designed to provide a detailed, structured and auditable record of farm planning conversations and progress on the ground. It is unclear how widely this is now being used by Greater Wellington Reginal Council.

5.2 Guidance on erosion and sediment control

There are numerous reviews, publications, guidelines and manuals relating to erosion and sediment control. Internationally, organisations such as the International Erosion Control Association (IECA), the Food and Agricultural Organisation (FAO), and the United States Department of Agriculture (USDA), and many other regulatory agencies, etc. have all produced these (e.g. IECA Australasia 2008; FAO 1977). In New Zealand most regional and district councils have produced some form of guidance as part of both voluntary and/or regulatory controls (e.g. Environment Bay of Plenty 2010; Northland Regional Council 2012; New Zealand Transport Agency 2014; Leersnyder et al. 2018).

5.2.1 Urban environments

In the urban environment, Auckland Regional Council published a set of ESC guidelines for earthworks in 1995. This was significantly revised and published as TP90 in 1999 (Auckland Regional Council 1999) and updated again in 2016 (Leersnyder et al. 2018). TP90 has formed the basis of ESC guidelines prepared by many other regional councils around New Zealand, including Environment Bay of Plenty (2010), Environment Waikato (2009), Hawke's Bay Regional Council (Shaver 2009a), Taranaki Regional Council (2006), Greater Wellington Regional Council (2006), and Environment Canterbury (2007).

The New Zealand Transport Agency also recently produced a set of ESC guidelines specifically aimed at the state highway infrastructure (New Zealand Transport Agency 2014). Practical advice on ESC for building sites is contained in the recently published *Builders Pocket Guide* (Environment Canterbury, 2014).

5.2.2 Rural environments

Pastoral farming

For rural New Zealand there has been a strong emphasis on the use of plants in erosion control because of their relatively low cost and high effectiveness (Basher, Manderson et al. 2016). Internationally there are many reviews and publications on how plants are used in erosion control, how they work, their establishment and management, and (to some degree) their effectiveness (e.g. Barker 1986; Greenway 1987; Gray & Sotir 1996; Gyssels et al. 2005; Sidle & Ochiai 2006; Stokes et al. 2008).

There are also numerous publications on the use of plants in erosion control programmes in New Zealand, including their establishment and management, and their effectiveness in reducing the occurrence and severity of erosion (e.g. Van Kraayenord & Hathaway 1986a, b; Pollock 1986; Lambrechtsen 1986a, b; Hawley & Dymond 1988; Phillips et al. 1990, 2008, 2011; DL Hicks 1991, 1995; Marden & Rowan 1993; Quilter et al. 1993; Thompson & Luckman 1993; Bergin et al. 1995; Douglas et al. 1998, 2009, 2011; Hicks & Anthony 2001; Hicks & Crippen 2004; Marden 2004; Phillips & Marden 2005; McIvor et al. 2011; Basher, Manderson et al. 2008; Davis et al. 2009; Satchell 2018).

The *Plant Materials Handbook for Soil Conservation* (Van Kraayenoord & Hathaway 1986a, b; Pollock 1986) summarised the state of knowledge up to the 1980s on vegetation options for managing soil erosion. *Control of Soil Erosion on Farmland* (DL Hicks 1995) was published by MAF and summarised a large amount of information on agricultural techniques for managing soil erosion throughout New Zealand. *The Soil Conservation Technical Handbook* (Hicks & Anthony 2001) describes a range of biological and engineering techniques for treating all types of erosion. Most regional councils use these sources and have developed locally relevant and practical resources to provide advice to farmers (fact sheets, newsletters, website information, etc.).

Forestry and horticulture

The forest industry developed a code of practice for plantation forestry (NZ Forest Owners Association 2007), which provides practical advice for managing ESC, as well as a road engineering manual that provides a comprehensive guide to planning and constructing forest roads and associated infrastructure to manage ESC problems (Gilmore et al. 2011). Many regional councils, including Auckland Council (Bryant et al. 2007), Environment Bay of Plenty (2012), Hawke's Bay Regional Council (Shaver 2009b), Northland Regional Council (2012), Greater Wellington Regional Council (2006), and Marlborough District Council (Williams & Spencer 2013), have produced ESC guidelines for forestry largely based on adapting TP90, with a focus on managing the ESC effects of earthworks.

Specific ESC guidance has also been produced for the horticulture industry (Franklin Sustainability Project 2000; Barber & Wharfe 2010; Barber 2014). These guidelines draw on research carried out in the Franklin Sustainability Project and from Auckland Regional Council's guidelines for earthworks and forestry (Auckland Regional Council 1999; Bryant et al. 2007).

6 Assessing effectiveness: past research

This section reviews how erosion control effectiveness and performance are assessed by first discussing what effectiveness and performance mean, then outlining the ESC techniques and the studies that have assessed them with respect to erosion type by land use, and finally reviewing the approaches for assessing effectiveness in relation to the key erosion processes in New Zealand. We focus on erosion control in rural environments, though urban environments are included for completeness. Reviews and reports by Basher (2016), and by Basher, Manderson et al. (2016), Basher, Moores et al. (2016) and Basher et al. (2019), contain more details. ESC often involves the 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 (Basher et al. 2019).

6.1 Definitions

What do we mean when we talk about the *effectiveness* or *performanc*e of ESC techniques? Thompson and Luckman (1993) offer a definition of effectiveness as 'the degree to which the land had been returned to a minimal state of erosion by the stabilisation methods employed'. Basher, Manderson et al. (2016) define effectiveness in the context of conservation planting and farm plans as 'the extent to which the soil conservation treatment applied achieves the desired outcome (e.g. the reduction in erosion compared to untreated areas, reduction in sediment load)'. They suggest that in order to evaluate effectiveness, good information on the original erosion problem, the suitability of the soil conservation treatment applied, the adequacy of the soil conservation treatment, and the effect of the soil conservation treatment on erosion is required. This largely followed on from the earlier work of DL Hicks (1989a, b, 1990, 1991, 1992a, b, c, and other reports) and by Thompson and Luckman (1993), in which semi-quantitative assessments were used following Cyclone Bola and other storms to assess the effectiveness of soil conservation measures.

Effectiveness, efficiency, and performance are related concepts, and the literature often uses these terms interchangeably when referring to erosion and sediment control. Effectiveness is about doing the right things and the degree to which the solution accomplishes its goal or delivers the desired outcome. The measure of effectiveness incorporates adequacy and suitability; in other words, if the measure can be demonstrated to be effective (e.g. a reduction in erosion rate has been achieved), then the measure will probably be adequate and suitable.

In this report we define key terms as follows.

- **Erosion control** − the primary purpose is to reduce or eliminate sediment from being generated.
- **Erosion & sediment control (ESC)** − a combined term that includes the reduction of sediment generation (erosion control) and the management of sediment once it has been generated (sediment control).
- **Performance** – a quantitative measure of how well a practice controls, reduces or traps sediment, or reduces sediment generation; i.e. the measure of sediment reduction (reduction in landsliding, bare ground reduction, etc., with the spatial and temporal scales also defined), usually expressed as a percentage reduction.
- **Effectiveness** – the degree to which an ESC or soil conservation treatment reduces erosion compared to untreated areas, or how erosion status has changed as a result of the treatment (i.e. the extent to which the treatment or ESC practice achieves the desired outcome). It can be qualitative or quantitative.

As the primary purpose of STEC is to improve information on the performance of erosion and sediment control at multiple spatial scales (i.e. 'smarter targeting of erosion control'), this review is a key component in the delivery of the programme's goal.

6.2 Surface erosion

ESC practices for runoff-generated erosion (sheet, rill, gully) can be broadly categorised as:

- runoff control to reduce water velocity and sediment generation, and to separate clean water and dirty water
- erosion control to reduce sediment generation
- sediment control to trap sediment before it moves offsite and into waterways.

Appendix 1 lists runoff and erosion and sediment control practices in common use in New Zealand (largely based on urban earthworks and infrastructure (from Basher, Moores et al. 2016).

Runoff control practices or water management practices are largely aimed at reducing water velocity and sediment generation, and in the case of construction help separate clean and dirty water. These practices include check dams, contour drains and cutoffs, diversion channels and bunds, flumes and pipe structures, level spreaders, hay bale barriers, and water table drains and culverts.

Sediment control practices for managing sediment discharges are primarily aimed at intercepting or retaining generated sediment before it reaches a waterway. These include the use of detention ponds, temporary measures such as silt fences, and vegetated buffers. There are no quantitative studies on the performance of silt fences in New Zealand.

There have been limited New Zealand studies in which quantitative measurements of ESC practices have been made. Approaches usually involve plot studies where treatments are compared to a control (Basher et al. 1997; Basher & Thompson 1999; Auckland Regional Council 2000; Basher & Ross 2001; Basher, Ross & Dando 2004; Marden et al 2007); use of erosion pins to measure surface lowering (Basher & Peterson 2018); measuring sediment retention in a sediment pond with or without a control (e.g. Winter 1998) and with chemical treatment (Moores & Pattinson 2008; Larcombe 2009); sediment yield from decanting earth bunds (Babington & Associates 2008; or sediment yield or sediment concentration from a 'treated catchment' involving several devices (Ridley & De Luca 2015). In some cases these experiments are conducted under natural rainfall conditions and in others using rainfall simulators (Babington & Associates 2008). There have also been laboratory investigations relating to sediment retention ponds (Khan 2012) and rainfall simulations over mulches (TA Cochrane, University of Canterbury, pers. comm.).

Urban environments

Erosion control, especially in relation to earthworks and construction, is best achieved by the use of fibrous, interwoven materials rather than loose mulches; material with a high percentage cover; relatively thick materials with a high water-holding capacity; flexible, relatively heavy materials that follow the ground contour; combining a number of treatments; re-establishment of vegetation cover as soon as possible; and mulches in combination with topsoil rather than subsoil (Basher, Moores et al. 2016).

For example, the performance of straw mulch at an earthworks site in Albany, north of Auckland, was assessed (Auckland Regional Council 2000) in 18 experimental plots, each of which had one of five land covers: established grass, mulched topsoil, bare topsoil, mulched subsoil, or bare subsoil. Runoff and sediment discharge were measured during a series of storm events.

Winter (1998) conducted a detailed field evaluation of an operational sediment retention pond at Albany. Monitoring was conducted over two periods. Nine storm events were monitored during the closed winter season between May and October 1995, while two events were monitored during the working summer season in November and December 1995. Inflows and outflows were measured using pressure transducers and rated flumes, while water samples were collected at flow-weighted intervals using an automatic sampler.

Two other field-based studies of the performance of sediment retention ponds have been conducted on operational construction sites north of Auckland area in recent years (Moores & Pattinson 2008; Larcombe 2009), though both these studies focused on the performance of chemically treated ponds. Chemicals act as flocculants to bind clay materials in suspension, causing them to drop out and be retained in the ponds. Dosing rates are assessed on the retention of sediment by measuring the suspended sediment concentrations on inflows and outflows across a range of rainfall and storm conditions.

Pastoral farming

In pastoral land, maintaining a persistent, complete pasture sward reduces the prevalence and severity of surface erosion processes of wind, sheet wash, and rilling (DL Hicks 1995). This can be achieved through strategic grazing management in spring to maintain a short, leafy pasture; reducing grazing pressure during drought, cold, or wet conditions to avoid loss of plant cover; the use of fertiliser to maintain sward vigour and growth; and establishing improved pastures using seed mixes comprising new cultivars of grass and legume species (Basher, Botha, Dodd et al. 2008). In a review of previous work, DL Hicks (1995) suggested that improving pasture could reduce surface erosion by 50–80% compared with levels occurring on land with unimproved pasture.

Grazing management is important in minimising soil loss by surface erosion. Animal treading by cattle has been shown to reduce infiltration rates and increase soil loss, especially where only a short grass canopy remains after grazing. A 20 mm canopy height has been suggested to minimise the effects of a short-term treading event on soil water infiltration rate and sediment loss, and that management of canopy height is more important than grazing intensity (Russell et al. 2001).

Horticulture and arable cropping

In horticulture and on arable crop land, ESC measures to mitigate sheet and rill erosion follow similar principles to ESC for urban and earthworks construction sites:

- runoff control to reduce water entering paddocks (interception drains, culverts) and to limit runoff generation within paddocks
- erosion control measures to reduce sediment generation (wheel-track ripping and diking, cover crops, cultivation management, strip cropping)
- sediment control measures to reduce sediment discharge from paddocks (sediment retention ponds, silt fences).

Compacted areas in fields (wheel tracks and headlands) are major sources of runoff and erosion, and a number of practices are targeted at reducing runoff and erosion from these areas.

Basher and Ross (2001) compared ripped and unripped wheel tracks in onion crops, and found that most erosion occurred in the winter/early spring period, when storm frequency and rainfall intensity were highest and infiltration rates in the uncultivated wheel tracks lowest. The trials showed that the cultivation of wheel tracks is a simple and effective practice to increase infiltration of rainfall and reduce erosion rates on clay-rich, strongly structured soils. This was supported by Basher et al. (2004), who found similar results on young volcanic soils at Ohakune under intensive vegetable cropping, where compacted wheel tracks had low infiltration rates (4 mm h^{-1}) compared with carrot beds (853 mm h^{-1}). However, it was suggested ripping might exacerbate soil loss from wheel tracks on light, weakly structured volcanic soils.

Forestry

Soil disturbance associated with clear-felling, earthworks for landing and road construction, and activities around stream channels all have the potential to cause erosion. In the past, earthworks for landing and road construction have been major sediment sources, but improved planning, engineering design and construction have reduced this problem, and much of the sediment generated from forestry is generated from the clear-cuts by landsliding and debris flows (Phillips et al. 2012). The principles of urban ESC are now being applied to forestry practices, but they focus mainly on earthworks and less on how to manage erosion from the clear-cuts.

The principles for erosion control in forestry include (Amishev et al. 2013):

- keep disturbed areas small and time of exposure short
- control erosion at source
- install perimeter controls
- retain sediment on site
- protect critical areas
- inspect and maintain control measures
- establish the new crop as soon as possible.

There has been little to no research on the effectiveness of ESC measures applied to manage surface erosion in the forest industry, though there have been several studies that have assessed surface erosion relating to different parts of the plantation forestry cycle, including roading (Fahey & Coker 1992; Fransen 1998) and following harvesting where soils are exposed due to logging disturbance (Marden & Rowan 1993; Fransen et al. 2001). These have involved a mix of plot studies assessing the impacts of natural rainfall and rainfall simulator experiments.

6.3 Landslide control using space-planted trees

The use of space-planted trees for erosion control (mostly in reducing shallow landslides on pastoral farming land, but also for stabilising earthflows and gullies) developed as a response to widespread erosion during storms in the 1930s and 1940s (Basher 2013a) and the need to develop treatments that enabled the continuation of pastoral farming. By the 1980s both local (catchment boards) and national (National Water and Soil Conservation Authority) government agencies were beginning to review the effectiveness of soil conservation techniques for controlling erosion (e.g. Dixie 1982; East Cape Catchment Board 1985. These early reviews were qualitative and focused as much on survival of the plantings as on assessing their effect on erosion. However, concern about assessing the value of investment in erosion control did result in attempts to develop a more scientific basis for assessing the physical effectiveness of space planting.

Space-planted poplars (*Populus*) and willows (*Salix*) are the most common ESC plants in New Zealand, particularly on hilly pastoral land. This is because they can be established as poles in the presence of grazing animals, and are appropriate for the control of landslide, earthflow, gully and streambank erosion (van Kraayenoord & Hathaway 1986a, b). Their use was reviewed by Basher, Botha, Dodd et al. (2008), Basher, Manderson et al. (2016), Basher, Moores et al. (2016) and Phillips et al. (2000, 2008). Other genera, such as *Acacia* or *Eucalyptus*, are sometimes used.

However, despite the widespread use of space-planted trees for erosion control in New Zealand, there has been surprisingly little experimental or quantitative work to establish their effectiveness in reducing erosion in relation to factors such as tree size and planting density, and there are no published studies on their measured effect on sediment yield (Douglas et al. 2009; Basher 2013b). Nor is there any information on their effectiveness over a range of different storm sizes (recurrence interval), with most published data on the effect of large storms. The published studies (Table 3) emphasise the importance of both initial establishment of the trees and subsequent maintenance to ensure their survival and effectiveness.

Root and canopy development are the primary drivers of effectiveness of space-plantings (and trees in general) on slopes for reducing the incidence and severity of landsliding and other mass-movement erosion types. Understanding these has been the driver for studies of above- and below-ground plant growth characteristics, including canopy growth rates, canopy closure modelling, root strength and decline, root growth rates, root morphology, root biomass, and root occupancy (e.g. Phillips et al. 2000; McIvor et al. 2008, 2009, 2011; Douglas et al. 2010; Schwarz et al. 2016).

Approaches

Past evaluations of the effectiveness of soil conservation planting have assessed the degree to which soil conservation treatment has reduced erosion compared with untreated areas, or how erosion status has changed as a result of the treatment (Table 2). Quantitative approaches have measured the effectiveness of individual trees or small groups of trees; for example, in terms of reduction in bare ground or the amount of landsliding (Hawley & Dymond 1988; Douglas et al. 2009, 2013; McIvor et al. 2011, 2015). Semi-quantitative approaches tend to be site-, transect- or catchment-based, have a broader perspective but limited direct measurement, and require an assessment of trends in erosion status (e.g. DL Hicks 1989a, b, 1992b, c; Thompson & Luckman 1993; Phillips et al. 2008).

Hawley and Dymond (1988) proposed a method based on analysing the relationship between landslide occurrence and tree location. Computer processing of digital imagery was used to determine the x and y location of each tree, and the fraction of land eroded at increasing distance from each tree was then determined (Figure 8). Using data from multiple trees, a graph of average fraction of ground eroded versus distance from trees was derived (Figure 8). The average radius of influence of trees can be calculated (11 m in the site studied), and the area saved by trees from landsliding identified. It assumes that individual trees are not planted consistently on land that is more or less likely to fail.

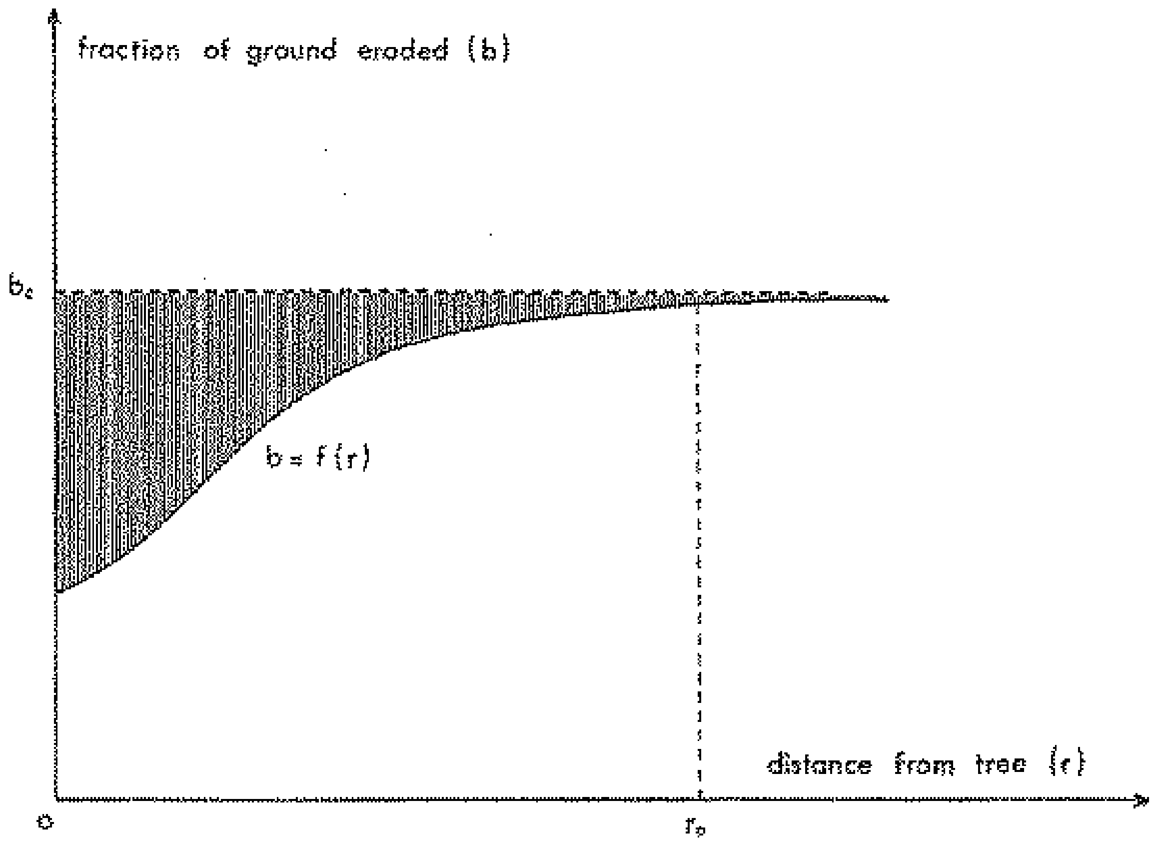

Figure 8. Hypothetical relationship between fraction of ground eroded (b) and distance from tree (r). The shaded area is a measure of the ground saved from landsliding. (source: Hawley & Dymond 1988)

Table 2. Studies of effects of space-planted trees under pastoral farming on shallow landslides and other erosion processes

Reference	Location, terrain, storm history	Erosion type(s)	Scope and Methods
McIvor et al. 2015	Coastal Hawke's Bay; moderately steep young sediments; storm rainfall estimated 700 mm	Shallow landslides	Aerial photo assessment to identify comparable sites with (86 sites) and without trees (25 sites), field measurement of landslide distribution, site and tree characteristics (number, species, DBH, tree spacing, distance of landslides from nearest tree). Used to calculate area of protection from trees (total area protected minus area of slip scars) and the effectiveness of trees linked with tree size, tree species, and tree spacing.
Douglas et al. 2009, 2013	Storms in 2004 (Manawatū – daily rainfall >200 mm) and 2006 (Wairarapa – daily rainfall >100 mm); steep young sediments	Shallow landslides	Compared occurrence of landslides on slopes with space-planted trees (poplars, willows, *Eucalyptus*) and pasture at 65 sites. Collected tree attributes (height, DBH, canopy radius, tree density/spacing (range 32–65 sph, 12–18 m). Assumed radius of influence of 10 m and calculated area of landslides within 10 m of a tree. The percentage of shallow landslide scar area at each tree (TSA) and paired pasture (PSA) site was calculated by expressing scar area as a percentage of total site (polygon) area.
Varvaliu 1997	Pakihikura valley, Rangitikei, storms August/September 1992, steep young sediments	Shallow landslides	362 slopes, aerial photo interpretation and field checking, measurement of area and % of slope eroded.
Lough 1993	Pohangina valley, storms August/September 1992, steep young sediments	Shallow landslides	Aerial photo interpretation and field checking, measurement of area and % of slope eroded.
Cameron 1991; DL Hicks 1991	Whareama catchment, Wairarapa; 305 sites on argillite and young Tertiary siltstones, storm 8–11 April 1991, storm rainfall 200–300 mm	Shallow landslides, gullying, streambank erosion	Field-based subjective assessment of storm damage (stability, type of erosion, damage to fences, tracks, pasture and drains, feasibility of treatment, type of soil conservation measures) along a road-based transect and relationship to landform, LUC unit and vegetation type (soil conservation planting, native scrub and forest). Damage mapped in field, office analysis to assign sites as stable, unstable/untreatable, unstable/unplanted, unstable/inadequately planted, unstable/adequately planted and calculated several ratios (need – proportion of sites needing treatment; extent – proportion of sites with treatment installed; adequacy – proportion of sites with adequate treatment) and frequency distribution of indices.
Pain & Stephens 1990	Eltham, Taranaki; steep young siltstone and mudstone; storm rainfall 202 mm over 3 days		Digital aerial photographic assessment compared with field-based visual assessment, single storm.

Reference	Location, terrain, storm history	Erosion type(s)	Scope and Methods
Hawley 1988; Hawley & Dymond 1988	Ngatapa, Gisborne; steep slopes underlain by ash over mudstone	Shallow landslides	Assessed location of landslides relative to space-planted trees to calculate average fraction of ground eroded vs distance to trees. Tree density 25 sph.
DL Hicks 1988, 1989a, 1992b	Waihora catchment, Gisborne; steep young siltstone and mudstone; post Cyclone Bola, storm rainfall of 300−600 mm	Shallow landslides, gullying, streambank erosion	Field and aerial photo subjective assessment of storm damage to hillslopes and channels along transects (generally adjacent to roads) to record extent of erosion, nature of soil conservation planting or other vegetation, stability/treatment status. Damage mapped in field, office analysis to assign sites as stable, unstable/untreated, unstable/inadequately treated, unstable/adequately treated. Analysis of relationship of damage to landform, LUC unit and vegetation type (soil conservation planting, native scrub and forest). Mapped area affected by mass movement, length of water courses affected, length of fences and tracks damaged using grid square sampling.
DL Hicks 1992b	Waihora catchment, Gisborne; steep young siltstone and mudstone; post Cyclone Bola, storm rainfall of 300–600 mm. Whareama catchment, Wairarapa, Waipa, Waikato	Streambank.	Same as DL Hicks 1988, 1989a, 1992b
Pain 1986	3 sites near Mangaweka, Manawatū; steep young mudstone with some inter-bedded sandstone	Shallow landslides	Digital aerial photographic assessment before and after space planting, comparison of treated and untreated hillslopes, field assessment of landslide occurrence; 1952–1985/86 period.
Phillips et al. 2008	Gisborne, steep Tertiary soft sedimentary	Earthflow, gully, slump	Field assessment based on Thompson & Luckman 1993. 17 earthflow sites, erosion, 13 gully sites, 1 slump site. Trees >12–15 yrs old and average diameter at breast height of 23–79 cm.

Hawley and Dymond (1988) analysed the effects of space-planted trees on landsliding on a small area underlain by mudstone at Ngatapa, near Gisborne. The trees were originally planted at 20 m spacing (25 stems per hectare, sph), but there was some mortality. Measurements were made on individual trees and converted to the average fraction of ground eroded, which increased with distance from trees (Figure 9).

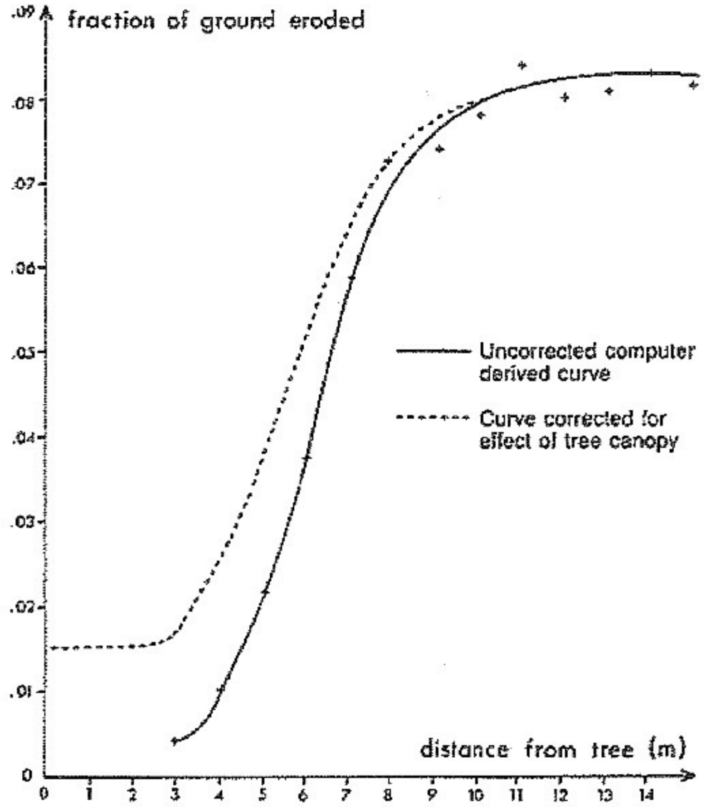

Figure 9. Relationship between average fraction of ground eroded and distance from trees. (source: Hawley & Dymond 1988)

A similar approach, but with a different metric for characterising the effects of trees, has been used in several recent studies (including the species, their size and density) in reducing landsliding (Douglas et al. 2009, 2013; McIvor et al. 2015). Orthophotos were used to locate sites where landsliding occurred following large storms in 2004 and 2006 (40 sites in the Manawatū and 25 sites in the Wairarapa) to identify small groups (5–10) of trees (mainly poplar, with some willow and *Eucalyptus*). Measurements were made of the area of individual shallow landslide scars within a 10 m radius of each tree in the measured group, assuming this was the radius of influence of individual trees (based on Hawley & Dymond 1988). The effect of the space-planted trees was then compared with landslide occurrence in comparable pasture sites without trees to assess the influence of the trees.

The percentage of shallow landslide scar area at each tree (TSA) and paired pasture (PSA) site was calculated by expressing scar area (for that part of scars occurring within a 10 m radius of any tree at the site) as a percentage of the total site area (Figure 10). Differences between TSA and PSA were tested statistically using a one-sample *t*-test.

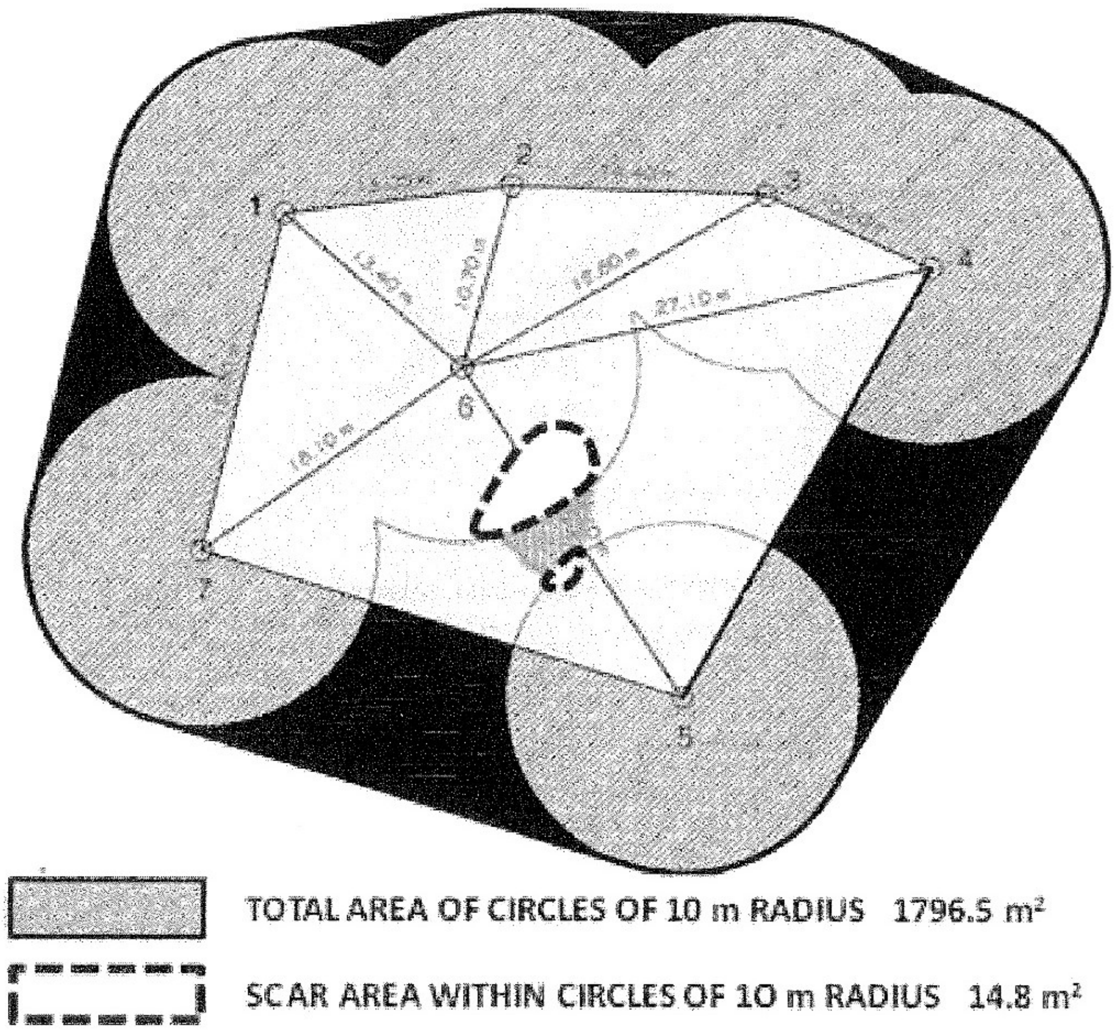

Figure 10. Method of calculating area of shallow landslide scars influenced by a group of seven trees (Source: Douglas et al. 2013). Scar area beyond 10 m from trees 5 and 6 was excluded from the calculation of scar area.

Based on similar methodology, McIvor et al. (2015) conducted a study following a storm event in April 2011 in Hawke's Bay. Eighty-six sites with trees were selected (defined as stands of one to 14 trees, mostly 20–30-year-old poplar and willow trees), and 25 control sites with pasture only. The data set included both mature trees and smaller-diameter (mostly willow) trees. Groups of trees were chosen by i) location on the upper and mid-slope, ii) the presence of slips nearby, and iii) trees with a small canopy, indicating a young age.

Knowledge of root and canopy development has also been used for recommending appropriate species and tree spacings to minimise erosion. For example, Phillips et al. (2000) reviewed plant performance for the possible erosion control treatments funded under the East Coast Forestry project. They argued that the first 8 years of any treatment are the most important for sediment reduction, and they developed a set of parameters related to above- and below-ground plant characteristics with which to evaluate different treatments. These were ranked in order of importance as:

canopy occupancy = lateral root site occupancy > root cross-sectional area per shear area >= root depth >> root biomass

Some of these parameters can be derived from other growth parameters (e.g. canopy occupancy from DBH, tree height, crown width). They used this to develop a method for assessing the sediment reduction effectiveness of treatments allowed as part of the East Coast Forestry project, based on individual plant performance criteria and their hydrological and mechanical influence on slope stability, and ranked the performance of potential treatments as follows:

mature reversion > plantation forestry >= supplementary planting >> within-gully treatment

6.4 Landslide control using closed-canopy woody vegetation (afforestation)

For widespread and severe erosion, afforestation is often used to control erosion, typically using conifers such as *Pinus radiata* or Douglas fir (*Pseudotsuga menziesii*), or scrub and native forest reversion.

Aspects of the effect of vegetation (including space-planted trees) on erosion and slope stability have been reviewed by several authors (e.g. O'Loughlin 1995, 2005; Glade 2003; Marden 2004, 2012; Blaschke et al. 2008; Phillips et al. 2012), including the performance of biological methods of erosion control (e.g. Thompson & Luckman 1993; Phillips et al. 2000, 2008; Basher, Botha, Douglas et al. 2008; McIvor et al. 2011; Douglas et al. 2013; Basher 2013b). These include process-based studies documenting the mechanisms underlying the impact of trees on slope stability (mechanical and hydrological), characterisation of above- and below-ground plant growth of species used for soil conservation, as well as data comparing erosion rates under different vegetation communities (e.g. pasture, young pines, mature closed-canopy pines, indigenous forest, and native vegetation (scrub).

Most data come from observations of storm damage and mostly provide data on landsliding rates. There are also data on the effect of forest cover on suspended sediment yield and the effects of afforestation, especially in controlling severe gully erosion.

Approaches

Most studies have used comparisons of aerial photographs (and, more recently, satellite imagery) taken after storms that triggered widespread landslides and compared their number or density for different land covers (e.g. DL Hicks 1988, 1989a, 1992c; Marden & Rowan 1993; Marden 2012). This was often coupled with field-based assessments (e.g. Pain & Stephens 1990).

6.5 Earthflow and gully control

Many of the erosion mitigation practices used for managing landslides are also used for earthflow and gully control. Although vegetation is the primary control measure, structural measures such as debris dams or check dams have been used in the past but are not common now.

The effectiveness of soil conservation planting in reducing earthflow erosion is difficult to quantify with methods used for shallow landslides because this type of erosion causes disruption of the soil surface and vegetation rather than resulting in extensive areas of bare ground that are easy to map and to determine change over time. Zhang et al. (1991, 1993) used arrays of stakes installed on the surface of earthflows to measure surface movement, and electronic tiltmeters were installed in holes to a depth of 6.5 m to monitor subsurface movement. Differences between rates of movement of forested and grassed earthflows were used to infer the effect of afforestation. More recently, time-lapse photos have been used to monitor the activity of complex landslide-flow processes (McColl et al. 2017), over time periods of months to years, and have shown that these processes are perhaps more active than was originally thought.

The effectiveness of soil conservation treatments for controlling gully and earthflow erosion in the Gisborne–East Coast region following Cyclone Bola was evaluated by Thompson and Luckman (1993). A comprehensive study of sites affected by gully erosion (136 sites) and earthflow erosion (142 sites) collected a standard set of data describing each site and the soil conservation treatment applied. The treatments were based mainly on the planting of poplar and willow trees (aged 10–30 years at the time of the assessment). Earthflow erosion was treated by afforestation, space-planted trees, localised close tree planting, gully control at the toe of the earthflow, graded diversion banks, surface smoothing and drainage. For gully erosion, afforestation, gully wall planting, channel (pair) planting and debris dams were evaluated.

The site types were grouped into a series of 12 classes for assessment of effectiveness, since different site types require different soil conservation treatment. From extensive field observations, inference-based procedures for interpreting this information were developed and documented (Luckman & Thompson 1993; Thompson & Luckman 1993) to ensure assessment of effectiveness was consistently applied. Computer-based knowledge systems were developed to integrate the field observations and available historical information, which were also compared with direct, subjective, field-based assessment of effectiveness based on erosion severity rankings.

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). Other than for the Gisborne–East Coast region, there is limited quantitative information on the influence of ESC techniques on gully erosion. Historically, debris dams and other structural measures were trialled, but the erosion rates of many of the larger gullies were so great that works quickly became overwhelmed (Allsop 1973).

The effect of afforestation in reducing gully erosion in the Gisborne−East Coast region was quantified using time series aerial photographs (Marden et al. 2005, 2008, 2011, 2012, 2014). The metrics used to evaluate treatment success include number and area of gullies, and sediment generation rate (t km^{-2} yr^{-1}). Active gullies were manually identified from bare ground mapping and their area across the whole region quantified in 1957 and 1997 (Marden et al. 2012), and in Mangatu Forest in 1939, 1960, 1972, and 1988 (Marden et al. 2005). Changes in the number and area of gullies were used to develop gully growth and gully stabilisation models, from which changes in sediment production in response to afforestation were calculated for Mangatu Forest (Marden et al. 2005), the entire Waipaoa catchment (Marden et al. 2014), and the region (Marden et al. 2011, 2012). The relationship between gully size and the probability of afforestation being able to stop gully expansion was also determined (Figure 11).

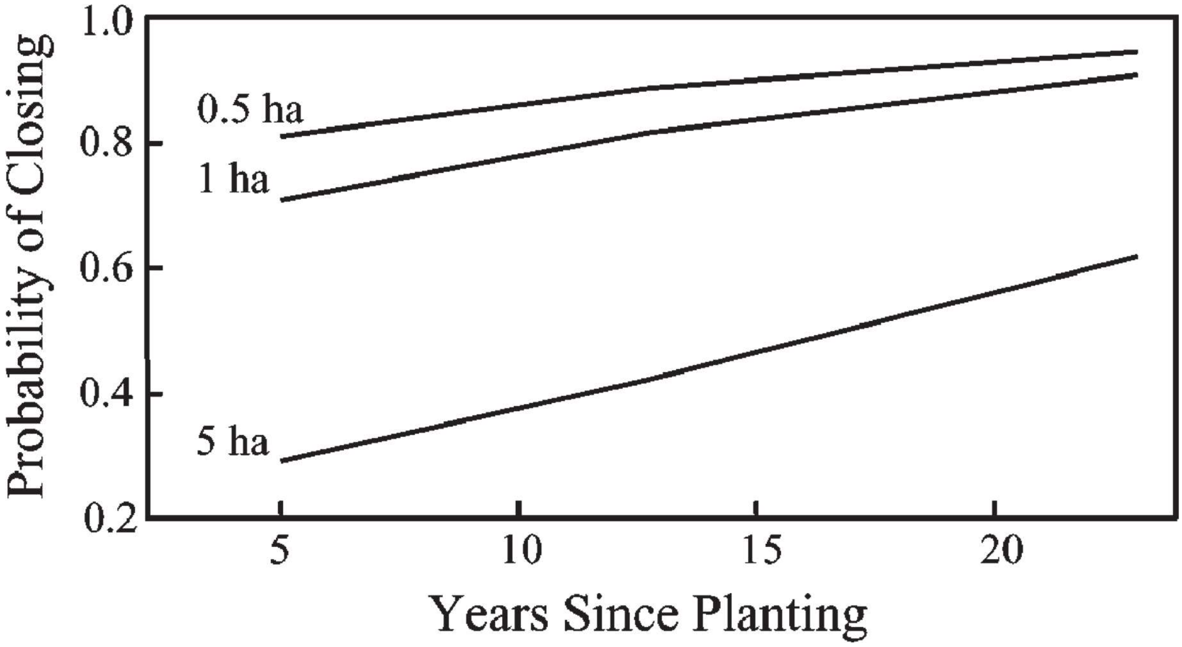

Figure 11. Predicted probability of gully stabilisation versus time since afforestation for different-sized gullies. (source: Marden et al. 2005)

Marden et al.'s (2008) calculated sediment generation rates for gully erosion under pasture and exotic forest for the three main catchments (Waipaoa, Waiapu, Uawa) for the period 1957–1997 reflect differences in underlying geology (relative proportion of Cretaceous and Tertiary terrain) and gully style (linear vs amphitheatre-shaped gullies), and the location and age of reforestation. Sediment production rates tend to be far higher on the Cretaceous terrain, where gully density is higher and large, amphitheatre-shaped gullies are more common. In addition, reforestation has been focused on the most erodible terrain, where gully stabilisation through reforestation is most difficult. Many of the gullies had only been replanted in the 1990s, and by 1997 the planted trees were not fully effective in reducing the extent of gully erosion.

6.6 Streambank erosion and riparian management

Bank erosion is likely to be an important source of sediment in New Zealand, although there has been very little quantitative research on rates of bank erosion or mitigation of bank erosion (Basher 2013a; Hughes 2016; Smith et al. 2019).

The influence of riparian management on bank erosion, and sediment delivery by overland flow, has been reviewed by Parkyn (2004), drawing on the international literature, and Hughes (2016) has reviewed local studies of the effect of riparian management on bank erosion.

Hughes (2016) identified only nine studies in New Zealand that assessed the effectiveness of riparian management interventions for reducing stream bank erosion (Table 3). Most used qualitative or semi-quantitative analytical methods and typically compared stream banks in pasture catchments (with unlimited livestock access) with stream banks where livestock were excluded and riparian shrubs/trees were present. Measurement approaches included: rate of bank retreat or change in river planform area, usually obtained from time sequence aerial photographs; LIDAR or terrestrial laser scanning; repeat, on-the-ground point or river cross-section surveys; and erosion pins.

Table 3. Bank erosion studies in New Zealand (mostly based on Hughes 2016)

Study	Measurement method	Intervention measure/Monitored effectiveness
Smith 1989	Runoff plots	Fenced grass riparian buffers. Space for time study. Bank erosion not measured, but TSS concentrations in hillslope runoff were c. 90% lower at treated sites.
Smith 1992	Suspended sediment yield	Riparian afforestation with pine trees increased sediment yield due to lack of riparian ground cover.
Williamson et al. 1992	Semi-quantitative assessment	Riparian zone retired from grazing. Space-for-time substitution study. No evidence that grazed banks >2m wide were more susceptible to erosion than retired banks. For streams >2m wide grazing on wet riparian soils resulted in increased erosion.
DL Hicks 1992b	Visual assessment	Visual comparison of bank erosion at planted sites with non-planted sites, generally after large flow events. Found that i) tree species used was important; ii) interlocking roots formed by several years' growth of dense tree plantings provided superior protection from bank erosion; and iii) removal of dead trees or trees that had fallen into the river reduced the occurrence of bank erosion. Tree planting can reduce bank erosion so long as: appropriate species are used; a sufficient length of the stream is treated; and the plantings are maintained. Where plantings were adequate, channel damage was reduced substantially (by >50% in the Waihora), but 40–60% of the plantings were rated as inadequate.
Williamson et al. 1996	Visual assessment	Planted and fenced riparian buffers. Before and after study indicated a decrease of actively eroding banks from 30% to c. 4%.
Boothroyd et al. 2004	Channel width measurements and visual assessment	Retention of riparian buffers during pine harvesting. Stream channels from clear-cut sites were significantly wider than pine forest sites with indigenous vegetation buffers (for both pre- and post-harvest sites).

Study	Measurement method	Intervention measure/Monitored effectiveness
Parkyn et al. 2003	Qualitative assessment (Pfankuch method)	Planted (with trees) and fenced riparian buffers. Space-for-time substitution study indicated that 3 out of 9 assessment sites (where riparian buffers were established) scored better.
DeRose & Basher 2011	Aerial photographs, orthophotography, LiDAR	Long-term (50-year) historical migration rates. Cliff erosion is the dominant process. No specific treatment effect assessed.
Hughes et al. 2012	Suspended sediment load estimates	Planted and fenced riparian buffers.* Before and after study. No measured change in sediment loads. No bank measurements made.
Wilcock et al. 2013	Monthly water quality sampling	Planted and fenced riparian buffers.* Before and after study. Reductions in TSS concentration of between 4 and 11%. Improvements attributed to livestock exclusion. No bank measurements made.
Collins et al. 2013	Turbidity measurements	Planted and fenced riparian buffers. Space-for-time study. Marginal difference (1.6 NTU) in mean nephelometric turbidity at treated sites. No bank measurements made.
Spiekermann et al. 2017	Sequential historical aerial photography, LiDAR Digital Elevation Model	Long-term lateral erosion rates range between 0.14 m yr^{-1} and 0.21 m yr^{-1}. No specific treatment assessed.
Smith et al. 2019	Channel mapping of riverbank migration rates to develop model	No treatment assessed. Improvements to SedNetNZ model. Measured bank migration rates averaged 1.6 and 1.4 m y^{-1}.

*Other catchment rehabilitation measures also implemented

Parkyn (2004) reviewed research on the efficiency and management of riparian buffer zones in reducing sediment input to streams (including grass filter strips, native and introduced trees, grazing management), including consideration of the effects of riparian buffer width and vegetation type. The removal of stock from streams and riparian areas has clear benefits for reducing sediment input to streams by reducing direct damage to stream banks and reducing soil compaction from stock. Much of the global research into the effectiveness of buffer zones for removing contaminants from surface runoff has focused on the effectiveness of vegetated filter strips (usually consisting of rank grass) in trapping sediment using laboratory or field experiments (e.g. Young et al. 1980; Dillaha et al. 1989; Magette et al. 1989; Daniels & Gilliam 1996).

There have been few New Zealand studies of the effectiveness of grass buffer strips (also called vegetative filter strips) in New Zealand (McKergow at al. 2008). However, numerous overseas studies have shown that they can be highly effective at reducing sediment delivery to streams by decreasing the velocity of runoff and allowing particles to settle (see reviews in Dosskey 2001; Yuan et al. 2009).

DOC and NIWA prepared a set of guidelines (Collier et al. 1995) that provide practical measures to improve the design of riparian buffer zones to manage bank stability (as well as light climate, water temperature, carbon supply, habitat diversity, flood flows, and contaminants). Generally, buffer widths need to widen as the slope length, slope angle and clay content of the adjacent land increase and as soil drainage decreases.

6.7 Catchment-scale assessment of erosion and sediment control

There are fundamentally two broad approaches for quantifying the effectiveness of ESC, including biophysical erosion control, at the catchment scale. Both tend to rely on models, measurements, or a combination of both.

The first utilises the potential for catchment water quality data to assess the effectiveness of ESC (including afforestation, soil conservation planting and farm plans) on *suspended sediment load*. This is often assessed in paired catchment studies in which one catchment is treated and the other remains as a control or uses long-term water-quality data sets and statistical techniques to determine changes in trends that can be correlated to changes within the catchment.

The second uses models to assess ESC effectiveness on erosion rates or *sediment yield*. While sediment modelling *per se* is clearly not a mitigation measure, it is included because of the relatively simplistic way the current suite of models in New Zealand treat mitigation (often by a reduction factor for each pixel, rather than relating specifically to actual treatments on the ground). If we had better information both on ESC implementation (what, where, survival, etc) and performance, then sediment modelling approaches might be more useful. These models are often used for scenario analysis or for assisting with catchment management policy implementation.

Of particular relevance to the second approach is the inclusion of farm plans as both a measure to be used in modelling and as a way to combine different ESC techniques. For example, Basher, Manderson et al. (2016) identified five primary sources of data and information of relevance to the evaluation of soil conservation works and farm plan effectiveness. These include hard-copy farm plans, LMO GIS files of individual farms, farm plan dossiers, regional farm plan data layers, and catchment and regional data sets.

These approaches are expanded on below.

6.7.1 Catchment water quality

Small catchment studies in New Zealand (from one to tens of hectares, and often not specifically focused on sediment load reduction) have indicated that afforestation treatments within paired catchments result in reduced catchment sediment yields compared to a control (e.g. O’Loughlin et al. 1984; Fahey & Marden 2006). However, at larger scales, where treatments are not uniform or complete within the catchment, the ability to interpret a change in water quality signal can be more difficult.

For example, Hicks and Hoyle (2012) and Snelder (2018) analysed the extensive suspended sediment record for the Horizons region to determine the effect of the SLUI programme on catchment sediment loads. The method relies on having continuous long-term monitoring of suspended sediment yield (using turbidity as a surrogate), calculation of storm event sediment yields, and using these data to model the relationship between storm sediment yield and peak discharge, then examining the time trends of the residuals of predicted vs observed storm sediment yields. This type of approach will potentially allow the impacts of soil conservation planting and farm plans to be directly calculated from catchment water-quality records, but is reliant on having high-quality, long-term suspended sediment data in catchments where there is a progressive programme of conservation planting and whole-farm plan (WFP) implementation being completed within a relatively short time frame. Such data allows the signal of land management change to be discerned from the noise of storm-driven and inter-annual variation in suspended sediment load.

Snelder (2018) found that the statistical models that were used to test the association between water-quality improvement and interventions controlled for the land areas that were subject to erosion in 2004. This indicates that improving water quality is not only associated with natural processes of recovery from the events in 2004, but also with the interventions implemented.

6.7.2 Modelling the effect of erosion and sediment control practices

Several models have been developed and used in New Zealand for addressing the effects of erosion and sediment control practices on erosion and sediment yield. They have been applied to both runoff-generated surface erosion as well as mass movement and gully erosion. Approaches include simple empirical models such as the Universal Soil Loss Equation (USLE), the New Zealand Empirical Erosion Model (NZeem®), CLUES, and WANSY, SHETRAN (Elliot et al. 2012), and hybrid empirical–process-based models such as SedNetNZ and GLEAMS (Elliott & Basher 2011. Most of the models are long-term, steady-state models that provide predictions of average annual sediment yields rather than event-based models. More detail on the modelling approaches and examples of their use are given in Basher, Moores et al. 2016 and Basher et al. 2019. Several models for estimating sediment yields in the Waikato-Auckland-Northland region have also been compared (Haddadachi & Hicks 2016).

Surface erosion

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, Moores et al. 2016; Basher et al. 2019). USLE is a widely used method in New Zealand for estimating sediment losses associated with urban development and road construction projects. 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. These models have been used both in urban environments (mostly in and around Auckland) and for cropping land uses. WEPP and RUSLE2 have been used to investigate inter-rill erosion under armouring (Cochrane et al. 2019).

Mass movement erosion

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:

E = aCRb

where E = the long-term average annual erosion rate (t km^{-2} yr^{-1})
R = the mean annual rainfall (mm yr^{-1})
C = a vegetation factor
a = an erosion terrain 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. It has been 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. NZeem® does not distinguish the contribution from different erosion processes, and so far has not been used to evaluate the effect of individual erosion mitigation practices. However, recently Monaghan et al. (2020) 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.

Dymond et al. (2016) used the sediment budget model SedNetNZ to assess the effect of implementation of WFPs and riparian retirement on sediment loads in the Manawatū catchment and Hawke's Bay region (Palmer et al. 2014, 2016; Spiekermann et al. 2017). They used factors for effectiveness and maturity that varied with the type of work implemented and had slightly different values to those used by Douglas et al. (2008). The analysis using SedNetNZ also provided information on the effect of WFPs on different erosion processes (surface 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 are summarised, as in CLUES, by River Environment Classification (REC) sub-catchment.

Other approaches include deterministic and probabilistic models. An example of the former, uses a physically based slope stability model (e.g. Schwarz et al. 2016) to assess the role that trees play as a biophysical erosion control. However, these have not been widely used in New Zealand. In Schwarz et al.'s study, root reinforcement is quantified as a cohesion term (apparent root cohesion) and linked to a hydrological model to account for the hydrological effect of vegetation. One of the limitations of such approaches is that the data requirements at catchment scale are extensive, especially in complex hill country terrain. In particular, soil data (including type and depth of different soil horizons) for the calculation of soil strength parameters can be difficult to obtain without extensive field work, and the requirements of the root strength and root distribution models often include *in situ* measurements of root tensile strength of a range of diameter classes (and species).

In the second approach, a landslide inventory is required to statistically quantify effectiveness based on the spatial distribution of biophysical erosion control (e.g. the location of individual trees) with respect to spatial variation in erosion, usually from shallow landslides. A multivariate statistical model, including a spatial representation of root reinforcement, can help explain the distribution of landsliding observed alongside other factors such as slope, soil type, etc., and can thus provide a statistical measure for the effectiveness of root reinforcement, as was attempted, at least in part, by Douglas et al. (2013).

Although these last two approaches are useful for estimating the effectiveness of trees at a local scale for reducing landslide erosion, upscaling remains a challenge to inform analysis of the effectiveness of erosion control across varying environmental terrains and scales. There is a gap in terms of spatial scale between physical models that quantify root reinforcement for homogeneous tree stands and landslide susceptibility modelling at catchment scale using land cover data as a proxy for the effect of the hydrological and mechanical influences of different vegetation classes. This largely has to do with data availability and the difficulty associated with upscaling physical models beyond a homogeneous tree stand or single slope. Both the physical and statistical modelling approaches require the location of trees to be known, and use allometric relationships between above-ground biomass and root distribution. Physical slope stability models require an estimate of the resistance (kPa), whereas a statistical approach may use a relative measure (e.g. a root reinforcement index used by Phillips et al. 2011 to quantify site occupancy).

The effectiveness of erosion control is also likely to vary depending on the magnitude of an erosion event. For example, the effectiveness of apparent root cohesion in soils highly susceptible to mass movement will differ depending on variation in pore water pressure, which is generally governed by the magnitude of a rainfall event.

6.7.3 Farm plans

Evaluation of the effectiveness of farm plans and associated works has rarely been undertaken, at least in a formal sense (i.e. if works were done or plants survived, they were often deemed effective).

The theoretical reduction achievable at 10 m tree spacings (70%) for space-planted trees, as estimated by Hawley and Dymond (1988), is frequently used as a reference for modelling scenarios that aim to quantify the effectiveness of 'well-implemented' whole farm plans (e.g. Schierlitz et al. 2006; Parfitt et al. 2007; Ausseil & Dymond 2008; Dymond et al. 2016; Basher et al. 2018; Neverman et al. 2019). This is generally done by reducing the sediment yields from hillslope erosion processes within the farm boundary by 70% due to the lack of spatially explicit data on implemented works. Yet there is no basis for assuming that WFPs achieve a 70% reduction in sediment yields across an entire farm, since it is rarely the case that all slopes susceptible to landslide erosion are planted at 10 m spacings. Also, the mortality rate of plantings is not factored in.

Douglas et al. (2008) and McIvor et al. (2011) proposed a model-based approach for estimating the effects of conservation works (afforestation, space-planted trees, retirement of indigenous vegetation) on sediment export from a farm in the Horizons region. Underpinning this approach is the need to collect data (using aerial photography) during implementation of a works programme on vegetation type and canopy cover, the area of each works (at the individual site level), and the age of the vegetation. The empirical model NZeem® (Dymond et al. 2010) was used to calculate the reduction in sediment export.

This type of approach was used by Dymond et al. (2010) to assess the effect of implementation of WFPs under SLUI in the Manawatū catchment using the simple assumption that a fully implemented WFP would reduce erosion by 70%. They analysed the impact of the current WFP implementation plan to predict its effect on mean sediment discharge (t yr^{-1}) of the Manawatū, as well as water clarity (Ausseil & Dymond 2008). The model predicted that after maturation of the soil conservation plantings, the mean sediment discharge of the Manawatū River would reduce by 48% (from 3.1 to 1.6 million t yr^{-1}). This reduction would approximately double water clarity and would move the median water clarity of the middle Manawatū from 0.9 m to approximately 1.8 m.

Using the sediment budget model SedNetNZ, Dymond et al. (2016) analysed the effect of WFPs on different erosion processes and different subcatchments of the Manawatū River. They used factors for effectiveness that varied with the type of work implemented and revised the time to maturity for some of them. This analysis predicted that current WFP initiatives would reduce the sediment load of the Manawatū by 34%. The assessment of the effect of SLUI has been updated by Manderson et al. (2015) and Basher et al. (2020) using a similar approach and similar assumptions about the effectiveness of WFPs and associated works.

6.7.4 Land and soil monitoring

Regional councils have developed a protocol for land and soil monitoring to provide regional-scale state and trend data on erosion for state of the environment reporting, including an assessment of land stability (Burton et al. 2009). While this approach is not aimed directly at assessing information on the performance of soil conservation measures, the sampling strategy incorporates some areas that have been treated by soil conservation planting and assesses responses to soil disturbance, such as conservation planting, or retirement and reversion.

The method provides an assessment of soil stability, soil disturbance, soil intactness, and their change over time. The attributes collected are as follows.

- *Soil stability* characterises whether soil is stable (completely vegetated), erosion-prone (unstable but inactive, completely vegetated), eroded (recently disturbed but revegetating), or eroding (freshly disturbed, bare ground). Associated information includes the percentage of bare soil, and the nature of disturbance (land-use related or natural).
- *Soil disturbance* is an assessment of whether soil is currently at risk of removal or deposition through natural processes or land use. Change in exposed area is used as an indicator of changes in soil disturbance through time. Where soil is currently disturbed, the nature of the disturbance is also recorded (natural or land-use-related erosion; topsoil, subsoil or other disturbance; the type of erosion or disturbance).
- *Soil intactness* characterises whether soil is currently staying in place and uses change in vegetated area as an indicator.

This procedure is based on grid-based point analysis of digital aerial photos, with the sampling area delineated by a 1 ha area centred on each grid point (Figure 12).

Figure 12. Greater Wellington Regional Council soil stability monitoring site, showing the 100-dot grid used to calculate the amount of bare soil. (source: Sorensen 2012)

This technique is now being used by many regional councils, including Auckland, Waikato, Horizons, Gisborne, Bay of Plenty, Wellington, Tasman, and Marlborough. Some regions, including Wellington, have completed repeat surveys that establish temporal trends (Crippen & Hicks 2011; Sorensen 2012).

In the Wellington region, Sorensen (2012) found that 44% of sample points were on stable surfaces, 35% on erosion-prone surfaces, 9% on eroded surfaces, and 6% on eroding surfaces. The land-use activity responsible for the majority of soil disturbance across the region was farm and forest tracking. Of the 72.8% of the region that needed soil conservation cover, 61.7% had woody vegetation to provide protection from erosion. Natural vegetation (mainly trees and scrub) provided the majority (34.6%) of soil conservation cover for the region. Of the 26.4% of farmland requiring soil conservation cover, 58% had some kind of soil conservation cover, whether natural, residual or planted, indicating that (at 2010) a further 42% (approximately 89,300 ha) of farmland in the region that is susceptible to soil erosion still needs some kind of soil conservation cover.

Phillips et al. (2008) also used field-based criteria to assess the effectiveness of space-planted trees in controlling earthflow, gully and landslide erosion in the Gisborne–East Coast area. Evaluation of treatment success was based on current erosion activity, including the surrounding area (using an LUC-based assessment of erosion severity), tree survival and tree condition to classify current land condition into five classes (Table 4). Treatment effectiveness was simply classed as successful or unsuccessful.

Table 4. Land condition classes of Phillips et al. (2008)

Land condition class	Description
Very poor	Land that shows very substantial, and commonly worsening, erosion activity such that agricultural use is severely impaired
Poor	Land affected by substantial and continuing erosion activity such that agricultural use is significantly impaired
Moderate	Land that is mostly stable or only moderately affected by the erosion process, and in which past erosion is the main determinant of land condition, and such areas are easily delineated and in only the early stages of recovery
Good	Land that is mostly stable or only slightly affected by the erosion process, and in which past erosion is the main determinant of land condition, although previously eroded areas, while easily delineated, have recovered substantially
Very good	Land that is effectively stable or insignificantly affected by the erosion process, past or present. Previously eroded areas are difficult to delineate clearly. Agricultural use is unimpaired by erosion processes or products.

6.7.5 Sediment fingerprinting

Sediment fingerprinting is, again, not a mitigation measure. Its relevance is in relation to how it might be used to assess erosion mitigation performance. Various fingerprinting or sediment tracing techniques have been developed that involve measuring one or more parameters to provide characteristics that can be used to distinguish one source of sediment from another (see Foster & Lees 2000; Collins & Walling 2004; Haddadchi et al. 2013), and thus could potentially be used to determine the effectiveness of erosion control.

However, sediment fingerprinting has never been applied to assessing the effect of conservation planting or erosion control in New Zealand or internationally, and would require significant development work to be used for this purpose. The most likely approach would be to use compound-specific isotopes (e.g. Gibbs 2008), which are diagnostic of the plant communities associated with sediment source areas. Analytical costs can be relatively high, however, and replicated sampling is needed to get reliable results.

6.8 Summary

Table 5 provides a summary of the studies where ESC practices have been used and assessed (or recommended for use in New Zealand), summarised by the erosion process they are targeted at controlling, together with the land use on which they were implemented.

Table 5. Summary of key studies providing information on erosion mitigation treatment performance (source: Basher, Moores et al. 2016)

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Land use	Reference
Surface erosion	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	Urban earthworks	Auckland Regional Council 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	Urban earthworks	Summarised in Basher, Manderson et al. 2016
	Temporary or permanent seeding	Sediment load reductions >90%	Sediment load (t km^{-2})	International	Urban earthworks	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	Urban earthworks	Auckland Regional Council undated
	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	Urban earthworks	Winter 1998
	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	Urban earthworks	Moores & Pattinson 2008
		Two ponds treated with PAC had overall sediment removal efficiency of c. 99%		New Zealand	Urban earthworks	Larcombe 2009
		Several ponds treated with PAC had overall sediment removal efficiency of c. 99%		New Zealand	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	Urban earthworks	Babington & Associates 2008

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Land use	Reference
Surface erosion (cont.)	Wheel-track ripping	Reduced erosion by 95% on clay-rich soils at Pukekohe	Sediment load (t ha^{-1})	New Zealand	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	Cropping	Deasy et al. 2010; Bailey et al. 2013
	Wheel-track diking	Reduced erosion by 60–96%	Sediment load (kg ha^{-1})	International	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	Cropping	Basher et al. 1997
		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	Cropping	Johnstone et al. 2011
		Reductions in erosion rate compared to bare ground of 40–>90%	Sediment load (kg ha^{-1})	International	Cropping	Summarised in Basher, Moores et al. 2016
	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	Cropping	Summarised in Basher, Moores et al. 2016
		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	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	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	Cropping	Summarised in Basher, Moores et al. 2016

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Land use	Reference
Surface erosion (cont.)	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	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	Pastoral farming	Tanner et al. 2013
Landslide	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	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	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 Hawke's 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	Pastoral farming	McIvor et al. 2015

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Land use	Reference
Landslide (cont.)	Space-planted trees (cont.)	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	Pastoral farming	Phillips et al. 2008
		Landslide area 39% less under space-planted trees than pasture in Manawatū 2004 storm	Area affected by landslides	New Zealand	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	Pastoral farming	Page et al. 1999
		In 1992 storm in Manawatū-Wanganui, area of landslides c. 35% less with space-planted trees than pasture	% area affected by landslides	New Zealand	Pastoral farming	Varvaliu 1997
		In 1992 storm in Manawatū-Wanganui, area of landslides 60% less with extensive space planting than pasture, and 10% less with scattered trees	% area affected by landslides	New Zealand	Pastoral farming	DL Hicks et al. 1993
	Afforestation	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	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	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	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	Pastoral farming	Reid & Page 2002

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Land use	Reference
Landslide (cont.)	Afforestation (cont.)	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	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	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	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	Pastoral farming	Hancox & Wright 2005
		Forest generally reduced landsliding by 90% and scrub by 80% in 2004 Manawatū−Wanganui storm	% area affected by landslides	New Zealand	Pastoral farming	Dymond et al. 2006
		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	Pastoral farming	Hicks & Crippen 2004
		Area affected by landsliding >90% less under forest and scrub compared with pasture	% area affected by landslides	New Zealand	Pastoral farming	Pain & Stephens 1990
		In 1992 storm in Manawatū–Wanganui area of landslides c. 35% less under forest (pine or indigenous) than pasture.	% area affected by landslides	New Zealand	Pastoral farming	Varvaliu 1997
		In 1992 storm in Manawatū−Wanganui, area of landslides 85% less under forest and scrub than pasture	% area affected by landslides	New Zealand	Pastoral farming	DL Hicks et al. 1993
Earthflow	Afforestation	Surface movement rates on forested earthflows were 2–3 orders of magnitude lower than on grassed earthflows	Movement rate (m $month^{-1}$)	New Zealand	Pastoral farming	Zhang et al. 1993

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Land use	Reference
Gully	Afforestation	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	Pastoral farming	Marden et al. 2005, 2008, 2011, 2012; Herzig et al. 2011
Bank erosion	Space-planted trees	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	Pastoral farming	DL Hicks 1992b
	Riparian fencing	Suggests bank erosion reductions ranging from 30 to 90% using data from Line et al. (2000), McKergow et al. (2003), Meals & Hopkins (2002), and Owens et al. (1996)	Sediment load	New Zealand	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	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	Pastoral farming	Williamson et al. 1996
		Monthly water quality sampling from Dairy Best-Practice catchments (including riparian fencing) showed 4–11% reduction in suspended sediment concentrations; sediment assumed to mainly be derived from bank erosion	Non-storm suspended sediment concentration (g m^{-3})	New Zealand	Pastoral farming	Wilcock et al. 2013

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Land use	Reference
Bank erosion (cont.)	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	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	Pastoral farming	Monaghan & Quinn 2010
		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	Pastoral farming	Hughes et al. 2012
Combination - landslide, bank erosion, surface erosion	Afforestation	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	Pastoral farming	Dons 1987
		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	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	Pastoral farming	Hughes et al. 2012

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Land use	Reference
Combination - landslide, bank erosion, surface erosion (cont.)	Afforestation (cont.)	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	Pastoral farming	Eyles & Fahey 2006
		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
Combination – landslide, earthflow, gully	Space-planted trees	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, DL Hicks 1989 a, b 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	Pastoral farming	DL Hicks 1989a, b, 1992c

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Land use	Reference
Combination – landslide, earthflow, gully (cont.)	Space-planted trees (cont.)	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	Pastoral farming	Phillips et al. 2008
Combination – landslide, bank erosion, gully	Space-planted trees	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	Pastoral farming	Cameron 1991
Combination – gully, earthflow	Space-planted trees	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	Pastoral farming	Thompson & Luckman 1993
Combination – bank erosion, surface erosion		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	Pastoral farming	Smith 1992
Combination – bank erosion, surface erosion		Indigenous forest catchment yielded 90% less sediment than a pasture catchment	Mean annual sediment yield (t km^{-2} yr^{-1})	New Zealand	Pastoral farming	Bargh 1977, 1978

7 Performance of erosion and sediment control measures

This section provides results from previous studies in which the performance of erosion and sediment control practices have been assessed. Much of this information comes from Basher 2016, and Basher, Manderson et al. 2016; Basher, Moores et al. 2016; Basher et al. 2019), parts of which are reproduced in Appendix 1.

While there is abundant guidance about available ESC techniques for different erosion processes and land uses (see section 5.2), most guidelines provide limited quantitative information on treatment performance, especially in terms of their specific design in relation to the large variation in both soils and rainfall across New Zealand.

7.1 Surface erosion, including runoff, and sediment controls

7.1.1 Urban environments

Mulches and surface covers

Erosion control on bare ground can be highly effective, with some treatments found to reduce sediment loss from bare earth by as much as 99%. However, not all were equally effective, with variations in performance a function of the percentage cover of the treatment; the potential for the cover to be displaced (by wind, rainfall or runoff); the thickness and associated water-holding capacity, flexibility and weight; the number of treatments (combination treatments are more effective than single treatments); and the establishment of vegetation (cover crops and hydroseeding).

Sediment loads discharged from mulched topsoil and mulched subsoil plots were approximately 94% and 85% lower than those from bare topsoil and bare subsoil plots, respectively (Auckland Regional Council 2000). Grassed plots generated around 87% lower sediment than bare topsoil plots. The highest loads were generated from the bare subsoil plots, being around double the load from the bare topsoil plots.

The same study also found that during high-intensity rainfall events, applying mulch to bare subsoil was less effective than applying it to topsoil. Mulching subsoils was found to make no significant difference to the discharge of clay and silt-sized particles during these types of storm event. The effect of topsoil in helping to lower sediment discharge (enhanced with the application of mulch) was linked to its higher organic matter content, allowing higher rates of infiltration when compared with subsoils.

Decanting earth bunds, sediment retention ponds and chemical treatment

Sediment removal efficiency of decanting earth bunds (DEBs) constructed in accordance with the design specified in Auckland Regional Council's TP90 guidelines (Auckland Regional Council 1999) were assessed by Babington and Associates (2008). During simulated rainfall trials, the performance of the DEB was found to vary in relation to event duration, antecedent soil moisture conditions, and the extent of available storage, with sediment removal efficiencies reported in the range 47–75%. In general, these events had peak flows similar to the 1-year average recurrence interval (ARI) rainfall event and a total storm volume similar to the 20-year ARI event. The study was able to estimate sediment removal efficiencies from only four of the events monitored (results in the range 23–79%). However, it is important to note that the report on the study describes various causes of significant uncertainty, even in relation to the results from these four storm events (Babington & Associates 2008). The study recommended that floating decants be adopted as standard practice on DEBs.

Sediment retention pond studies have been limited to just a few in Auckland (Winter 1998; Khan 2012). In Winter's study, the overall sediment removal efficiency of the pond over the 11 storm events was calculated to be 90%, with 376 and 39 tonnes of sediment entering and leaving the pond, respectively. Efficiency during the individual storms monitored ranged from 70% to 99% and was inversely related to peak inflows/outflows and event mean concentrations of suspended solids in outflow samples. During two-thirds of all storm events over the period of the study there was insufficient rainfall to generate outflow from the pond, and as a result 100% of influent sediment was retained during these smaller storm events. The average sediment removal efficiency during the two summer storms (96%) was higher than during the nine winter events (87%).

Despite removal efficiencies in excess of 90%, turbidity and concentrations of suspended sediments in effluent discharged from construction sites can still be markedly higher than environmental guidelines and/or background concentrations in receiving aquatic environments (Winter 1998; Gharabaghi et al. 2006; McCaleb & McLaughlin 2008). To address this issue, in recent years enhanced erosion and sediment control practices that utilise chemical treatments have become increasingly common.

Differences in suspended sediment concentrations in influent and effluent samples collected where chemical treatment was used are in the range of 90−99% for well-designed ponds receiving chemical treatment (Auckland Regional Council 2004; Moores & Pattinson 2008; Larcombe 2009). Less marked differences in influent and effluent concentrations were associated with ponds that had poorly performing decanting devices, multiple inflow points, high inflow energy, or poor separation of inlets and outlets. However, there are several issues that can affect the performance of sediment retention ponds (see Basher, Moores et al. 2016 for more details).

In situations where multiple devices have been assessed for their combined effects on the natural environment (Ridley & De Luca 2015), the results of manual sampling showed that median and 95th percentile total suspended sediment (TSS) concentrations in outflow samples were 98–99% lower than concentrations in inflow samples over the period of monitoring. The quality of treated effluent indicated by the manual sampling programme is supported by the results for the much larger number of outflow samples collected by automatic samplers, with the median and 95th percentile TSS concentrations in automatically collected samples slightly lower than in the manually collected samples.

ESC practices have generally been found to be less effective for retaining clays and silts than sand, and chemical treatment is used to enhance the binding of sediments at source or to promote the settling of fine particles in sediment retention devices.

7.1.2 Pastoral agriculture

Orchiston et al. (2013), in a paired catchment study, showed that strategic grazing of dairy winter forage paddocks can considerably reduce volumes of overland flow, and by implication assist in reducing overall yield of sediment entering waterways (no performance data were given).

Detainment bunds

Clarke et al. (2013) report on the use of detainment bunds for mitigating soil losses from pastoral agriculture and observed that the largest retention across all sampled events was 2.7 tonnes of sediment in one event. Levine et al. (2019; 2020) also reported results on sediment retention in the Lake Rotorua watershed, and found that in the 12-month study of 37 ponding events at two sites, the annual loads of suspended sediment were 36% lower than the inflow loads, with an attenuation efficiency of 78%. Dorner et al. (2018) report the efficacy of detention bunds in pastoral agriculture systems for capturing sediment, based on Bay of Plenty studies, to be as high as 90%, though studies cited in the same report suggest estimates of 70% (Doole 2015; Daigneault & Samarasinghe 2015). Careful matching of ponding volume to the size of the contributing catchment is essential to ensure success with sediment capture and minimise risk of destruction during large events. The design criteria of a minimum ratio of 120:1 (120 m^3 ha^{-1} of catchment area) ensures an adequate detainment pond volume to enable settling to occur. However, not all landscape types are suitable for detainment bund installation and achieving adequate storage relative to catchment size.

Wetlands

Wetlands, both artificial and natural, can also be used for sediment management. Reported mitigation efficacy is around 60−80% removal of sediment (McKergow et al. 2007; Tanner et al. 2013; Doole 2015; Daigneault & Samarasinghe 2015). However, they are not effective in areas of free-draining soils because they cannot intercept enough water. Wetlands must be protected from high flows to avoid failure during extreme weather events. Wetlands are also expensive to develop if they are not already present or are severely degraded.

7.1.3 Horticulture and arable cropping

Johnstone et al. (2011) observed that diking reduced surface runoff and in-field ponding on a range of soil types, crops and slope steepness. The volume of winter runoff from a trial bed that had been diked was reduced by over 90% compared with an un-diked control, and although the authors state there were clear effects on the amount of sediment lost in the runoff, no data were presented other than a visual comparison of runoff.

Cover crops, which are grown to be incorporated back into the soil, are used widely in the New Zealand vegetable industry, but there are few data on their performance in reducing sediment loss. However, plot studies at Pukekohe illustrate the mitigating effect of vegetation on erosion rates.

At a trial site on clay loam, strongly structured soils, Basher et al. (1997) provide erosion rate data from plots of bare, cultivated soil and grass plots. When the plots were bare, soil loss from the bare plots was two orders of magnitude higher (5,700–6,900 t km^{-2} yr^{-1}) than soil loss from grass plots (30–50 t km^{-2} yr^{-1}).

7.2 Landslide control using space-planted trees

All the published studies (see Table 6) emphasise the importance of both initial establishment of the trees at the required spacing and subsequent maintenance to ensure their survival and effectiveness, as well as being planted in the right part of the landscape. This was emphasised by early research that found performance was strongly limited by inadequate spacing and poor survival (e.g. Hawley & Dymond 1988; DL Hicks 1988, 1989a, 1992c; Thompson & Luckman 1993), and this may still be an issue. For example, a study by Marden and Phillips (2013) examined survival of poplar and willow poles planted in the Gisborne – East Coast area and found 24% of poles had died within 24 months, and 40% had died within 45 months. They attributed this to a combination of poor pre-treatment of poles, poor planting technique, site factors, and stock damage.

Most of the empirical data on the performance of space-planted trees for erosion control are based on individual or small groups of trees rather than hillslope-scale performance.

Depending on site-specific environmental conditions (e.g. soil type), established poplar and willow trees influence the amount of landsliding within a radius of up to 10−15 m on an individual tree basis, and the influence of neighbouring trees through intermeshing of roots has also been shown to be important (Hawley & Dymond 1988). The degree of slope stabilisation achieved decreases with increasing distance from trees and is dependent on age and species of tree (Phillips et al. 2014).

In Hawley and Dymond's (1988) study, the influence of trees was negligible in preventing shallow landslides beyond 11 m from the stem. They calculated 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%. 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%.

Published reductions in shallow landsliding using (10 m) space-planted trees range from 70 to 95% (Hawley & Dymond 1988; Douglas et al. 2009, 2013; McIvor et al. 2015); but measured or assessed reductions are often far less than this because plantings are inadequately spaced and/or poorly maintained (e.g. Hawley & Dymond 1988; Cameron 1991; Thompson & Luckman 1993; DL Hicks et al. 1993; Varvaliu 1997).

In Douglas et al's (2009, 2013) studies, trees were found to have reduced landslide occurrence by 95% compared with paired pasture control sites (0.4% vs 7.9% scar area, respectively), and scars occurred on fewer sites with trees than those with pasture (10 vs 45). For the 10 tree sites with scars, the area of scars was <3.5%, except at one site where it was 11.3%. The greatest extent of landsliding occurred where trees had a DBH of <30 cm. Mature trees reduced landsliding by 95% when planted at spacings closer than 13–18 m.

Younger trees (DBH <30 cm) were less effective, and there was no difference between willows and poplars.

In McIvor et al.'s 2015 study, landslide erosion was 78% less on sites compared to the pasture control sites. Mature plantings of groups of both poplar and willow reduced landsliding within a zone of c. 10 m of the trees to almost zero. There was a moderately strong relationship between DBH and area of protection for poplars, whereas it was weak for willows. Where plantings had a mean DBH of <20 cm, their effectiveness was reduced depending on spacing. For trees with a mean DBH of c. 10 cm, effectiveness was negligible regardless of spacing.

Earlier studies that quantitatively assessed the effectiveness of soil conservation measures in reducing landslides following storms found varying levels of percentage erosion reduction compared to pasture (Varvaliu 1997; Lough 1993; DL Hicks et al. 1993). Less quantitative methods also found a range of effectiveness (Cameron 1991; DL Hicks 1991, 1988, 1989a, 1992c).

The performance of soil conservation measures in the Waihora catchment during Cyclone Bola is described by DL Hicks (1989 a, b; 1992c). 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 catchment, Hicks estimated that erosion was 22% lower (measured as area of damage) than it would have been in the absence of soil conservation measures. He also estimated it 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. Similar surveys were carried out in Taranaki (DL Hicks 1990), Wairarapa (DL Hicks 1991) and Manawatū–Rangitikei (DL Hicks et al. 1993).

Schwarz et al. (2016), using a modelling approach based on New Zealand data, concluded that a planting density between 330 and 160 stems per hectare (spacing of 5.5 and 8 m, respectively) would assure significant root reinforcement for slope stabilisation and reduce the volume of rainfall-triggered shallow landslides by up to 100%.

Space planting can achieve reductions of a similar magnitude to closed-canopy vegetation (afforestation), but its effectiveness is highly dependent on successful establishment of the trees and subsequent maintenance to ensure their survival and effectiveness (i.e. adequacy of treatment is paramount) (see Marden & Phillips 2013).

Table 6. Performance of space-planted trees and closed canopy vegetation on erosion

Reference	Location, terrain, storm history	Erosion type(s)	Key Findings
McIvor et al. 2015	Coastal Hawkes Bay; moderately steep young sediments; storm rainfall estimated 700 mm	Shallow landslides	Tree spacing varied from 9 to 11 m. Landsliding reduced by 78% on sites with trees compared to pasture sites. Mature poplars and willows reduced landsliding within a zone of c. 10 m of the trees to almost zero. Where plantings had a mean DBH of <20 cm, their effectiveness was reduced dependent on spacing. For trees with a mean DBH of c. 10 cm, effectiveness was negligible regardless of spacing.
Douglas et al. 2009, 2013	Storms in 2004 (Manawatū – daily rainfall >200 mm) and 2006 (Wairarapa – daily rainfall >100 mm); steep young sediments	Shallow landslides	Trees reduced landslide occurrence by 95% compared to paired pasture control sites (0.4% vs. 7.9% scar area, respectively), and scars occurred on fewer sites with trees than pasture (10 vs 45). There were no significant differences between species in their effectiveness in reducing landslide occurrence. On the tree sites where landslides occurred, % scar area was <3.5%, except at one site where it was 11.3%. The greatest extent of landsliding occurred where trees had a DBH of <30 cm. Suggest that if all poles survive to produce trees, trees could be thinned to increase understorey pasture production without compromising slope stability, providing retained trees have DBH > 30 cm and are no further apart than 18 m.
Varvaliu 1997	Pakihikura valley, Rangitikei; storms August/September 1992; steep young sediments	Shallow landslides	Average % eroded of unstable slopes was 11.7% under pasture, and 7–8% under space-planted trees, pines and indigenous forest. Soil conservation planting reduced landsliding by 33 to 37%.
Lough 1993	Pohangina valley; storms August/September 1992; steep young sediments	Shallow landslides	Average % erosion on unstable slopes in pasture was 6.7%, compared to 2% with space-planted poplars, mānuka scrub (0.4%, native forest (0.5%), and pines (1.5%).
Cameron 1991; DL Hicks 1991	Whareama catchment, Wairarapa; 305 sites on argillite and young Tertiary siltstones; storm 8–11 April 1991, storm rainfall 200–300 mm	Shallow landslides, gullying, streambank erosion	Adequately installed measures reduced gullying by 50%, bank erosion by 24%, landsliding by c. 70% relative to unstable, unplanted slopes. Soil conservation measures installed on: 67% of unstable channels, but only 55% of these were adequately installed 52% of unstable footslopes, but only 39% of these were adequately installed 43% of unstable hillslopes, but only 43% of these were adequately installed. Soil conservation measures reduced catchment sediment supply by: 35% from gullying 21% from bank erosion 22% from landsliding. Soil conservation measures were only installed in 2/3rds of unstable channels and half the unstable slopes. Only 50% of the treated channels and 40% of hillslopes had adequately installed and maintained soil conservation measures.

Reference	Location, terrain, storm history	Erosion type(s)	Key Findings
Pain & Stephens 1990	Eltham, Taranaki; steep young siltstone and mudstone; storm rainfall 202 mm over 3 days		8% of c. 10,000 ha of pasture affected by landslides (visual) cf. 9.6% (digital assessment of 5 sample areas). Extent of landsliding affected by vegetation type: pasture 9.6%, native forest 0.27%, pines 0%, regrowth 0.97%.
Hawley 1988; Hawley & Dymond 1988	Ngatapa, Gisborne; steep slopes underlain by ash over mudstone	Shallow landslides	From the relationship between average fraction of ground eroded vs distance to trees, calculated that if trees had been planted at 10 m spacing (100 sph) with 100% establishment and survival, there would have been a reduction in landslide damage of 70%. However, the spacing of 14-year-old trees was 20 m, and 66% of the planted trees had survived, so the actual reduction in landslide damage due to space-planted trees was only 14%.
DL Hicks 1988, 1989a, 1992c	Waihora catchment, Gisborne; steep young siltstone and mudstone; post Cyclone Bola, storm rainfall of 300−600 mm	Shallow landslides, gullying, streambank erosion	Describes general relationship between LUC units and storm damage (most hillslope and stream damage on class 7 with lesser amount on class 6). Criteria for adequacy were: appropriate planting pattern for type of instability, all unstable areas planted at adequate density (<10 m spacing), trees were mature and healthy. About 7% of transect hillslopes damaged by fresh mass movement. Farm conservation measures reduced damage on 34% of hillslopes where they were installed and maintained, but did not reduce damage where they were inadequately installed or maintained (66% of hillslopes). Mass movement was 22% less than it would have been in the absence of conservation planting. Stream bank plantings reduced bank erosion compared with untreated streams. Damage repair costs were 20% lower than they would have been in the absence of conservation planting, and could have been 63% less had measures been installed to an adequate standard wherever they were required.
DL Hicks 1992b	Waihora catchment, Gisborne; steep young siltstone and mudstone; post Cyclone Bola, storm rainfall of 300–600 mm; Whareama catchment, Wairarapa. Waipa, Waikato	Streambank.	In both areas, two-thirds of sites were planted but half of these were untreatable. In Waihora, 51% of banks eroded under grass compared with 2–3% under poplars and willows; erosion reduced by 50% where planting adequate and maintained, 40% of sites not planted, and 27% inadequately treated. In Whareama, number of bank failures/km lower under willows (3) and poplars (12) than grass (16); only 33% of banks adequately treated. In Waipa, % of bank eroded reduced from 23% under grass to <10% under willows and poplars); only 33% of banks adequately treated.
Pain 1986	3 sites near Mangaweka, Manawatū; steep young mudstone with some inter-bedded sandstone	Shallow landslides	Early attempt at assessing effectiveness of trees in reducing landsliding using digital image analysis. Most landslides occurred before the earliest imagery (1952). Limited effects of space-planted trees, but mostly due to experimental design – many landslides occurred under trees, but trees were preferentially planted in more susceptible (concave) sites, or only a short time since trees planted.
Phillips et al. 2008	Gisborne; steep Tertiary soft sedimentary	Earthflow, gully, slump	Successful treatment for both earthflows and gullies occurred with willows and poplars at final spacings of 4–6 m, though this was highly variable. Treatment unsuccessful where tree cover was sparse (because of losses) or where trees were planted wider than 10 m apart. Recommend initial plant spacings of 4 m for gully erosion control and 5–6 m for earthflows and 8 m + for landslides.

Reference	Location, terrain, storm history	Erosion type(s)	Key Findings
Pearce et al. 1987; Marden et al. 2008	Gisborne; steep Tertiary soft sedimentary	Earthflow	Successful treatment for earthflows …difference in movement rates between reforested and grassed earth flows represents an order of magnitude reduction in erosion rate by earth flows after reforestation, with interception loss by the forest canopy being the principal contributing factor. Surface displacement of the earth flow slowed within 4 years of planting.
Marden 2012; Marden et al. 2005	Gisborne; steep Tertiary soft sedimentary	Gullies	Gully area decrease after afforestation within one rotation. Time required to shut down gullies dependent on gully size and time since planting. Linear gullies stabilise more quickly than amphitheatre gullies.
Marden 2012; Bergin et al. 1993, 1995; Dymond et al. 2006	Gisborne; steep Tertiary soft sedimentary. Manawatū	Shallow landslides	*P. radiata* and kānuka forests – comparison of landslide densities. Forest age has a significant effect on the number of landslides initiated. Areas under indigenous forest and exotic plantations >8 years old were 16 times less susceptible than pasture and exotic pines <6 years old and 4 times less susceptible than regenerating scrub and exotic pines 6 to 8 years old to landsliding. Reverting kānuka and mānuka damage to 10-year-old stands was estimated to be 65% less than that sustained by pasture and 90% less in 20-year-old stand. Landsliding under forest was 90% less than that under pasture, and 80% less than that under scrub.

7.3 Landslide control using closed-canopy woody vegetation (forestry)

The effectiveness of closed-canopy vegetation (forest and scrub) on erosion has been reviewed by O'Loughlin (1995, 2005), Glade (2003), Basher, Botha, Dodd et al. (2008), Basher, Manderson et al. (2016), Basher, Moores et al. (2016), Marden (2004, 2012), Blaschke et al. (2008), and Phillips et al. (2012).

Several studies have found that landsliding was 70–90% lower, measured as landslide density (landslides per hectare) or volume ($m^3\ ha^{-1}$), under closed-canopy vegetation (indigenous forest, pines >8 years old, or scrub) than pasture (DL Hicks 1989b, 1990, 1991; Pain & Stephens 1990; Phillips et al. 1990; Marden et al. 1991; Marden & Rowan 1993; Bergin et al. 1993, 1995; Fransen & Brownlie 1995; Hancox & Wright 2005) (Tables 7 and 8). The amount of landsliding under young pine trees (<6–8 years old) was similar to that under pasture.

Marden et al. (1991) compared volumetric landslide rates in the Uawa catchment during Cyclone Bola for pasture and trees of different age to demonstrate how tree age affected the amount of landsliding. The rate of landsliding was 87% lower than pasture under pines >8 years old, and 40% lower for trees between 2 and 8 years old, while trees <1 year-old produced 24% more sediment than did pasture. In the Waipaoa catchment, Page et al. (1999) estimated areas of tall, woody vegetation produced 90% less sediment from landsliding than did pasture during Cyclone Bola, and land with soil conservation plantings produced a 22% reduction in sediment generation (based on DL Hicks 1992a).

Table 7. Landslide density (landslides per hectare) before and after Cyclone Bola (source: Marden & Rowan 1993)

	Landslide density		% reduction*	
Vegetation type	**Pre-Bola**	**Post-Bola**	**Pre-Bola**	**Post-Bola**
Pasture	0.139	0.564		
Indigenous forest	0.031	0.066	78	88
Pines >8 years	0.028	0.048	80	92
Pines 6–8 years	0.07	0.162	50	71
Pines <6 years	0.135	0.496	3	12
Regenerating scrub	0.029	0.12	79	79

* Compared with pasture

Table 8. Landslide density (landslides per hectare) and volume ($m^3\ ha^{-1}$) before and after Cyclone Bola (source: Phillips et al. 1990)

				% reduction		
Vegetation type	**Pre-Bola landslide density**	**Post-Bola landslide density**	**Post-Bola landslide volume**	**Pre-Bola landslide density**	**Post-Bola landslide density**	**Post-Bola landslide volume**
Pasture	0.23	0.68	916			
Pines >8 years	0.06	0.06	48	74	91	95
Pines 6–8 years	0.20	0.21	370	12	69	60
Pines <6 years	0.18	0.62	790	22	9	14

Fransen and Brownlie (1995) compared landslide density in adjacent catchments in northern Hawke's Bay hill country before and after afforestation of one of the catchments (Table 9). At three different times after afforestation in 1971/72 (1981, 1988, 1994) landslide density under pine trees was >80% lower than on pasture, and this difference increased as the trees grew. These differences were similar for two metrics (percentage landslide area, landslide density).

Table 9. Differences in landslide density (landslides km^{-2}) and area of landslides (percentage of total catchment area) in Pakuratahi and Tamingimingi catchments (source: Fransen & Brownlie 1995)

	Pakuratahi		Tamingimingi		% difference Tamingimingi/Pakuratahi	
	% landslides	Landslide density	% landslides	Landslide density	% landslides	Landslide density
1943	1.37	296	1.18	232	–16	–28
1970	0.07	16	0.16	45	56	64
1981*	0.01	2	0.06	17	83	88
1988	0.14	22	0.91	130	85	83
1994	0.02	7	0.34	75	94	91

*Pakuratahi was afforested in 1971/72

Hancox and Wright (2005) found on average the percentage area affected by landsliding from the 2004 Manawatū storm was 80% lower under forest than pasture, and 57% lower under poplars and willows (Table 10).

Table 10. Differences in percentage area affected by landslides under different vegetation cover in four study sites of the Manawatū–Wanganui region during the February 2004 storm (source: Hancox & Wright 2005)

	% area affected				% reduction		
Area	Pasture	Bush/scrub	Pine	Poplar/willow	Bush/scrub	Pine	Poplar/willow
Mangawhero	49.6	4.7	6.5	12.5	91	87	75
Whangaehu	42.5	6.6	9.2	30.3	85	78	29
Turakina	31	6.5	7.1	7.4	79	77	76
Pohangina	35.9	11.6	7.9	18.4	68	78	49
Average	39.8	7.5	7.7	17.2	81	81	57

Dymond et al. (2006) mapped landslide scars throughout the area affected by this storm, from satellite imagery, and showed that the effect of woody vegetation in reducing the probability of landsliding tended to increase as slope steepness increased – similar results were found in Taranaki by DeRose (1996) and DeRose et al. (1996). Although no average data were presented, Dymond et al. (2006) estimated from their measurements that forest generally reduced landsliding by 90% and scrub by 80%, with only minor differences in response to vegetation cover between different Tertiary-aged rock types (soft mudstone, consolidated and unconsolidated sandstone), but the extent of landsliding varied with rock type.

Hicks and Crippen (2004) compared mapping from the same satellite imagery with higher-resolution aerial photos and found the satellite imagery assessment slightly underestimated the amount of bare ground. They also compiled estimates of the percentage bare ground from mass movement for a range of vegetation types (Table 11). Damage (as percentage area of landsliding assessed from 20 randomly chosen sites) to forest (pines or indigenous) was c. 70% less than to pasture, c. 30–40% less where extensive trees were present, and little different where only scattered trees were present.

Table 11. Differences in percentage area affected by landslides under different vegetation cover in 20 randomly chosen sites of the Manawatū–Wanganui region during the February 2004 storm (source: Hicks & Crippen 2004)

Vegetation	Mass movement % area	% reduction
Pasture	4.9	
Pasture with scattered scrub	4.8	2
Pasture with scattered indigenous trees	3.4	31
Pasture with scattered exotic trees	4.9	0
Pasture with extensive scrub	5.1	–4
Pasture with extensive native trees	3.3	33
Pasture with extensive exotic trees	3	39
Conifers	1.6	67
Indigenous scrub	2.6	47
Indigenous forest	1.5	69

DL Hicks (1989a b, 1991) found the incidence of mass movement in Cyclone Bola (as percentage of hillslope eroded) was much less under plantation or indigenous forest compared with pasture or reverting scrub. The proportion of uneroded hillslopes increased from 6% under pasture to 16% under pine forest, 27% under scrub, and 33% under indigenous forest. These data were compiled as frequency distribution plots of landslide damage in classes (no mean values), making direct comparison with other studies difficult, but clearly illustrating the effect of vegetation in altering the frequency distribution (Figure 13). Similar results were observed in Taranaki hill country during Cyclone Hilda in 1990 (DL Hicks 1990).

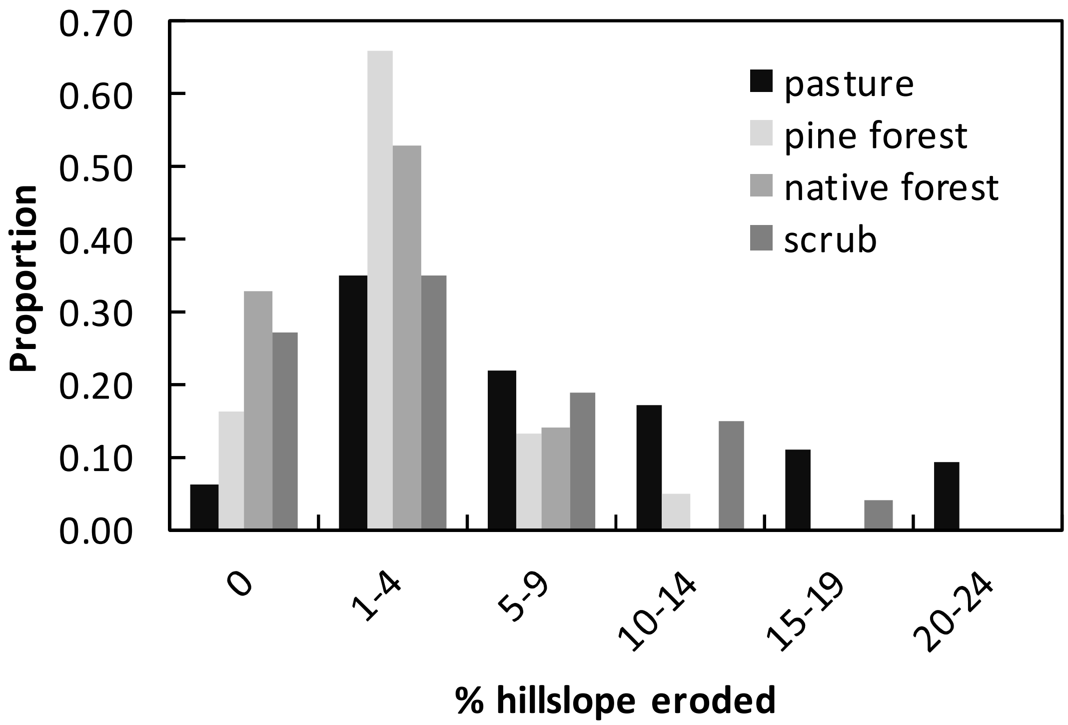

Figure 13. Frequency distribution of proportion of hillslope eroded under different vegetation types in Cyclone Bola. (source: DL Hicks 1989a, 1991)

Scrub reversion can also be effective in reducing landsliding. Bergin et al. (1993) reported that after Cyclone Bola areas of scrub had 74% less landsliding (measured as area affected by landslides) than pasture, and that the age and density of scrub affected the amount of landsliding: in 8-year-old scrub the amount of landsliding was reduced by 54% compared with pasture, in 16-year-old scrub by 91%, and in 30-year-old scrub there was little landsliding. Similarly, Bergin et al. (1995) found that landslide damage reduced by 65% in 10-year-old scrub and by 90% in 20-year-old scrub.

The effect of vegetation in reducing landsliding also appears to increase with storm rainfall and varies with the nature of the terrain (Omura & Hicks 1991. Landslide frequency and sediment generation from varying rainfalls under pasture and tall, woody vegetation (forest, scrub) in the Waipaoa catchment were calculated by Reid and Page (2002). Under pasture there was a 25-times increase (compared with under tall, woody vegetation) in areal landslide density for a 600 mm rainfall, and a 5-times increase for a 260 mm rainfall. They also presented data on long-term average rates of sediment generation from pasture and forest for six different land systems (combinations of rock type, landform and erosion processes). Tall, woody vegetation typically produced c. 70% less sediment than pasture, although in one land system it produced 91% less sediment; these differences resulted from both the type of land system and the variable frequency of landslide-generating storms in different land systems.

7.4 Earthflow and gully erosion

O'Loughlin and Zhang (1986) describe early work on the mechanisms by which trees influence earthflow movement rates and compare wet-winter movement rates under pasture (1.5–2 m month^{-1}) and pine trees (0.05 m month^{-1}). Using similar data, Pearce et al. (1987) summarise 4 years of data collection and suggest movement rates are an order of magnitude lower under pine trees (0.05 m month^{-1} and annual movement of 0.2–0.5 m) than pasture (0.5 m month^{-1} in winter and annual movement of 3–5 m). With a longer period of record (up to 6 years) the differences between grassed earthflows (c. 1 m month^{-1} and forested earthflows (0.005–0.001 m month^{-1}) were far larger (Phillips et al. 1990; Marden et al. 1992; Zhang et al. 1993).

From a single set of studies in the Gisborne area, Zhang et al. (1993) found that, over 4 years, surface movement rates on forested earthflows were two to three orders of magnitude lower than on grassed earthflows. However, subsequent monitoring showed recurrent displacements of forested (indigenous and exotic) earthflows can occur under a closed canopy forest with critical failure thresholds, leading to the initiation of movement determined by the duration of antecedent soil moisture surplus and elevated pore water pressure (Marden et al. 2008).

Thompson & Luckman (1993) comment on the performance of biological erosion control on earthflows (which included both space planting and afforestation), suggesting treatment was 'successful' at 63% of sites they assessed so long as trees were closely (<5–8 m) and extensively (>60% of earthflow surface) planted. Earthflow sites with shallow, untreated toe gullying were successful where tree spacing was 5–8 m or less, covering >60% of the earthflow area.

If the gully was treated, wider spacing (8–10 m) combined with planting 40% of the earthflow area was successful. Where gully depth at the toe of an earthflow was >2 m, an appropriate gully treatment combined with planting of >20% of the earthflow area at spacing up to 5–8 m was needed. If wider tree spacing was used (8–10 m) >60% of the earthflow area need to be planted. Reforestation was also successful in treating earthflows. The results suggested that the interaction between roots of neighbouring trees at close tree spacing was a major factor in conferring treatment success.

Phillips et al. (2008) adopted similar field-based criteria for assessment of effectiveness of space-planted trees in controlling earthflow, gully and landslide erosion at 30 sites within the East Coast Forestry project, with all treatments at least 12–15 years old. Evaluation of treatment success (classed as successful or unsuccessful) was based on current erosion activity, including the surrounding area (using an LUC-based assessment of erosion severity), tree survival, and tree condition to classify current land condition into five classes (very poor to very good). These data showed that successful treatment for both earthflows and gullies occurred with willows and poplars at final spacings of 4–6 m, though this was highly variable. Unsuccessful treatments were where remaining tree cover was sparse (because of losses) or where trees were planted wider than 10 m apart. They concluded that to obtain effective erosion control for active gullies, initial plant spacings needed to be at 4 × 4 m (625 stems ha^{-1}) or less, and for earthflows, spacings of 5–6 m (400–280 stems ha^{-1}) were recommended. Effective erosion control for shallow landslides could be achieved at wider spacings of 8 m or wider. They also provided a set of recommended erosion control treatments.

In the Gisborne–East Coast region in 1957, 95% of the total area of gullies was under pasture and <1% under indigenous forest (Marden et al. 2012). By 1997 the number of gullies had reduced (from 3,360 to 2,150) but the total area had increased (from 5,600 ha to 7,710 ha), and only 50% of the total gully area was under pasture. Reforestation had stabilised 2,367 ha of gullies but 1,720 ha of gullies (mostly formerly pasture) remained active under pine forest (22% of total gully area in 1997) (Table 12).

Table 12. Changes in the number and area of gullies in the Gisborne–East Coast region between 1957 and 1997 under different vegetation types (source: Marden et al. 2012)

	Number of gullies		Area of gullies			
			(ha)		%	
	1957	1997	1957	1997	1957	1997
Pasture	3,160	1,350	5,319	3,850	95	50
Indigenous forest	25	75	28	660	0.5	9
Shrubland	175	340	253	1,480	4.5	19
Exotic forest	0	385	0	1,720	0	22
Total	**3,360**	**2,150**	**5,600**	**7,710**		

In summary, the 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. Within this size range these relationships were stronger for linear than for amphitheatre-shaped gullies (Marden et al. 2005) and similar for gullies in both Cretaceous and Tertiary terrain (Marden et al. 2011). Thompson and Luckman (1993) also found that treatment of gully erosion was successful at only 42% of sites they examined, and it required very closely spaced trees to be highly effective. Where gullies were >5 m deep, space-planting was ineffective.

7.5 Streambank erosion and riparian management

DL Hicks (1992b) assessed vegetation performance for bank erosion in several regions and concluded tree planting can reduce bank erosion so long as appropriate species are used, a sufficient length of the stream is treated, and the plantings are maintained. Where plantings were adequate, channel damage was reduced substantially (by >50% in the Waihora), but 40–60% of the plantings were rated as inadequate.

Past investigations have shown that the exclusion of cattle from riparian zones within pastoral agricultural land uses will reduce sediment loss (Hughes & Quinn 2014), with reported levels of 30−90% (McKergow et al. 2007), 35% (Fernandez & Daigneault 2017), 40% (Monaghan & Quinn 2010), or 60% (Semadeni-Davies & Elliott 2012). Further, previous research indicates that the exclusion of all livestock will reduce sediment loss by

20−25% (McDowell et al. 2013), 24% (Semadeni-Davies & Elliott 2012), 35% (Fernandez & Daigneault 2017), 50% (Monaghan & Quinn 2010), 60% (Daigneault & Samarasinghe 2015), or 80% (Palmer et al. 2013).

Riparian planting on fenced streambanks can also help stabilise streambanks, with their root systems lifting mitigation performance by 10−20% (McKergow et al. 2007), 15% (Monaghan & Quinn 2010), or 15−25% (Sweeney & Newbold 2014).

Hughes (2016) concluded that in the studies reviewed, although riparian management appeared to have been mostly effective (in terms of an observable or inferred reduction in bank erosion or decreased suspended sediment concentration/yield), this had only been established semi-quantitatively at best. Hughes noted that in the one study where extensive riparian management (stock exclusion) had been carried out in headwater streams, there was no observable change in sediment yield over a 12-year period. He also noted that while the studies reviewed demonstrated the benefits of livestock removal, the effects of riparian planting were more equivocal and are only likely to be observable in the long term. For example, Smith (1992) found riparian afforestation with pine trees increased sediment yield (by a factor of 2). She attributed this increase to a lack of riparian ground cover in the afforested catchment allowing ready sediment availability.

Hughes (2016) also suggested that for riparian management to be effective, an understanding of bank erosion processes is needed (i.e. the relative role of mass failure, fluvial entrainment and preparatory processes such as wetting/drying and stock trampling). There is likely to be scale-dependence of these processes, with preparatory processes dominating in headwater streams, fluvial entrainment in mid-reaches, and mass failure in lower reaches of catchment. He suggests this can be used to identify the riparian intervention measures that may be most effective in different parts of a catchment. He illustrates this concept using the Williamson et al. (1992) study that found livestock grazing of the riparian areas had a greater effect on narrow (<2 m), low-order channels than on wider, higher-order channels where banks were higher and fluvial entrainment was a more important contributor to bank erosion.

International studies reviewed by Parkyn (2004) on the efficiency and management of riparian buffer zones in reducing sediment input to streams (including grass filter strips, native and introduced trees, grazing management) typically report trapping efficiencies exceeding 50% for sediment and sediment removal rates increasing non-linearly with buffer width. Grass filter strips (5–10 m width) are particularly effective at removing sediment from overland flow (Gharabaghi et al. 2002). Parkyn (2004) notes that the effectiveness of grass buffer strips as filters for sediment is less in steep, hilly terrain than in rolling land, as overland flow is concentrated in channelised natural drainage-ways, giving rise to high flow velocities, and buffers therefore need to be wider. She suggests that optimal widths for sediment removal can be highly variable but recommends a minimum of 10–20 m.

Basher (2016) reviewed erosion mitigation on cropland and found very little New Zealand data to predict the effect of slope (steepness and length), soil properties (texture, organic matter), or erosion mitigation on erosion rates from cropland. This review included an assessment of the international literature on grassed riparian buffer strips (also called vegetative filter strips). He concluded that they can be highly effective in reducing sediment delivery to streams by decreasing the velocity of runoff and allowing the particles to settle, and presented two graphs showing the relationship between sediment trapping efficiency and buffer width, which broadly indicated that buffers greater than 10 m provided 80% or more trapping efficiency.

7.6 Summary

There is a reasonable amount known about the various erosion processes and the general way in which ESC techniques are used to control them in New Zealand. However, details on how their effectiveness is assessed, and the quantitative data on performance that are produced are relatively scarce, particularly in relation to different soil types, regions and climatic variables such as triggering storm rainfalls.

Notwithstanding the lack of consistent methodology for assessing the mitigation performance of erosion and sediment control techniques and the paucity of quantitative data derived from New Zealand studies, the commonly used effectiveness values for the various mitigation treatments are listed in Table 13.

In general terms the effectiveness of various treatments can be summarised as follows.

- Different combinations of erosion process and extent require different erosion and sediment control treatments.
- There are feasible treatments for most erosion problems, but they sometimes require a combination of biological and structural erosion mitigation and their effectiveness can vary widely. Recommended erosion control treatments are based on type(s) of erosion, risk of erosion, current activity of erosion, size and depth of feature, and extent of treatment required.
- In urban environments, many studies have reported order of magnitude or greater reductions in sediment loads and concentrations. However, despite removal efficiencies in excess of 90%, turbidity and concentrations of suspended sediments in effluent discharged from construction sites can still be markedly higher than environmental guidelines and/or background concentrations in receiving aquatic environments. In particular, erosion and sediment control practices have generally been found to be less effective for the retention of fine soil particles, especially clays but also silts, than for coarse, sand-sized particles.
- In cropland, ripping of wheel tracks reduced erosion by 95% on strongly structured clay soils. At Pukekohe a cover crop trial produced a relatively small reduction in soil loss (26–38%).
- Riparian buffers or grassed buffers typically retain 40–100% of the sediment mass that enters them, but their effectiveness varies widely depending on many factors (width, type, sediment particle size slope gradient, etc). The first few metres of a buffer play a dominant role in sediment trapping.
- In pastoral farmland, maintaining a persistent, complete pasture sward reduces the prevalence and severity of surface erosion processes.
- Grazing management to maintain adequate cover and canopy height is important in minimising soil loss by surface erosion.

- A small number of quantitative studies have measured the effectiveness of individual trees or small groups of trees in pastoral farmland.
  - Published reductions in landsliding using space-planted trees from quantitative studies can range from 70 to 95%, but measured or assessed reductions are often far less than this because plantings are inadequate.
  - Individual trees influence the amount of landsliding within a radius of c. 10 m.
  - Poor survival of trees has been identified as a major constraint to performance of space-planted trees (due to poor pre-treatment of poles, poor planting technique, site factors and stock damage).
- 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.
  - Trees younger than about 8 years, before canopy closure, are less effective than older, closed-canopy trees.
  - Mature, closed-canopy, indigenous or exotic forest also typically reduces sediment yield by 50–90% compared to pasture catchments.
  - The period following plantation forest harvesting is when erosion and sediment yield rise, and levels tend to drop to pre-harvest levels within several years or when canopy closure is reached.
  - Roads and landings can contribute sediment generated by surface erosion, but compared to landslides the contribution to sediment yield is small, though during construction these have the potential to generate significantly more than when in operation.
  - Riparian buffers can contribute to reductions in sediment input to streams, but there is lack of certainty about the exact benefits and what size or setback is required to be effective, as there are no New Zealand studies that have quantified this.
  - There appear to have been no New Zealand studies that are forestry specific to test that the ESC design criteria in council guidelines are appropriate.
- Bank erosion can be an important source of sediment because it delivers sediment directly into stream channels. There has been very little quantitative research on rates of bank erosion or mitigation of bank erosion in New Zealand.
  - A combination of 'soft' biological erosion control and 'hard' engineering works is used to control bank erosion, along with stock exclusion.
  - Research suggests livestock removal from riparian areas improves bank stability, but the effects of riparian planting are more equivocal and are only likely to be observable in the long term.
  - Riparian buffer strips are commonly used to reduce sediment input from surface erosion to streams and have been shown to reduce sediment input by >50%.
- In summary, the 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%.

Table 13. Summary of erosion mitigation treatments used for different erosion processes and land uses, and the commonly used performance values (sources: Basher, Moores et al. 2016; Basher et al. 2019)

Erosion process	Mitigation treatment	Performance (% 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 is 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%.
	Continuous, dense, improved pastures	50–80	Pasture	Compared to unimproved pasture.
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), 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), effectiveness should be scaled in proportion to area treated. Also assumes trees not harvested: if harvested reduce effectiveness to 80%.

Erosion process	Mitigation treatment	Performance (% 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), 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), 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 suggest 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 setback.
	Riparian fencing + planting	50	Pasture	

8 Discussion

Past assessments of the effectiveness of ESC and soil conservation treatments have used both semi-quantitative and quantitative approaches. Effectiveness is essentially evaluated as the degree to which an ESC or soil conservation treatment reduces erosion compared to untreated areas, or how erosion status has changed because of the treatment. The performance of the ESC treatment is the measure of sediment reduction (reduction in landsliding, bare ground reduction, etc with spatial and temporal scales also defined), and it is usually expressed as a percentage reduction.

In general, knowledge of the effectiveness of ESC approaches and of erosion control planting and farm plan implementation remains relatively limited. This particularly applies to the quantitative assessment of performance across a range of soil and climate conditions, which means that modelling approaches that employ quantitative parameters are likely to be inaccurate (in absolute terms) and are only useful for scenario modelling or indicating broad 'directions of travel' when mitigation measures are implemented at the farm and catchment scales.

While quantitative assessment techniques are objective, they are often time consuming to implement and historically have been costly. Further, the time frames that some ESC treatments take to become effective usually limit the investment in monitoring them. However, advances in remote sensing, automatic mapping and object identification from remotely sensed images, and LiDAR could potentially increase the efficiency of these types of approaches.

ESC practices targeted at surface erosion can be highly effective at reducing the generation of sediment and its discharge from, for example, earthworks construction sites (often by an order of magnitude). While many of these practices are used in relation to urban development, they are increasingly being used in rural environments, such as in forestry.

Past quantitative approaches in the rural environment tended to focus on individual trees or small groups of trees (Hawley & Dymond 1988; Douglas et al. 2009, 2013; McIvor et al. 2015) and did not consider the wider context (DL Hicks 1989a) of either the hillslopes within which the trees were planted, including unplanted areas potentially vulnerable to future erosion, or the whole farm within which the sites were located. They are also typically focused on relatively small individual sites.

Previous semi-quantitative approaches focused on the whole site that had been treated, but generally provide fewer quantitative data. They rely on having clear standards for data collection and assessment and have a strong component of field-based assessment. While conservation planting effectiveness has been assessed in several studies at the hillslope and site scale, this has not been applied to whole-farm plans other than by modelling.

Studies that have monitored or made direct measurements of water quality (including suspended sediment) in catchments in which ESC practices have been implemented have shown the value of these type of studies for assessing ESC treatment effectiveness. While this approach works well at the scales of a few to tens of hectares, at larger scales many other factors can influence the signal that might be present in the data that can be attributed to ESC treatments. However, the limited number of such studies and their high cost of establishment, sampling and maintenance mean that while they are valuable for assessing ESC effectiveness, there are unlikely to be many such studies in the future.

While farm and catchment scale models provide a way forward (Douglas et al. 2008; Dymond et al. 2016; Basher et al. 2020), implementing a reliable approach requires good-quality data, both on the effectiveness and performance of the ESC and soil conservation methods implemented, and also on the type of erosion process treated, its size and degree of activity at the time of treatment, the areas treated, and the survival (if it is plant-based). Information on survival is also required to ensure the assumptions built into the modelling regarding performance of soil conservation treatments are valid.

Both space-planted and closed-canopy trees can be highly effective at reducing erosion at a hillslope scale, especially by shallow landsliding, but also for gullying and earthflows (e.g. Hicks 1989a; Zhang et al. 1993; Marden 2012; Marden et al. 2011, 2012). Closed-canopy woody vegetation reduces landsliding by up to 90%, with a reduced effect before canopy closure. Little information is available on trees' performance in controlling bank erosion.

Space planting may also achieve reductions of a similar magnitude, but its effectiveness is highly dependent on successful establishment of the trees and subsequent maintenance to ensure survival and effectiveness (i.e. adequacy of treatment is paramount). Hicks (1989a) demonstrated that only 34% of potentially unstable hillsides where farm conservation measures were installed actually worked, compared to 66% where measures failed for a variety of reasons, principally due to installation. Similarly, Thompson and Luckman (1993) found ESC treatment had been unsuccessful at 58% of gully erosion sites and 37% of earthflow sites, often because of poor installation and survival of trees.

However, the same magnitude of effects may not be evident at the whole-farm scale or on downstream sediment yield because of the influence of sediment delivery and scale effects at larger catchment sizes. The influence of soil conservation treatment on catchment sediment load will depend on the proportion of a catchment treated, connectivity between hillslope erosion and waterways, and how much sediment is derived from areas that are not treated. Even at the small catchment scale, the effect of soil conservation planting or vegetation change can be difficult to distinguish from other influences (such as large floods and bank erosion) on catchment sediment yield (e.g. McKergow et al. 2010; Hughes et al. 2012).

8.1 Time frames for ESC 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, largely because of the time frames (years to decades) and the cost to do this, and instead is derived from the observed performance of vegetation of different ages 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 values for 'time to maturity' for biologically based ESC practices (Table 14).

Table 14. Effectiveness of soil conservation works and the required time to reach maturity (source: Dymond et al. 2016)

Soil conservation work	Maturity (years)	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

Vegetative practices used to control surface erosion (e.g. cover crops, re-grassing) take less time than woody vegetation to become established but do require near-complete cover to be effective. However, many of the practices used for earthworks erosion management (e.g. silt fences, geotextiles, mulches, sediment retention ponds) are effective immediately if installed appropriately, though their effectiveness may change through time. For example, Basher, Moores et al. (2016) suggest that silt fence performance may reduce as the fabric clogs up, reducing its permeability.

Grass buffer strips require time to grow sufficiently tall and dense to remove sediment effectively, and the time scales for this are likely to be short (up to a year). Riparian fencing for stock exclusion is immediately effective, although it may take time for streambanks 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 with time.

8.2 Mitigation methods and relationship with sediment quality

Sediments link hillslopes to river channels (Sklar et al. 2017). If water clarity and/or turbidity are the attributes that are used to define and monitor freshwater river quality, and they in turn are dependent on finer sediment size fractions, understanding the size of sediments entering channels becomes important if they are going to be managed or mitigated. However, very little is known about what controls the size distribution of particles produced on hillslopes and how particle sizes evolve before sediments are supplied to channels (Sklar 2017). Indeed, understanding more about this is a central thread of the STEC programme.

In rural New Zealand there has been little attention paid to considerations of sediment quality (particle size, shape, composition, etc). Even within urban environments sediment and runoff mitigation methods are less focused on these attributes than gross control.

Most effort in the rural environment has been focused on understanding erosion rates, fluxes of sediment, and deposition rates in order to construct sediment budgets.

Little New Zealand 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 however 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 size 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 to streams.

Practices for controlling mass-movement erosion or gully erosion using trees (space-planted 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 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 an 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 in 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.

8.3 Recent policy developments relating to sediment management

The National Policy Statement for Freshwater Management (NPS-FM) was the Government's first step towards improving the way freshwater is managed in New Zealand. The NPS-FM guides and directs the development of freshwater management provisions in regional plans. The National Objectives Framework (NOF) is the key regulatory instrument to support regions to set freshwater objectives and limits and will include some national bottom lines and direction and guidance for how these are set. The NOF does not currently define attributes for suspended or deposited fine sediment, although draft attributes were proposed in September 2019 (MfE 2019b). Several ongoing workstreams are providing 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 DM Hicks et al. 2016).

Managing land to maintain or improve water quality will require a good understanding of the links between erosion mitigation and water quality, including the lag between changing vegetation cover or land management and its impact on water quality, and the effects of scale. Establishment monitoring approaches to provide data and understanding of links between hillslopes and channels, and between small and large catchments in a cost-effective manner, will require data collection across a range of scales, and a focus on both storm and intra-storm sediment loads.

As part of the on-going work, MfE have identified, observed and predicted exceedances of proposed bottom-line sediment thresholds and have tested the social, cultural, economic, and environmental implications of adding the proposed attributes to the NPS-FM (Depree et al. 2018 Franklin et al. 2019; DM Hicks et al. 2016, 2019; Neverman et al. 2019). This required 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 (Basher et al. 2019; Neverman et al. 2019). Once included in the NPS-FM, the setting in regional plans of objectives, limits and methods for sediment-related attributes will become compulsory.

8.4 Research gaps and data needs

In general terms there is a reasonable amount of information on ESC in New Zealand – what to do, how to do it, and where to do it – but the information on how effective the practices are still has a long way to go, both in terms of how to evaluate effectiveness (standardised approaches and methodologies) and in the provision of data that describes the performance of ESC practices for different situations in New Zealand.

Alongside the development of guidelines for ESC in the last decade (outlined in section 5.2), there has been substantial growth of a private sector ESC industry that undertakes much of the planning and implementation of ESC practices on development or construction sites, and which is also responsible for training contractors and other council staff on ESC methodology. The industry also carries out research and experimentation to improve ESC practices in New Zealand.

Basher, Moores et al. (2016) suggested several information gaps in ESC practices in New Zealand (Appendix 2) and grouped them into four broad categories depending on 'land use'. They concluded:

> *while there is abundant guidance for ESC techniques for different erosion processes and land uses in New Zealand, there remain significant information gaps in information on treatment performance.*
>
> *The gaps include data on treatment performance of individual ESC practices, information on ESC treatment performance across a range of event sizes,*

performance of ESC practices under the full range of soil and rainfall characteristics and land uses in New Zealand, and scale issues.

In the rural environment there is also an obvious gap between what is known in terms of the effectiveness of individual implemented works and what the overall effectiveness of these measures is at the farm scale and catchment scale. The extent to which space planting has been implemented across susceptible slopes on farms (right tree for the right place) is unknown. For example, councils often report the area for which farm plans have been prepared, and they sometimes report the area for which erosion control works have been implemented, but generally locating or defining where works are spatially is not done in any uniform way. This makes it more difficult to assess the likely impact that works might have on catchment sediment yield.

9 Conclusions

The objective of this report was to review the use of ESC methods in New Zealand and establish the biophysical performance of the commonly used ESC measures for controlling erosion and reducing sediment delivery to waterways. This required defining what is meant by effectiveness and performance (section 6.1). We defined effectiveness as the extent to which the soil conservation treatment or ESC practice achieves the desired outcome (e.g. the reduction in erosion compared to untreated areas and/or reduction in sediment load). Assessing effectiveness requires good information on the original erosion problem, the suitability of the treatment applied, the adequacy of the treatment, and the effect the treatment has on erosion. Consistent and repeatable methodologies are required to enable comparisons of ESC practice effectiveness. ESC performance, while related to effectiveness, is the actual measure of sediment reduction, and it is usually expressed as a percentage relative to a control situation.

The approach taken in this report was to:

- provide some historical background to erosion in New Zealand (section 3.1)
- briefly present the key erosion processes (section 3.2)
- outline the range of practices and treatments used to target the various erosion processes (often with reference to land use) (section 5) and list sources of guidance on their use (section 5.2 and Appendix 1)
- review how the effectiveness of each practice/treatment is assessed (section 6)
- review how performance is assessed (section 7) and then present the range of values of performance (section 7.6).

We also included in the discussion a number of related topics and where there are gaps in our understanding or in data (section 8).

New Zealand has a natural environment and history of land management that predisposes the country to soil erosion, and erosion rates are naturally high by world standards. However, compared to many other countries New Zealand has a relatively short history of soil conservation and the use of erosion and sediment control practices. Much of the focus on erosion control in the early days (mid- to late 20th century) focused on rural land and pastoral agriculture, as this land use was, and still is, a significant component of New Zealand's economy.

Biological erosion control using space-planted trees and/or afforestation were the main practices used in these rural environments to control the incidence of rainfall-triggered shallow landslides, gully erosion and earthflows. In recent decades, as urban expansion occurred at an increasing rate (particularly in and around New Zealand's largest city, Auckland), more attention became focused on controlling surface erosion related to earthworks and construction activities. This, in part, was driven by an increasing recognition that many coastal waters in and around Auckland had high rates of sedimentation. Many of the practices currently in common use today were trialled here, and the experience on how to use them gradually permeated throughout the rest of the country.

While there is abundant guidance about available ESC techniques for different erosion processes and land uses (section 5.2), most guidelines provide limited quantitative information on treatment performance, especially in terms of their specific design in relation to the large variation in both soils and rainfall across New Zealand.

A 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.

ESC practices used in New Zealand (and those used globally) are based on a set of principles for controlling different erosion processes.

- Runoff-generated erosion (surface erosion) is managed by runoff control to reduce water velocity and to separate clean water from dirty water; erosion control to reduce sediment generation; and sediment control to manage sediment movement offsite.
- Mass movement erosion is controlled by practices that influence slope hydrology and/or soil strength.
- Streambank erosion is controlled by practices that reduce hydraulic scour or increase bank strength and resistance to erosion.

ESC practices can be highly effective in reducing the generation of sediment, but effectiveness can vary widely and be dependent on many factors (e.g. space-planted trees reduce erosion, mainly by landsliding, by 30–95% in individual studies, but tree density, slope position, storm rainfall and other factors govern performance).

In general there has been little detailed study of the factors affecting variation in performance, but it is likely that several factors affect mitigation performance, including the 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.

ESC practices can be highly effective at reducing the generation of sediment by surface erosion and its discharge from earthworks construction sites (often by an order of magnitude). These have established both the performance of a range of ESC practices and the factors that determine performance. Particular attention has been directed at methods to retain clay size sediment using chemical treatment.

ESC practices to control water and wind erosion on cropland have been little studied in New Zealand. There has been a focus on assessing surface erosion and the importance of compacted areas (especially wheel tracks in row crops) generating runoff and sediment.

Research on erosion on pastoral farmland has focused on the performance of space-planted trees and afforestation in reducing landsliding, gully erosion, and earthflow movement. This has both established performance effectiveness and developed recommended treatment options for biological erosion control. There has been limited research on bank erosion control or the performance of riparian buffer strips.

Earthworks and clearfelled areas of plantation forests can generate large amounts of sediment by both surface erosion processes and mass movement. Both regional council and industry guidelines for ESC focus on earthworks using similar practices to those employed on other construction sites, but there are no forestry-specific New Zealand studies to establish the performance of these practices, or to determine the relative contribution of sediment from infrastructure (primarily by runoff-driven processes) and from the clear-cuts (primarily by mass movement processes). Recommended ESC practices are largely based on the experience of practitioners.

ESC practices that use trees or shrubs (afforestation, space planting, riparian or gully planting) take a long time to become fully effective (typically 10–15 years), those that use vegetation to control surface erosion (e.g. cover crops, re-grassing, vegetative buffer strips) take months to become effective, while many structural practices (silt fences, sediment ponds) 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 controlling 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. There remain key information gaps in relation to these aspects of performance.

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. In the absence of abundant and high-quality data on performance, modelling approaches are useful for scenario analyses and relative performance rather than for determining absolute values, which will have high levels of uncertainty associated with them.

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Appendix 1 – Erosion and sediment control practices by land use (after Basher et al. 2016b)

Table A1. Urban earthworks and infrastructure

Practice	Description of method	Design criteria variables	Reference
Erosion and sediment control plan	Not an ESC practice *per se*, but a framework within which to plan ESC management		Auckland Regional Council 1999
	Runoff control		
Check dams	Small dams constructed across a swale or channel to act as grade control structures and reduce velocity of runoff	Contributing catchment size, slope of catchment, spacing between dams, height of dam, ephemeral watercourses only, construction materials (rock rip-rap, filter socks, sandbags, other non-erodible material)	New Zealand Transport Agency 2014
Contour drains and cutoffs	Temporary excavated channels or ridges constructed slightly off the slope contour to reduce slope length and runoff velocity	Contributing catchment size, slope of catchment, spacing, bank height, channel depth, gradient, shape, stable outlet	New Zealand Transport Agency 2014
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	Location, flow capacity, shape, gradient, stable walls and floor, stable outlet	New Zealand Transport Agency 2014
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	Gradient, stable entry and exit, construction materials (geotextiles, pipes, rock, sandbags, etc.), pipe size, contributing catchment area, catchment slope	New Zealand Transport Agency 2014
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	Flow capacity, location (to allow flow to spread not concentrate), size (length, width, depth), stable inlet and outlet, grade of spreader is 0%, construction of spreader lip	Auckland Regional Council 1999
Hay bale barriers	Temporary barriers of hay bales used to intercept and direct surface runoff from small areas	Location, size and slope of contributing catchment	Auckland Regional Council 1999
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	Design flow, shape, slope, drain armour, spacing of check dams, size and spacing of culverts, stable outfall	Environment Waikato 2009

Practice	Description of method	Design criteria variables	Reference
	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.	Location, size, shape, construction materials, depth and size of aggregate	New Zealand Transport Agency 2014
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	Divert run-off from above, soil type and texture, rainfall intensity, machinery type, degree of compaction	New Zealand Transport Agency 2014
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	Slope length, slope steepness, spacing of benches, bench design (width, slope, flow length, diversion channel design), stable outlets, slope face management (grassing, filter socks, etc), diversion of run-off from above	New Zealand Transport Agency 2014
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	Site preparation (installation of other ESC practices), seedbed preparation, fertiliser requirements, seed application (mixture, rate, application method, irrigation), timing	New Zealand Transport Agency 2014
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	Location, site slope, soil conditions, seed mixture and amendments/binders, fertiliser requirements	New Zealand Transport Agency 2014
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 re-grassing and may need crimping or binders	Location, site slope, type of mulch, rate of mulch application, site conditions (e.g. windiness)	New Zealand Transport Agency 2014
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	Surface preparation, site conditions (e.g. temperature, gravel content, compaction), need for irrigation, turf application	New Zealand Transport Agency 2014

Practice	Description of method	Design criteria variables	Reference
	Erosion control (cont.)		
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 fibre 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	Type of material and product specifications, method of anchoring on slope, location of installation, site preparation	New Zealand Transport Agency 2014
Soil binders and chemical treatment	Organic or chemical soil-stabilising agents that penetrate the soil and bind particles together to form a protective crust, which reduces windblown dust generation and raindrop impact	Type of binder, application rate and method, divert run-off from above, avoid trafficking, soil conditions	Environment Canterbury 2007
	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	Location, size and slope of contributing catchment, soil conditions, size and shape of pond (volume, length, width, depth, volume of dead and live storage, forebay size), decanting device (type, design and position), inlet and outlet design (including level spreader and emergency spillway), baffle location and type, chemical treatment (type, dose rate), emergency spillway	New Zealand Transport Agency 2014
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	Similar to above	New Zealand Transport Agency 2014
Silt fences	Temporary barrier of woven geotextile fabric used to capture sediments carried in sheet flow	Type of fabric, location, contributing catchment size, slope steepness and length, spacing of returns, maximum, length, height, support type and spacing, soil type and texture	New Zealand Transport Agency 2014

Practice	Description of method	Design criteria variables	Reference
	Sediment control (cont.)		
Super silt fences	Temporary barrier of woven geotextile fabric over a chain link fence used to capture predominantly coarse sediments carried in sheet flow	Type of fabric, location, contributing catchment size, slope steepness and length, spacing of returns, maximum length, height, support type and spacing, soil type and texture	New Zealand Transport Agency 2014
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	Filter material, size of sock, slope steepness and length, spacing of returns, location, support type and spacing	New Zealand Transport Agency 2014
Flocculation including FlocSocks	Added to sediment retention pond inflows via a rainfall-activated system to accelerate coagulation and settlement of fine colloidal particles	Flocculant type and dose rate, dosing system, location of dosing point	New Zealand Transport Agency 2014
Dewatering	Removal of water from excavations, trenches and sediment control devices by pumping	Volume of water and the levels of sediment, disposal of water	New Zealand Transport Agency 2014
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)	Type of barrier, runoff management to and away from device	New Zealand Transport Agency 2014
Sediment sump	Temporary pit constructed to trap and filter water before it is pumped to a suitable discharge area	Location, number, size/volume, fill type, stable discharge area	Auckland Regional Council 1999
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	Location, contributing catchment area and slope, slope, width, spacing of stable returns	Environment Canterbury 2007
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	Fill type and size, groundwater levels, permeability, inlet protection, design of forebays	Environment Canterbury 2007
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	Stream width, velocity, water depth, fabric type, flotation and weighting devices, length and height of curtain	Environment Canterbury 2007

Practice	Description of method	Design criteria variables	Reference
		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	Location, timing of construction, fish migration, loading, design storm flow, culvert size, inlet and outlet protection	New Zealand Transport Agency 2014
Permanent watercourse crossings	Bridge, culvert or ford installed across a watercourse where permanent access is required across a small watercourse	Location, design storm flow, loading, culvert size, inlet and outlet protection	Environment Waikato 2009
Dam (with pumping or diverting)	Temporary practices used to convey surface water from above a construction activity to downstream of that activity	Dam materials, design flow, pump size and installation, stable outlet	New Zealand Transport Agency 2014
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 discharges it back into the channel below the works to avoid scour of the channel bed and banks	Location, design flow, diversion channel design, diversion dam design	New Zealand Transport Agency 2014
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	Many and varied	New Zealand Transport Agency 2014
Rock outlet protection	Rock (rip-rap or gabion baskets) placed at the outfall of channels or culverts	Location, slope, rock size, base protection	Environment Waikato 2009

Table A2. Forestry

Practice	Description of method	Design criteria variables	Reference
Harvest plan	Not an ESC practice *per se*, but outlines the requirements for erosion and sediment control		Bryant et al. 2007
	Runoff control		
Diversion channels and bunds	Permanent non-erodible channels and/or bunds to convey clean runoff to stable outlet	Location, flow capacity, shape, gradient, stable walls and floor, stable outlet	Bryant et al. 2007
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	Contributing catchment size, slope of catchment, spacing, bank height, channel depth, gradient, shape, stable outlet	Bryant et al. 2007
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	Contributing catchment size, road/track slope, spacing, surface protection	Bryant et al. 2007
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	Road gradient, spacing, slope	Bryant et al. 2007
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	Catchment area, design flow, construction material	Bryant et al. 2007
Check dams	Small dams constructed across a swale or channel to act as grade control structures and reduce velocity of runoff	Contributing catchment size, slope, spacing between dams, height of dam, ephemeral watercourses only, construction materials (rock rip-rap, filter socks, sandbags, other non-erodible material), channel protection	Bryant et al. 2007
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	Design flow, shape, slope, drain armour, spacing of check dams within drain, size and spacing of culverts, stable outfall	Williams & Spencer 2013

Practice	Description of method	Design criteria variables	Reference
		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	Contributing catchment size, soil type and texture, rainfall intensity, machinery type, degree of compaction	Bryant et al. 2007
Log corduroying	Placement of logs to provide a solid working platform, usually in wet processing areas or on access roads to minimise sediment generation	Location, log placement	Bryant et al. 2007
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	Location, depth	Bryant et al. 2007
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.	Location, timing, catchment area, site slope, soil conditions, seed mixture, application rate, fertiliser requirements	Bryant et al. 2007
Rock lining of channels	Protection of bare drains and roadside water tables in erosion-prone soils against erosion	Catchment area, drain gradient, shape, construction materials, design flow	Bryant et al. 2007
Geotextiles	Fabrics used to protect soil surfaces against raindrop impact and sheet/rill erosion, particularly in spillways and diversion channels	Location, fabric type, method of anchoring on slope, site preparation	Bryant et al. 2007
Benched slopes	Benches constructed on the outside of roads/tracks to place stable fill	Location, size, slope	Williams & Spencer 2013
Slash management	Placement of slash to avoid mobilisation in water bodies and off landings	Storm frequency-magnitude, topography, soils, catchment size, proximity of trees to watercourses, watercourse values, benching, storage space, water control, slash placement	Northland Regional Council 2012
		Sediment control	
Haybale barriers	Temporary sediment retention devices to intercept and divert runoff for very small catchments	Catchment area, location, spacing, anchoring to slope	Bryant et al. 2007
Earth bund	Ridge of compacted earth (preferably compacted subsoil) built on the contour to detain runoff and trap sediment	Catchment area, soil materials, height, length, stable outlet	Bryant et al. 2007
Slash bund	Temporary bunds of slash for very small catchments to trap the initial 'pulse' of coarse sediment	Catchment area, location, shape, size, amount of slash	Bryant et al. 2007

Practice	Description of method	Design criteria variables	Reference
	Sediment control (cont.)		
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	Catchment area, length, height, batter slope, area, compaction	Bryant et al. 2007
Silt fence	Temporary barrier of woven geotextile fabric used to capture sediment carried in sheet flow from small areas	Catchment area, slope steepness, location, slope length, spacing, anchoring to slope, fabric type	Bryant et al. 2007
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	Catchment area, location, type of fabric, contributing catchment size, height, spacing, support type and spacing	Bryant et al. 2007
Silt trap	Temporary small sediment retention pond system	Catchment area, location, size, stable inlet and outlet	Bryant et al. 2007
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	Location, size and slope of contributing catchment, soil conditions, size and shape of pond (volume, length, width, depth, volume of dead and live storage, forebay size), decanting device (type, design and position), inlet and outlet design (including level spreader and emergency spillway), baffle location and type, chemical treatment (type, dose rate)	Bryant et al. 2007
Sediment trap/soak hole/sump	Constructed hole in porous soils used to control runoff from roads/tracks and trap sediment	Location, spacing, size/volume, soil conditions, stable inlet, use of silt fence	Environment Bay of Plenty 2012
	Streamworks		
Harvesting operations	Planning of harvesting operations to minimise impacts on stream channels	Fell trees away from streams if possible, remove slash from streams, don't haul through streams, stabilise margins post-harvest	Bryant et al. 2007
Dry stream crossings	Temporary crossings of ephemeral channels protected by log corduroying	Location, catchment area	Bryant et al. 2007
Permanent watercourse crossings	Bridge, culvert or ford installed across a watercourse where permanent access is required across a small watercourse	Location, catchment area, design storm flow, culvert size, inlet and outlet protection, road runoff diversion, stabilised approach	Bryant et al. 2007

Practice	Description of method	Design criteria variables	Reference
		Streamworks (cont.)	
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	Dam materials, design flow, pump size and installation, stable outlet	Bryant et al. 2007
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	Location, design flow, diversion channel design, diversion dam design	Bryant et al. 2007

Table A3. Horticulture and arable cropping

Practice	Description of method	Design criteria variables	Reference
Erosion management plan	Not an ESC practice *per se*, but a framework within which to plan ESC management		Barber 2014
	Water erosion		
	Runoff control		
Interception drains	Drains to intercept and control runoff from above. If gradient steep then requires check dams	Catchment area and slope, design flow, gradient, soil materials	Barber 2014
Culverts	In drains to pass paddock entranceways	Catchment area, design flow, culvert size	Barber 2014
Benched headlands	Used to direct runoff to paddock edge or drain (stable outlet). May be grassed to trap sediment	Paddock size, slope length, runoff volume, soil materials	Barber 2014
Diversion bund	Earth bund used to divert runoff away from vulnerable paddock or to prevent water discharging directly from a paddock	Location, flow capacity, shape, gradient, stable walls and floor, stable outlet, connection to other ESC measures	Barber 2014
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	Contributing catchment size, slope of catchment, spacing, slope of drain, length, soil materials, depth	Barber 2014
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	Catchment area, swale width, slope length, design flow, gradient, soil materials	Barber 2014
Stabilised (raised) access ways and discharge points	Metalled access point used to control runoff and direct to a stable outlet or other ESC measure	Location, connection to other ESC measures, culvert size	Barber 2014
	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	Type of crop, rate of growth	Barber 2014
Wheel-track ripping	Shallow cultivation of compacted wheel tracks in row crops to increase infiltration and reduce erosion	Slope length, soil materials, type of implement	Barber 2014
Wheel-track diking	Use of an implement to create a series of closely spaced soil dams in compacted wheel tracks	Slope length, soil materials, type of implement	Barber 2014

Practice	Description of method	Design criteria variables	Reference
		Erosion control (cont.)	
Paddock length	Used to break up long paddocks, control runoff and erosion	Slope length, soil materials	Barber 2014
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	Type of implements, number of cultivation passes, surface roughness, moisture content, cultivation direction, slope	DL Hicks & Anthony 2001
Strip cropping	Strips of permanent vegetation retained between crops to break up slope length and reduce water and wind erosion	Spacing, width, vegetation type	DL Hicks & Anthony 2001
		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	Contributing catchment area, width, species composition	Barber 2014
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	Contributing catchment area, slope, spacing, fabric type	Barber 2014
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	Contributing catchment area, location, design flow, volume of dead and live storage, decant type and rate, emergency spillway	Barber 2014
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	Location, size and slope of contributing catchment, soil conditions, size and shape of pond (volume, length, width, depth, volume of dead and live storage, forebay size), decanting device (type, design and position), baffle location and type, stable outlet	Barber 2014
		Wind erosion	
Cultivation management	Used to manage soil structure, organic matter, surface roughness, reduce soil erodibility and erosion. Includes minimum tillage, no-tillage and stubble retention	Type of implements, number of cultivation passes, surface roughness, aggregate size, moisture content, cultivation direction, time soil is bare, field width, soil materials	Ross et al. 2000
Windbreaks	Used to reduce windspeed at ground level and wind erosion	Width of shelterbelt, tree species	Ross et al. 2000
Strip cropping	Strips of permanent vegetation retained between crops to break up paddock length and reduce wind erosion	Spacing, width, vegetation type	DL Hicks & Anthony 2001

Table A4. List of erosion and sediment control practices used for pastoral farming

Practice	Description of method	Design criteria variables	Reference
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	Stocking level, stock type, timing and duration of grazing, species composition, fertiliser management, fencing	DL Hicks & Anthony 2001
Contour furrows	Furrow constructed with slight gradient to break up slope to control runoff	Slope, spacing, contributing area, soil type	DL Hicks & Anthony 2001
	Mass movement (shallow landslides, slumps, earthflows)		
Spaced planting	Planting of spaced poles to reduce soil water content, increase soil strength and reduce erosion	Location of planting, tree species, spacing, extent of planting, pole protection, stock management	DL Hicks & Anthony 2001
Afforestation	Blanket planting of closely spaced trees to reduce soil water content, increase soil strength and reduce erosion	Location of planting, extent of planting, spacing, tree species	DL Hicks & Anthony 2001
Reversion	Removing stock and fencing in erosion-prone areas to encourage reversion to woody vegetation to reduce erosion	Location, seed source, species composition, rate of reversion	DL Hicks 1995
Surface drainage	Use of surface ditches, cutoff drains and graded banks to reduce infiltration and dewater ponding areas on slumps and earthflows	Location, depth, stable outlet	DL Hicks & Anthony 2001
Sub-surface drainage	Horizontal boring to reduce subsurface water content of earthflows and slumps	Location, depth below surface, number of drains, capacity of drains,	DL Hicks & Anthony 2001
Surface recontouring	Smoothing the land surface to enhance runoff, reduce ponding and soil water content	Location, topography, soil materials	DL Hicks & Anthony 2001

Practice	Description of method	Design criteria variables	Reference
		Gully erosion	
Spaced planting	Planting of spaced poles to stabilise the sides and floors of gullies.	Tree species, spacing, extent of planting, pole protection	DL Hicks & Anthony 2001
Afforestation	Blanket planting of closely spaced trees to reduce soil water content, increase soil strength and reduce erosion	Planting pattern, tree spacing, species, location (extent) of planting, timing of planting of different parts of gullies	DL Hicks & Anthony 2001
Graded banks	Series of earth banks formed on long slopes to control surface runoff and divert to a stable outlet	Location, gradient, spacing, stable outlet	DL Hicks & Anthony 2001
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	Location, flow capacity, construction material and design	DL Hicks & Anthony 2001
Pipe drop structures	Pipes used to discharge water across from gully heads or sidewalls to the gully floor. Often used where flow is small	Location, flow capacity, construction material and design	DL Hicks & Anthony 2001
Sink holes	Constructed hole in porous soils used to control runoff and trap sediment. Typically used in highly porous volcanic soils	Location, spacing, size/volume, soil conditions, stable inlet, use of silt fence	Eyles 1993
Diversion banks	Earth bank used to divert runoff away from gully head to stable outlet	Catchment area and slope, design flow, gradient, soil materials	DL Hicks & Anthony 2001
Grassed waterway	Grassed waterway used to divert runoff away from gully head to stable outlet	Catchment area and slope, design flow, gradient, soil materials, shape, vegetation type	DL Hicks & Anthony 2001
Drop structures	Spillway constructed of concrete, geotextiles, rock, sheet piling used to safely convey runoff over gully head	Location, catchment area and slope, design flow, gradient, construction material	DL Hicks & Anthony 2001
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	Location, catchment area and slope, gully activity, gradient, construction material, anchoring, height	DL Hicks & Anthony 2001

Practice	Description of method	Design criteria variables	Reference
	Streambank erosion		
Tree planting	Planting of spaced poles or native vegetation to stabilise streambanks. Can include tying together of the vegetation to enhance survival	Location, tree species, spacing, extent of planting, pole protection, fencing	DL Hicks & Anthony 2001
Vegetation lopping and layering	Felling of existing vegetation and layering to stabilise stream banks	Location, extent, density, anchoring	Gibbs 2007
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	Structure type, location, extent, shape	Gibbs 2007
Debris traps	Low dams on the bed of small streams, constructed from netting and posts, to stabilise channels, reduce bank erosion and trap sediment	Location, spacing, height, construction materials	Gibbs 2007
Gravel extraction	Removal of gravel to take pressure off the outside of bends and reduce bank erosion	Amount of gravel removed	Gibbs 2007
Bank shaping	Battering of streambanks to reduce potential for bank erosion	Location, height of bank, shape of bank	Gibbs 2007
Channel diversion/realignment	Realignment of channel away from actively eroding banks to reduce bank erosion	Location, disturbance, construction method	Gibbs 2007
Riparian fencing	Permanent fencing of streambanks to exclude grazing and reduce damage to streambanks by stock	Width of setback, riparian vegetation, type of fence	DL Hicks 1995
Controlled grazing	Temporary fencing of streambanks to allow infrequent grazing and reduce damage to streambanks by stock	Width of setback, riparian vegetation, frequency of grazing, type of stock	DL Hicks 1995

Appendix 2 – ESC information gaps by land use identified by Basher, Moores et al. (2016)

1 Research gaps for improved ESC on urban earthworks and infrastructure project sites were identified in the following areas:

- Processes for introducing new ESC practices or products and standardised testing protocols. Currently there is no agreed process for testing and introduction of new products or practices in New Zealand. A standard protocol needs to be developed to address key design, manufacture, installation, and maintenance specifications to provide confidence for the construction industry and councils that any new practices introduced will achieve the desired water quality outcomes.
- Performance of ESC practices during high-magnitude, low-frequency events. Research is required to quantify the relationship between event size and ESC performance since these high-magnitude, low-frequency events may contribute most of the annual sediment load, and it is during these events that ESC practices are most likely to perform poorly. This would provide a basis for improvements to ESC performance during these events.
- Regional performance of ESC practices under different soil and rainfall characteristics. New Zealand research into the performance of ESC practices on urban earthworks sites is dominated by Auckland-based studies and research is needed on ESC performance under different soil and rainfall conditions to ensure there is not systematic under- or over-estimation of ESC performance and design in other parts of NZ.
- Receiving environment effects of chemical treatment. Research is needed to investigate whether concentrations of aluminium in receiving waterbodies exceed toxicity guidelines, including both the water column and in bed sediments.
- Local research into the use, chemical makeup, and residual effects of different chemical flocculants currently being used on construction sites throughout New Zealand should be undertaken to ensure their suitability for use.
- Local research into the types, application rates, effectiveness, and receiving environment effects of polymers used for dust control and soil stabilisation.

2 Research gaps for improved ESC for forestry include:

- Testing the performance of forestry ESC methods in regional council guidelines. Having been largely been derived from ESC guidelines for urban earthworks, these methods need to be tested in a forestry context as they may lead to the systematic under- or over-estimation of ESC performance and under- or over-design of ESC practices for forestry. There is also a need for better understanding of the relative sediment contribution from infrastructure and clear-cuts to sediment generation and delivery to streams to guide where best to target ESC practices.
- Significance and management of debris flows. There is an urgent need to identify the areas at risk from debris flows and to develop terrain hazard zoning, risk management and debris flow mitigation approaches suitable for use at operational forestry scales.

- Impact of tethered harvesters on soil disturbance and slash generation. There is a need for research to characterise soil disturbance by this recently developed harvesting technique and its effects on sediment and slash generation and delivery to streams.
- Management of slash and wood on clear-cuts and in streams. Better understanding is needed of the risks and benefits of slash to improve recommendations for slash management.
- Performance of riparian strips and information on design width. A need remains for research into the effectiveness of riparian buffers in reducing sediment delivery to streams, what width of buffer is needed, and how buffer width should vary with environmental conditions (e.g. slope steepness, valley floor landforms) and erosion processes, and what type of vegetation is most effective.

3 Research gaps for improved ESC for horticulture and arable cropping include:

- Identifying where erosion and sediment control practices are needed. Lack of knowledge of erosion rates on cropland makes it difficult both to identify objectively where ESC practices are needed and to provide background data against which the performance of ESC practices can be compared.
- Performance of ESC practices. A very limited amount of research has quantitatively characterised the performance of ESC practices on cropland and there remains a need for trial work to establish the performance efficiencies of ESC practices including wheel track ripping and diking, riparian buffer strips, the effects of cultivation practices on runoff and erosion, and sediment retention pond (SRP) design and performance. There is a need to assess the performance of ESC practices across a range of storm event sizes and soil characteristics.

4 Research gaps for improved ESC for pastoral farming include:

- Translating small-scale ESC results to farms and catchment scale. Most research on erosion mitigation by tree planting (especially spaced-tree planting) is carried out at the scale of individual trees to small groups of trees and there is a need for better information on erosion mitigation at a range of spatial scales to underpin understanding of the impacts of erosion and erosion mitigation on downstream freshwater values, and to be able report on erosion trends
- Significance of bank erosion. Research on the magnitude of bank erosion, scale dependence of bank erosion processes, and timescales for response to bank erosion mitigation are all needed to improve design and management of riparian buffers to control sediment input to streams
- Grazing management to reduce surface runoff and sediment. There is still a need for better information on both diffuse and point sources of sediment for sheep, beef, dairying, and deer farming, and on the role grazing management can play in reducing sediment generation and delivery, and how this varies with soil, climate and topography.