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Sediment reduction and mitigation principles – a review of New Zealand literature

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Sediment reduction and mitigation principles – a review of New Zealand literature

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Sediment reduction and mitigation principles – a review of New Zealand literature

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Summary

Project and client

- Waikato Regional Council (WRC) is producing a strategic document on erosion from farmland and other sources in the Waikato region.
- WRC contracted Manaaki Whenua – Landcare Research to undertake a literature review to provide information on erosion and sediment, and its control.
- This information will help WRC explain the impact of erosion and sedimentation on communities, and the consequent loss of natural capital and ecosystem services. It will also help to communicate the sediment story for different farming systems and civil defence issues.

Objectives

- The objective of this report was to conduct a general review of the New Zealand literature on erosion and sediment reduction, with a focus on literature relevant to the Waikato region.

Methods

- A literature search of New Zealand-based studies on erosion and reduction through mitigation was conducted.
- Studies relevant to the Waikato region were a particular focus. In the absence of such information, inferences from studies outside the region were applied to the local context.
- A review of modelling studies was out of scope.

Summary of key findings

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/or other land management practices (e.g. grazing intensity). Their effectiveness can vary widely.

Recommended erosion control treatments are based on type(s) of erosion, risk of erosion, current activity of erosion, land management, size and depth of feature, and extent of treatment required.

Erosion and sediment reduction by agricultural land use

- 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 for minimising soil loss by surface erosion.
- Detainment bunds and similar structures generally work well for reducing sediment loss, but it is important to optimise the design and allow adequate settling time, and such structures may be less effective in high-flow events.

- Surface soil erosion caused by intensive winter grazing of forage crops is typically much greater than for other land uses, such as pasture, and is associated with the extent of bare ground. A recently studied mitigation in grazed winter forage crops, 'strategic grazing', can greatly reduce sediment losses.
- Careful management of critical source areas is important to reduce sediment losses.

Erosion reduction for landsliding using space-planted trees and plantations

- Reductions in landsliding using space-planted trees can range from 70 to 95%, but measured or assessed reductions are often far less than this because plantings are inadequate. Poor survival of trees has been identified as a major constraint to the 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.

Streambank erosion and riparian buffers

- Bank erosion can be an important source of sediment because it delivers the sediment directly into stream channels. There has been very little quantitative research on rates of bank erosion or its mitigation in New Zealand.
- 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 (i.e. furthest from the stream) play a dominant role in sediment trapping.
- Riparian buffer strips are commonly used to reduce sediment input from surface erosion to streams and have been shown to reduce sediment input by more than 50%. Removing livestock from riparian areas improves bank stability, but the effects of riparian planting are likely to be more observable in the long term, unless riparian vegetation is well established.

Summary of effectiveness of erosion and sediment control (ESC) practices

In summary, the commonly used values for erosion and sediment reduction as a result of ESC practices are as follows:

- 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%.

1 Introduction

Waikato Regional Council (WRC) is producing a strategic document on erosion from farmland and other sources in the Waikato region. Sediment (the product of erosion) is a risk to freshwater, as defined in the National Policy Statement for Freshwater Management 2020.

WRC's strategic document will have two distinct sections.

- Section 1, produced by WRC, will contain general information, such as the impact of sedimentation on communities, the loss of natural capital and ecosystem services, communication of the sediment story for different farming systems, and civil defence issues.
- Section 2, produced by Manaaki Whenua – Landcare Research, will contain a literature review (i.e. this report).

2 Objectives

The objective of this report was to conduct a general review of the New Zealand literature on erosion and sediment reduction, with a focus, where appropriate studies exist, on literature relevant to the Waikato region.

3 Methods

A search was conducted of New Zealand-based studies from the published scientific literature (peer-reviewed) and grey literature (e.g. reports) on erosion and sediment reduction through mitigation. Literature and studies relevant to the Waikato region were a particular focus. In the absence of such information, inferences from studies outside the region were made to the local context.

Out of scope was a review of modelling studies, except for an overview to provide context for the objectives of a current/parallel study of catchment erosion modelling in the Waikato region by MWLR.

4 Context overview

4.1 History of erosion, and erosion and sediment control (ESC), in New Zealand

A natural environment and recent history of land management predispose New Zealand to soil erosion and erosion rates that are very high by world standards (Basher 2013). Erosion processes are naturally active as a result of steep slopes, weak rocks, high rainfall, and frequent high-intensity rainstorms (e.g. McSaveney 1978; Soons & Selby 1992; Hicks et al. 2011; Basher 2013). Deforestation of much of the country has been relatively recent (in the last 150 years) and extensive, and the introduction of large numbers of grazing animals and intensive land use in some areas have 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 natural processes driven largely by climate and geology, and these have been accelerated by human activities. Typically, most of a river's suspended sediment load is derived from relatively small parts of the river's catchment. These locations are often referred to as 'critical source areas' (CSAs), which usually have spatially distinct zones of generation and transport that vary greatly according to geology (rock type and composition), degree of deformation, uplift rates, land cover, and land use. In New Zealand, a CSA commonly refers to areas at sub-paddock scale where most diffuse pollution will originate. Contemporary sediment loads should be evaluated in relation to natural or background levels to ensure that any targets set for reducing sediment loads are realistic.

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).

Erosion control is a key ecosystem service in New Zealand because of its widespread occurrence in many different forms (Basher 2013). 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 general terms, information on and knowledge about erosion control are reasonable, but New Zealand currently lacks the quantitative data to ensure erosion control is targeted and cost-effective.

In the last two decades a number of reviews have highlighted the state of knowledge of erosion processes and their mitigation, including:

- biological erosion control (Phillips et al. 2000, 2008; Basher, Manderson et al. 2016; Basher, Moores et al. 2016; Douglas et al. 2008; Mackay et al. 2012; McDowell et al. 2013; Phillips et al. 2020)
- 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 et al. 2008)
- methods to manage sediment and their economic assessment (Dorner et al. 2018).

Although a wide range of methods are used for erosion control in New Zealand, biological methods are by far the most common (Basher 2013). Many 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 an 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). Pastoral farming is less affected by space-planted trees than by afforestation, allowing continued grazing but still affording a level of erosion control, particularly against rainfall-triggered shallow landslides. There is a long history of planting trees to control erosion and using farm plans with a soil conservation focus.

With increasing urbanisation and population growth, development associated with urban and roading development has 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 ESC 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, because of changes in government policy many of these forests have become production forests. Many have been or are currently being harvested (second rotations), and the erosion problems that were evident under pasture or reverting scrublands are reoccurring, particularly in the period following harvesting and before the new trees are fully established (Marden 2004; Phillips et al. 2012). Some areas of the Waikato region experience similar issues, particularly on steep hill country, such as in the western and northwest parts of the region, and in parts of Coromandel.

4.2 Current state: policies and regulatory drivers

Sediment is the product of erosion and is produced from different erosion processes (see section 5). Sediment accumulation on the beds of streams and rivers, and in estuaries and the near-shore marine environment, can cause ecological impacts by smothering benthic habitats. Sediment in the water can change its clarity, reducing the ability of fish to see their prey.

Sediment is a contaminant in itself, but fine sediments can also carry other contaminants with them, including heavy metals, organic compounds, and microbes that are harmful to human and ecological health.

4.2.1 Section 30 Resource Management Act 1991

Every regional council is required under the RMA (1991) and its various amendments, to ensure land is controlled for the purposes of conserving soil and the maintenance and enhancement of the quality and quantity of water in water bodies and coastal water and of their ecosystems as well as the avoidance or mitigation of natural hazards. Avoiding or remedying erosion and preventing sediment from entering waterbodies is thus a required function. Most councils, including Waikato Regional Council, have implemented soil conservation and/or catchment programmes aimed at meeting these requirements.

4.2.2 Sediment and the National Policy Statement for Freshwater Management

Sediment is an *attribute*[1] under the National Objectives Framework in the National Policy Statement for Freshwater Management 2020 (NPS-FM 2020) (MfE 2022a). New provisions are in place in the NPS-FM 2020 for monitoring and managing sediment:

- a limit-setting attribute for suspended sediment in rivers
- an action plan attribute for deposited sediment in wadeable rivers.

Councils must set target attribute states for suspended and deposited sediment in consultation with tangata whenua and communities. The suspended and deposited sediment attributes are part of 22 compulsory attributes in the NPS-FM 2020, many of which have a minimum standard or national bottom line; these contribute to understanding how freshwater provides for ecosystem health and human contact.

4.2.3 Whole-farm plans

Farm planning dates from the 1950s, when soil conservation plans were first undertaken. Since then regulatory drivers and environmental compliance have increased, particularly as intensification has increased (Stokes et al. 2021). 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.

Farm plans range from paper-based to digital plans and can be focused on soil conservation, improving water quality by reducing sediment and nutrients, and improving farm profitability. For example, a package called FOCUS was developed in the Wellington region to develop and formalise the links between catchment and farm planning, with several modules, including the ability to track activities, outputs and outcomes (McKergow et al. 2015).

The current coverage of farm plans for soil conservation purposes is understood to be relatively low across the Waikato region. Although most dairy farms will have a farm plan with an industry body, it is likely that erosion mitigation and sediment reduction have not been a focus.

However, to meet new regulations that came into force in 2023, freshwater farm plans will become the key tool for farmers to meet the needs of the Essential Freshwater package introduced in 2020. The regulations have taken effect in parts of Waikato and Southland from 1 August 2023, and they will be rolled out to all regions by the end of 2025. Freshwater farm

[1] An attribute is something we can measure and monitor that tells us about the state of a river or lake.

plans have been legislated under Part 9A of the Resource Management Act 1991 (RMA) and the Resource Management (Freshwater Farm Plans) Regulations 2023. The regions in Waikato requiring farm plans from 1 August 2023 to 1 July 2025 are described in Part 1 of the legislation (New Zealand Government 2023).

The regulations are in effect in the Waipā freshwater management unit in Waikato, and in the Aparima and Fiordland and Islands freshwater catchments in Southland. The remaining freshwater management units and freshwater catchments in Waikato and Southland will be rolled out between 1 February 2024 and 1 July 2025. Farm operators in areas where freshwater farm plans are in effect will have 18 months to prepare their first plan for certification. Farmers will need to do an on-farm freshwater risk assessment and identify actions to manage (or mitigate) those risks.

On-farm actions to manage risks to freshwater will be tailored to each farm, based on:

- the farm landscape
- farming activities
- the local catchment.

Freshwater farm plans will need to be certified and audited, and the results of certification and auditing will be reported to the regional council. Many farmers already have a farm environment plan or are part of an industry programme, and freshwater farm plans will build on that work.

Erosion and sediment delivery to water are key risks that need to be identified and incorporated into the freshwater farm plan, along with assessment of current actions in terms of mitigating these risks. Where current actions or mitigation methods are not sufficient to manage the identified risks, an action plan for implementing new mitigation actions is required. The action plan has a 5-year duration. Thus, freshwater farm plans will be a key tool for farmers and growers to manage their freshwater requirements, including documenting actions they are taking to meet other regulatory requirements. In some instances, farmers will be able to use their freshwater farm plan to meet other freshwater regulatory requirements (e.g. intensive winter grazing).

In response to the impending legislation and the developing implementation processes, Macintosh et al. (2021) discussed the issues and merits of such implementation. They reported that on-farm mitigation actions in farm plans should be quantitative and risk-based, focusing on key catchment water-quality priorities and their cost-effectiveness. An important point raised was that implementing mandatory farm plans at a national scale, with minimum standards and metrics, will help to demonstrate good practice to achieve water quality improvement (Macintosh et al. 2021). Standardised data capture will help to relate trends in water quality to on-farm action (Macintosh et al. 2021), but there are still a number of challenges and knowledge gaps (McDowell & Kaye-Blake 2023).

Burkitt and Bretherton (2022) have argued for placing an emphasis on understanding a farm's natural resources (e.g. geology, soils, landscapes) in the development of future farm plans. These authors noted that information and skills associated with the farm system are often readily available at the farm scale, but that the mapping scale of physical resources, including soils, is not. S-map is New Zealand's digital soil map (S-Map Online | Manaaki Whenua -

Landcare Research), which is published at a regional scale (1:50,000) so it only provides a very broad estimate and is not yet available for all areas (MfE 2023c). More information on standards for soil mapping developed in conjunction with many regional councils is available from Grealish 2017.

4.2.4 Intensive winter grazing of forage crops

The Resource Management (National Environmental Standards for Freshwater) Regulations 2020 address the negative environmental effects of intensive winter grazing with specific provisions. In May 2022, amendments to the National Environmental Standards for Freshwater 2020 changed the requirements for land managers and regional councils relating to intensive winter-grazing activities.

The amendments include a permitted activity condition requiring critical source areas (CSAs) that are within, or adjacent to, an area being used for intensive winter grazing to be protected, and require livestock to be excluded from CSAs from 1 May to 30 September in order to meet permitted activity conditions (MfE 2023a). The regulations ensure intensive winter grazing is actively managed to reduce sediment loss into waterways. The regulations include a standard (26A) for pugging (MfE 2023c).

Several guidance documents to support improved management of critical source areas, reducing pugging and using ground cover to reduce sediment and nutrients to waterways, were published in 2023. These are designed to improve intensive winter grazing practices in a way that is consistent with these regulations and minimises impacts on the environment. The guidance is available from: Introduction to the intensive winter grazing guidance package | Ministry for the Environment

4.2.5 Resource Management (Stock Exclusion) Regulations 2020

These regulations have been issued to exclude certain types of stock from waterways. Excluding stock from natural wetlands, lakes, and rivers more than 1 m wide is intended to reduce freshwater pollution, prevent bank erosion and sediment loss, and allow riparian plants to grow (MfE 2022b).

For any pastoral system already in place on 3 September 2020 the provisions take effect at varying dates depending on the stock type and situation (MfE 2022b). Councils may adopt more stringent stock exclusion requirements in their regional plans, but any existing rules that are more stringent continue to apply (MfE 2022b).

For all dairy, dairy-support and beef cattle, pigs, and deer there must be a minimum setback of 3 m from the bed of a lake or river (MfE 2022b). Stock can enter the 3 m setback area only when crossing the river or lake, and there is an exception where an existing 'permanent fence' or existing riparian planting already effectively excludes stock (MfE 2022b). Further details are available from MfE 2022b. There has been recent consultation in July 2023 addressing issues related to lower-intensity farming.

4.2.6 NES-PF (plantation forestry), now NES-CF (commercial forestry)

The National Environmental Standards for Plantation Forestry (NES-PF) provided nationally consistent regulations to manage the environmental effects of forestry. A range of guidance is available to help foresters and councils interpret the regulation. The Erosion Susceptibility Classification (ESC) is used to identify the erosion risk of land as a basis for determining where a plantation forestry activity is (a) permitted, subject to certain conditions being met, or (b) requires resource consent because it is on higher-risk land.

The ESC tool divides the New Zealand landscape into four erosion categories that are colour-coded according to risk.

- **green** (low) and **yellow** (moderate) – land less likely to erode; plantation forestry activities are permitted
- **orange** (high risk) and **red** (very high risk) – land is more likely to erode; most forestry activities can't be carried out on red-zoned land without resource consent; some activities, such as earthworks, also require consent on orange-zoned land with steeper slopes.

The categories are based on the local topography (steepness of the slope), dominant erosion process (such as wind or water), and rock type. The ESC is a spatial database tool that allows a user to assess erosion susceptibility for locations in New Zealand via an online map. The underlying data used in the ESC are taken from the Land Use Classification (LUC) system.

HOW DOES THE ESC WORK?

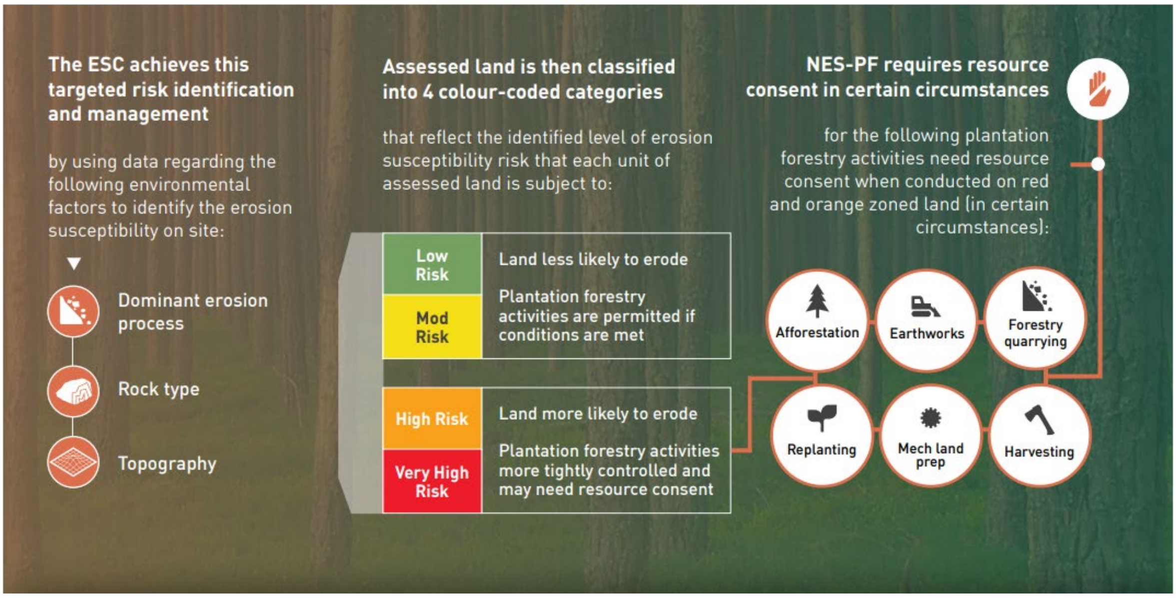

Figure 1. Pictorial representation of how the ESC works. Reproduced from MPI guidance (https://www.mpi.govt.nz/dmsdocument/28485-The-NES-PFs-Risk-assessment-tools-guidance)

Amendments to the NES-PF were announced in October 2023 (https://www.mpi.govt.nz/forestry/national-environmental-standards-commercial-forestry/). The NES-PF is now called the National Environmental Standards for Commercial Forestry (NES-CF), which aim to manage the environmental effects of plantation and exotic continuous-cover forestry (carbon forestry). The changes give councils more power to decide where new forests are located, and exotic carbon forests are now managed in the same way as plantation forests. There are also other technical amendments, including a new permitted activity standard for managing forestry slash on the cutover.

4.3 State of Environment: Waikato region

Annual state of environment reports and past surveys (e.g. Hicks 2003) indicate that soil erosion continues to be a problem for the Waikato region (WRC 2023). Forestry operations contribute to sediment loads, as does the clearance of indigenous forest and scrub for pastoral development. Tracks on farmland represent a large area of bare soil and erosion risk. Erosion from earthworks to meet the increasing demand for housing also poses a risk, albeit temporarily while earthworks are in place.

Catchments draining to the west coast exhibit more erosion than other parts of the region. Extensive areas of the Whāingaroa Harbour catchment (Raglan) have been fenced and planted, and other harbour catchments are deemed priorities for erosion control.

WRC have been monitoring soil quality (Taylor et al. 2017), soil stability (Norris & Wyatt 2023), stream bank riparian conditions (Norris et al. 2020), and related factors for a number of years, and these technical reports are used to inform the annual state of environment report for the region. Of particular relevance to this study are the reports listed above and in Table 1. Environmental indicators used by WRC for state of environment monitoring for the Waikato region are summarised in Table 1.

Table 1. Environmental monitoring indicators used by Waikato Regional Council

Indicator	Description	Measure
Soil stability	Soil disturbance from natural erosion and land-use activities; bare soil under land uses and land cover; 2 km × 2 km matrix of 6,155 points (Norris & Wyatt 2023)	Indicates potential sediment source
Riparian stock access	Stock access to waterways based on the presence or absence of fencing, vegetation, and stream characteristics; presence or absence of pugging disturbance; 432 sites (Norris et al. 2020)	Indicates potential sediment source
Riparian vegetation	Riparian bank stability; based on the presence or absence of vegetation and vegetation size and structure (Norris et al. 2020).	Indicates potential sediment source
Stream bank erosion	Whether stream banks are eroded or uneroded; whether erosion was 'past', 'recent' or 'active; whether pugging disturbance has occurred or not (Norris et al. 2020)	Indicates potential sediment source
Sediment yield	Suspended sediment yield estimates for selected catchments (24 monitored catchments (Hoyle 2014)). Up to 2020, monitored riverine suspended sediment concentrations were measured at 26 monitoring sites; a rating curve was then used to estimate sediment yields (Wyatt et al. 2022).	Indicates sediment yield for selected catchments
Suspended sediment concentration	Up to 2020, monitored riverine suspended sediment concentrations were measured at 26 monitoring sites (Wyatt et al. 2022). Note the total water quality monitoring sites in the ‘Waikato River monitoring programme’ (WaiRiMP) and the ‘Regional rivers water	Indicates suspended sediment concentrations

Indicator	Description	Measure
	quality monitoring programme' (ReRiMP). Water quality samples were collected at 121 sites (Ryan & Jenkins 2023).	
Land use	Estimates regional land cover and land use, based on Land Cover Database (LCDB5; including timesteps of 1996, 2001, 2008, 2012, and 2018); change in cover 1996–2018 (Jones & Borman 2023).	Indicates potential pressures and risk that could increase sediment sources
Stock unit density	Estimates the density of stock by converting farm animals to a common stock unit and dividing by the area of land the stock is grazing on (Hill 2011; WRC 2023).	Indicates potential pressures and risk that could increase sediment sources

Analysis of soil disturbance data found that 21% of the region's surveyed points had some form of land-use disturbance and 9.7% of the surveyed points contained natural erosion (Norris & Wyatt 2023). Farm and forestry tracks contributed most to total land-use disturbance, followed by cultivation, sealed roads, and harvested forest. In terms of erosion caused by natural processes, surface erosion was the most prevalent, followed by gully erosion processes, slope failures, and riparian erosion/deposition (Norris & Wyatt 2023).

The assessment of soil stability across the eight Waikato catchment management zones suggested that the west coast has the highest percentage of surveyed points classified as 'unstable', followed by the Coromandel, Lake Taupō, and lower Waikato zones (Norris & Wyatt 2023). When comparing land-use types across the region there were considerable differences with respect to soil stability and disturbance. Drystock pasture had the highest proportion of points classified as 'unstable', followed by natural forest, natural scrub, and dairy pasture. Soil conservation programmes and catchment schemes are an integral part of sediment management in the Waikato region and have been for decades.

5 Overview of erosion

5.1 Erosion in the Waikato region

Historically, land-use conversion from native forest to pasture, involving forest and scrub removal, created large increases in sediment loads, particularly in the basins in the upper Waikato and upper Waipā Rivers, which drain Taupo Pumice terrain.

All erosion processes found in New Zealand can be found in the Waikato region. The exact proportions of each process will vary from catchment to catchment, and will depend on terrain, geology, soil, climate, and land use. In general terms, the steeper land will have a predominance of landslide/mass movement and surficial erosion, while streambank erosion will dominate valley bottoms and flood plains. Gullies are not as common as in other regions of the North Island but can occur in volcanic terrain to the south of the region in pumice coverbeds. Earthflows are limited.

Sediment production, transfer, and deposition have historically been controlled by the geology of the region, with human activities on the land and in the waterways increasingly modifying the sediment regime (Hill 2011). The rivers and catchments are now largely considered highly modified systems. The human activities that have variously affected the supply, transfer, and storage of sediment in the Waikato include forest clearance and other land-use conversion, hydro-electric power development, sand and gravel extraction, and channel management works.

Some of the eroded sediment is likely to be eventually deposited in some of the estuaries and harbours in the region. Several studies of estuarine deposition or sediment source tracing are available, including for Raglan Harbour, Whangamatā Harbour, and Whangapoua estuary (Sheffieldt et al. 1995; Mead & Moores 2005; McKergow et al. 2010; Roddy 2010). Sources of sediment vary with, for example, McKergow et al. (2010) reporting that about half of the fine sediment load for catchments to Raglan Harbour was supplied by a single sub-catchment and probably sourced from streambank erosion.

5.2 Surface erosion

Surface erosion 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. In addition to the presence of bare ground, factors that influence surface erosion include slope angle and length, aspect, soil texture, soil compaction, and rainfall, especially rainfall intensity and duration (Basher 2013).

Surface erosion is a locally important source to streams, affecting local water quality, but may not contribute a large amount to catchment-wide sediment loads in the Waikato region's large catchments. Surface erosion (sheet wash and rock/scree deposits) was estimated to have contributed to 66% of bare soil from natural disturbance (Norris & Wyatt 2023). This was determined from a soil stability survey in the region, which indicates the presence of erosion based on aerial images.

5.3 Streambank erosion

Streambank erosion is an important component of catchment sediment budgets. It is one of the least understood erosion processes in New Zealand, but is common along rivers and streams throughout the country (Smith et al. 2019). Bank erosion is generally associated with lateral channel migration and involves a wide range of styles of erosion, ranging from small banks to cliffs. Streambank erosion has been one of the most common processes mitigated by both biological and structural erosion control (Basher 2013).

Information on sediment loads, the importance of riverbank erosion, and the role of hydro-reservoir sediment trapping within the Waikato and Waipā catchments was reviewed by Hughes (2015). Bank erosion is likely to be an important source of sediment in the Waipā River and the tributaries of the Waikato River, but there are limited field data on bank erosion in Waikato or geologically similar catchments (Hughes 2015).

There is a general lack of information on riverbank erosion rates in New Zealand catchments. Hughes (2015) also reported that small streams were poorly represented in the limited data available at that time. This was deemed important, given that 90% of the reaches in the Waipā catchment had a mean annual flood discharge of less than 100 m/s. Similarly, Basher (2013) found little quantitative research on bank erosion in New Zealand, particularly over the long term. In the Waikato region some early research was undertaken to construct a sediment budget for the Mangaotama Stream, a tributary of the Waipā River (Hughes 2015).

In the Waikato region, across all land uses, riparian processes (stream bank scour and streambank deposition) contribute 10% of natural disturbance (Norris & Wyatt 2023). Streambank erosion is perceived to be a significant sediment source in areas of pastoral land use, particularly along unfenced banks accessible to stock (Hicks & Hill 2010).

In a survey of riparian conditions, the majority (83%) of surveyed bank length across the region in 2017 was uneroded (Norris et al. 2020). The proportion of bank length affected by streambank erosion across the region was approximately 17% in 2017 (compared with 12% in 2012), and in both years this was reported as having significantly increased from 5% in 2002 (Jones et al. 2016; Norris et al. 2020). A strong correlation between the fencing of both banks and reduced streambank disturbance, including active erosion, demonstrates that fencing is an effective management practice for reducing potential sediment in waterways (Storey 2010). Further analysis across the region indicated that fencing (i.e. removal of stock from near the stream) has a considerable impact on streambank erosion (active or recent) and soil disturbance from pugging, when averaged over a large number of Waikato sites (Norris et al. 2020).

McConchie & Toleman (2003) suggested wake-induced waves (from water craft) were more effective at suspending and transporting sediment than wind-generated waves on the Waikato River. They further concluded that, of the sites investigated, those most susceptible to wake-induced erosion were characterised by a lack of vegetation and soft, unconsolidated bed and bank sediments.

5.4 Mass movement erosion

Because New Zealand is dominated by hilly and mountainous terrain, the most widespread type of erosion is mass movement (landslides, earthflows, slumps), especially rainfall-triggered shallow landslides. A wide variety of landslides occur in the New Zealand landscape, 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, earth slips, 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.

Rainfall-triggered shallow landslides are a common feature on the steeper, hilly parts of the Waikato region. The hills to the northwest and southwest of Hamilton and the steep volcanic terrain on the Coromandel Peninsula are particularly susceptible. However, shallow landslides can occur anywhere in the Waikato region where the land has a slope over 25˚ and when intense rainfall occurs (e.g. Selby 1967). Deeper-seated landslides can occur in similar areas but are more local in extent.

5.5 Earthflow erosion

Earthflow erosion is the slow movement of soil and associated regolith along basal and marginal shear planes, accompanied by internal deformation of the moving mass (Eyles 1983, 1985; Lynn et al. 2009). Earthflows range from shallow (less than 1–2 m) to deep-seated (over 10 m), but are 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 over 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.

Earthflows occur in the Waikato region but are not as common as in other regions.

5.6 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). This type of erosion 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 mountain lands. It also occurs in Northland and the Volcanic Plateau (Eyles 1983, 1985).

In the Waikato region, gullies (tunnel, large, and open) contribute to 13% of natural erosion and are the second-most dominant process after surface erosion. Gullies can occur in volcanic terrain to the south of the region in pumice cover beds, and there have been spectacular examples of these gullies in the past.

5.7 Wind erosion

Wind erosion has been a concern in New Zealand, with dust clouds commonly observed blowing off cultivated paddocks. The extent and significance of wind erosion were 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. These latter areas have high-altitude (over 700 m), volcanic-ash-mantled, gently rolling to moderately steep slopes that have poor vegetation cover (Basher & Painter 1997). The map indicates that the area affected is likely to be mainly south of the Waikato region. Areas of the Waikato that are susceptible to wind erosion include LUC class 3 land on exposed sites with cropping (e.g. Upper Waipā headwaters; Priest 1969). Wind erosion is also likely to be more prevalent in coastal areas of the west coast, where sand dunes predominate.

6 Erosion and sediment control: practice, land management, plans, and guidance

6.1 Overview of techniques commonly used to control erosion and reduce sediment 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 2). Many techniques/approaches follow those developed in other countries. In New Zealand, 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.

Table 2. Techniques commonly used to control erosion and reduce sediment in New Zealand

Erosion type	Soil conservation principle	Erosion and sediment 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
Shallow mass movement (landslides, debris avalanches, earthflows)	• Maintain root strength contribution to slope stability • Reduce soil water	• Space-planted trees • Reversion to scrub • Afforestation • Planting for permanent tree cover • Adjust grazing pressure and fencing • Drainage control • Debris dams • Control at toe (earthflows) • Spring taps
Deep-seated mass movement (landslides, slumps, earth and rock flows)	• Maintain root strength contribution to slope stability • Reduce soil water	• Space-planted trees • Reversion to scrub • Afforestation • Planting for permanent tree cover • Adjust grazing pressure and fencing • Drainage control • Debris dams • Control at toe

Erosion type	Soil conservation principle	Erosion and sediment control practice
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 • Planting for permanent tree cover • 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 • Shelterbelt establishment
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 • Reseed stream banks • Control stock access by fencing • Subsurface drainage at seepage sites

Sources: Luckman & Thompson 1993; Hicks 1995; Hicks & Anthony 2001; Basher, Manderson et al. 2016; Basher, Moores et al. 2016.

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 – to trap sediment before it moves off-site and into waterways.

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.

Sediment control practices 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.

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. 2008). In 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 (Phillips & Marden 2005; Douglas et al. 2013). 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.

Stream 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 historical deforestation and large storms that caused significant slope erosion. 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, these 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, 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 factors that are relevant to thinking about how to design for different environmental conditions and assessing the performance of ESC practices.

Finally, an integral part of erosion control is the production of a plan that describes what is being done (actions) and how the environmental effects (risks) are to be mitigated. Such plans and approaches are either voluntary or (increasingly) mandatory as part of meeting regulations and consent requirements.

Additional information on mitigation measures can be found in a recently released tool by Land and Water Science called 'LandscapeDNA' (https://landscapedna.org/). In this open-access, web-based platform the user can click on any point on the map of New Zealand and obtain information on its current state and risks. However, of more value is the information related to how those risks can potentially be managed through a range of actions (https://landscapedna.org/actions/); i.e. mitigations, with details of each measure provided, and an assessment of cost-effectiveness and performance.

6.2 Mitigation effectiveness and mitigation performance: definitions

Erosion and sediment control 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 implementing pastoral soil conservation farm plans, and in modelling studies (Basher et al. 2019).

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 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 it will probably be adequate and suitable.

Following Phillips et al. (2020), 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.

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

Notwithstanding the lack of a consistent methodology for assessing the mitigation performance of erosion and sediment control techniques and the paucity of quantitative data from New Zealand studies, the commonly used effectiveness values for the various mitigation treatments are listed in Table 3.

It is important to understand that erosion and sediment control mitigation practices will never be 100% effective, because the *performance* of any mitigation measure rarely approaches 100%. "Effective" erosion and sediment control means doing the 'best' possible, because 100% control or sediment reduction cannot be achieved. In the case of rare and extreme events such as Cyclone Gabrielle, mitigation effectiveness will inevitably be reduced and maybe completely over-ridden.

WRC has implemented a catchment monitoring programme designed to assess the effectiveness of soil conservation in priority catchments. Monitoring methods include measurements of soil stability, riparian characteristics, photo points, and suspended sediment monitoring (Grant et al. 2009). The catchment monitoring programme is currently being reviewed.

Table 3. Summary of erosion mitigation treatments used for different erosion processes and land uses, and the commonly used performance values in New Zealand

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 the 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 dyking	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 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), effectiveness should be scaled in proportion to area treated.
	Afforestation	90	Pasture	This 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 at 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 the effect of width of fencing setback.
	Riparian fencing + planting	50	Pasture	

Sources: Basher, Moores et al. 2016; Basher et al. 2019.

6.3 Streambank and riparian mitigations

An overview of potential edge-of-field to waterway mitigation options for agriculture – including nutrient and sediment mitigations positioned at edge-of-field, edge-of-waterway (riparian), riparian buffer zones, saturated buffers, and integrated buffers – was provided by Tanner et al. (2020). Riparian buffer zones for improving water quality in agriculture is one of the most common best management practices, often including exclusion of grazing animals (McKergow et al. 2016; Wright-Stow et al. 2018; Tanner et al. 2020). In 2015, nationally, 96% of dairy cows had been excluded from waterways over 1 m wide and over 30 cm deep on land grazed by cows (McKergow et al. 2016).

Livestock exclusion is the most basic form of riparian management, but fencing and planting have additional benefits (McKergow et al. 2007). Livestock exclusion reduces trampling damage and direct streambank erosion, but it is difficult to separate the effect of livestock exclusion from the impacts of other mitigations in catchment-scale studies; for example, in the dairy catchment studies in Toenepi reported earlier, and elsewhere (McKergow et al. 2007; Wilcock et al. 2007; Wilcock et al. 2013).

Reductions in sediment loss include 30–90% at catchment scale from livestock exclusion and reducing treading damage from waterbody margins, and 20–80% from riparian grass filter strips, depending on the circumstances (McKergow et al. 2007). Grass filter strips can result in reductions in sediment loss but may be dependent on local circumstances and management (McKergow et al. 2007).

Water quality is improved by riparian management and buffer zones, which filter surface runoff, remove nutrients from shallow subsurface flow, stabilise stream banks and reduce erosion, and reduce sediment and nutrient supply (McKergow et al. 2007). Other benefits include biodiversity, improved habitats, temperature regulation from shading, and refuge from predators and floods (Wright-Stow et al. 2018). In the Waikato region several studies and examples (Kakahu Stream, and a riparian seepage wetland near Te Poi, Waikato) were reported, including typical width ranges (McKergow et al. 2016).

Riparian areas in plantation pine forest in the Whangapoua Forest on the Coromandel Peninsula were examined at 28 sites. Bank erosion and channel widths were greater at harvested sites where pines occurred at the stream edges, compared with other forest and riparian treatments, while periphyton biomass was greatest at clear-cut harvested sites (Boothroyd et al. 2004). Bank erosion was significantly higher in harvested sites without riparian buffers. Initial regrowth can be effective for trapping sediment from upslope but gives minimal shading of streams (Boothroyd et al. 2004).

Early monitoring up to the early 1990s of riparian vegetation and stream-bank stability in the Upper Waipā catchment indicated that riparian plantings that were immature were generally inadequate for limiting bank erosion (Ritchie 2012). Since then, a detailed study of 385 waterway sites on farms across Waikato (comprising 197 in dairy and 188 in drystock land use) reported that the majority (about 60%) of riparian margins were relatively narrow (had a buffer width of less than 5 m) as at 2012 (Jones et al. 2016).

Riparian margins in pastoral land across the Waikato region in 2012 were dominated by non-woody vegetation (occupying about 74% of bank length, mainly pastoral grasses), suggesting there was further need to encourage restoration of woody riparian vegetation in the region (Jones et al. 2016). The proportion of bank length affected by streambank erosion across the Waikato region was considered relatively small (12%) in 2012. One-quarter of the bank length across the region was characterised as disturbed, and, of this, 13% was attributed to pugging disturbance and influenced by the amount of stock access and fencing (Jones et al. 2016).

This survey work was repeated and extended in 2017 across the Waikato region to 432 waterway sites, comprising 244 in dairy and 188 in drystock (Norris et al. 2020). The proportion of surveyed bank length fenced across the Waikato region has steadily increased at about 2.2% of bank length per year (from 28% in 2002 to 61% in 2017), which indicated that approximately 40% of surveyed bank length in pastoral land remained unprotected against stock access (Norris et al. 2020). Fifty-four percent of riparian margins were classed as narrow (i.e. less than 5 m).

It is worth emphasising that the proportion of bank length affected by streambank erosion across the region was approximately 17% in 2017 vs 12% in 2012, and that in both years this was reported as having significantly increased from 5% in 2002 (Jones et al. 2016; Norris et al. 2020). The magnitude and frequency of storm events are likely to have influenced the streambank erosion observed, while pugging from livestock also caused disturbance.

In summary, over the 15-year monitoring period the rate of change in bank length effectively fenced was about 3.1% and 1.3% of bank length per year for dairy and drystock, respectively. In terms of future management, the percentage of bank length remaining unfenced across qualifying streams and rivers is 21% across the region, 47% in the Central Waikato, and 35% in the Lower Waikato management zones.

Further details are available elsewhere, including discussion of remaining fencing needs in relation to the eight management zones in Waikato, the Waikato Regional Council plan changes, and other regulations (Norris et al. 2020).

McKergow et al. (2016) identified a number of barriers and knowledge gaps to the more effective use of riparian management, including the need for clear goals by communities and further assessment of buffer placement, width, and length. Careful riparian mitigation design is needed for non-uniform runoff flow, and there are ongoing effects of legacy deposits of sediment in pastoral streams from early land clearance (McKergow et al. 2016).

6.4 Lowland catchment streams

The Toenepi catchment, a 15 km^2 tributary of the Piako River in Waikato, has been part of a national study of five dairy-dominated catchments that commenced in 2001. Previous studies of Toenepi have reported degraded water quality (Wilcock et al. 1999). Management practices, soil quality, and water quality have been studied since then, and background to the wider project and early results in the Toenepi catchment are available (Monaghan et al. 2004; Monaghan et al. 2008).

Results from these five catchments, including Toenepi, showed a reducing trend in suspended solids and improvement in water clarity, as measured by black disc visibility (Wilcock et al. 2013). It was concluded that reductions in sediment loads were likely to be due to the greater use of fences for stock exclusion from streams and riparian areas, and the use of land application of effluent (Wilcock & Wright-Stow 2012; Wilcock et al. 2013). In the Toenepi catchment, stream fencing increased from about 46% in 1995 to over 80% in 2008 (Wilcock et al. 2013).

Farm plans are an important tool to reduce sediment loads to streams. The number of farm plans was increased in the Waikato region from 2,016 in 1995 to 3,732 in 2015, representing 15% of the region with farm plans in 2015, along with 80% of major streams riparian-fenced in 2015 (Monaghan et al. 2021). Estimates of reductions in sediment yield from dairy farms were primarily attributed to stock exclusion from riparian zones due to riparian fencing, and therefore less bank erosion (Monaghan et al. 2021). In the study of Monaghan et al. (2021), major streams were defined as over 1 m wide, over 30 cm deep, and permanently flowing. Results from the MWLR 'Survey of Rural Decision Makers' were used to estimate the percentage of farms with riparian retirement implemented to restrict stock access to major streams.

Based on monitoring across the whole Waikato region, the average proportion of surveyed bank length effectively fenced has significantly increased recently, from 28% in 2002 to 61% in 2017 (Norris et al. 2020). In this study, 'effective fencing' was defined as that which is sufficient to prevent stock access to the waterway and is adjacent to riparian margins (Norris et al. 2020).

6.5 Critical source areas

Critical source areas (CSAs) are areas within a paddock or catchment that contribute a disproportionately large quantity of contaminants (such as sediment) to water (relative to their extent), particularly from overland flow (McDowell & Srinivasan 2009; Monaghan et al. 2017), leading to poor water quality (MfE 2023c).

Protection of CSAs reduces pugging damage, and is most effective at reducing losses of sediment, faecal microorganisms, and nutrients. Minimising either the source of or the transport pathway from CSAs will decrease the risk of these contaminant losses. While the mitigations recommended in MfE 2023c and MfE 2023a are for winter-grazed forage crops, many of the principles apply to other crops and pastures. CSA examples (including from WRC, such as races, river crossings, silage pits and feed bunkers) are provided in MfE 2023a.

Key management considerations for managing CSAs under intensive winter grazed crops include the following (MfE 2023c).

- CSAs should be identified in the planning and pre-sowing stages.
- Ideally, paddocks with large CSAs (including areas prone to ponding) should be identified, fenced, left with vegetative cover, and not grazed.
- Locating intensive winter grazing paddocks away from CSAs and providing sufficient buffer zones also limit losses and should be factored into the site-selection process.

More detailed recommended management actions and photos to identify CSAs are available in the technical guidance for managing intensive winter-grazed crops. These include (MfE 2023a):

- management before winter grazing
- paddock selection (e.g. consideration of soil type; further information on soils and planning prior to forage crop sowing is available in MfE 2023c)
- CSA protection (e.g. fencing, vegetative cover, and buffers)
- cropping methods.

Further mitigations during and after grazing in winter are recommended in MfE 2023c and MfE 2023a. Managing CSAs should also be undertaken as part of the wider regional farm environment or freshwater farm plan process.

6.6 Stock treading on lowland pastures

Although several surveys have investigated the state of soil physical properties from pugging and soil compaction on pasture in Waikato (Singleton & Addison 1999; Singleton et al. 2000; Taylor et al. 2010; Taylor et al. 2017), there is a gap in the literature for the Waikato region on the mitigation of treading damage, especially treading-induced sediment loss.

A study at Ruakura on a Te Kowhai silt loam (Gley Soil) evaluated conventional dairy cow grazing, 3-hour grazing, and never-pugged and never-grazed treatments as potential mitigation options (Drewry 2003). Several studies examined similar mitigation strategies and tools for minimising treading damage in Southland/Otago (Drewry & Paton 2000; Houlbrooke et al. 2009; Laurenson & Houlbrooke 2016), and elsewhere (Betteridge et al. 2003; Houlbrooke et al. 2011), but sediment from runoff on lowland farms remains a knowledge gap.

6.7 Intensive winter grazing of forage crops

A very successful mitigation is the use of 'strategic grazing' on intensively grazed winter forage crops. Monaghan et al. (2017) showed that by grazing the at-risk CSA late in the winter season, sediment and nutrient loss were reduced significantly. Compared with standard grazing with dairy cows, strategic grazing reduced sediment loads in overland flow by 94%. The strategic grazing approach located most of the soil pugging away from areas where water accumulated, and infiltration rates were maintained in protected areas. The volume of overland flow for the non-protected catchments was 60–80% greater than for catchments with protected CSAs (Monaghan et al. 2017; MfE 2023c).

For strategic grazing, cows entered the crop at the top of the paddock and were break-fed downhill towards the CSA, thereby helping to protect at-risk areas (e.g. heavy-textured soils, CSAs) of the paddock from pugging damage and impacts to water quality. The CSA was the last break that was grazed at the end of winter (MfE 2023c). As reported by MfE (2023c), this study used dairy cows in southern New Zealand, so other stock classes may have different impacts, and further research is needed in other regions and for different crops.

6.8 Sediment traps and detainment bunding

A recent review examined the use of sediment traps in agriculture and whether they are viable or effective (Smith & Muirhead 2023). They reported on several types of sediment traps: geotextile silt fences, silt traps and decanting earth bunds, detainment bunds, modified drainage ditches, and farm ponds. Silt fences are a temporary measure in small catchments, usually less than 0.5 ha, using wind or weed matting (which do not have good filtering characteristics) or geotextiles (Barber 2014; Smith & Muirhead 2023). Further details and design criteria are described for vegetable production in Barber 2014, with construction guideline links on the Auckland Council website.

Silt traps and decanting earth bunds are often constructed along the flat contour at the bottom of a paddock to capture runoff water and allow time for sediment to settle in cultivated paddocks (Barber 2014; Smith & Muirhead 2023). The recommended capacity is 0.5% (50 m^3/ha) for catchments of less than 5 ha, and 1% (100 m^3/ha) for catchments over 5 ha (Barber 2014). Full details are included in the *Franklin Sustainabilty Project Soil and Drainage Management Guide*, including diagrams and installation notes. This can be downloaded from http://agrilink.co.nz/archive.php.

Decanting earth bunds and silt traps need to dewater to remove the cleaner water without removing the settled sediment. If the decanting rate is too fast, the sediment will not have time to settle, and if too slow or there is insufficient spillway for large events, there will be poor sediment capture (Barber 2014). Further details, design criteria, and notes are described for cultivated paddocks and vegetable production in Barber 2014.

Detainment bunds are a combination of decanting bunds and sediment retention ponds for the control of overland flow and associated pollutants (sediment and phosphorus), typically in catchments of less than 42 ha (Smith & Muirhead 2023). Recent research studies in New Zealand included pastoral dairy farms in the Hauraki Stream, Awahou Stream, and Waiteti Stream catchments, all in the Lake Rotorua catchment, Bay of Plenty (Clarke et al. 2013; Levine et al. 2019; Levine et al. 2021). These sites were on free-draining soils, including a Typic Orthic Podzol (Awahou Stream catchment site) (Levine et al. 2019), and a Buried Allophanic Orthic Pumice (Hauraki site) (Levine 2020).

Levine et al. (2021) reported that the detainment bunds located on pastures at the Hauraki and Awahou sites attenuated the equivalent of 51 and 59% of the annual inflow suspended sediment loads, respectively. They emphasised the importance of optimising the design to maximise the amount of runoff infiltrating into soil, and reported that further research is needed, including on costs and benefits, sediment size characterisation, longer-term studies, and causes of reduced infiltration in dairy pastures.

Smith and Muirhead (2023) evaluated the effectiveness of sediment traps in agricultural landscapes, showing that the average effectiveness was 59%, with a range from 32% to 85% (including international studies). However, some negative values were also discussed due to remobilisation of sediment, reduced retention time from storm events bypassing or overflowing the storage area, and where the ratio of storage volume to catchment area is low (e.g. less than 100 m^3/ha; Smith & Muirhead 2023).

Practices with high effectiveness for erosion and sediment control in cultivated land include the following.

- Bunds of earth as a barrier are constructed along a paddock edge to prevent water flowing (suitable for use on slopes over 3˚). Bunds create ponds of water where sediment settles out.
- Green manure or cover crops after harvesting of the main crop are ploughed into the soil, stabilising the bare soil.
- A ‘silt fence’ is fastened to a wire fence to filter sediment from surface runoff.
- Wheel-track ripping – suitable after use of heavy vehicles on cultivated soil: ripping allows water to percolate into the soil rather than flow down the tracks.

Practices with moderate effectiveness include:

- constructed level-benched headlands that run across the slope of a field, which are suitable where slopes are over 3˚ and encourage infiltration of water
- wheel-track dyking – a series of closely spaced indentations in wheel tracks, which slows surface runoff and settles suspended sediment

6.9 Vegetable cropping

Erosion and sediment control guidelines for vegetable production in New Zealand (Barber 2014) include:

- paddock assessment and mitigation measures for controlling water entering the paddock
- control measures for keeping soil on the paddock
- sediment control measures to manage the water and suspended solids that move off the paddock.

These mitigation measures mirror normal erosion and sediment control practices and principles used for other land uses, particularly those associated with urban development earthworks. Because of the smaller local scale at which they are applied, some mitigation practices are specific to vegetable growing, in part because of differences in soil type and runoff factors from cultivated land compared to earthworks. Various mitigation measures and their effectiveness and costs are listed in Table 4.

Table 4. Control measures, with estimated effectiveness and costs

Control measure	Range in effectiveness (%)	Cost per hectare ($)
Detailed erosion management plan	–	$80–$180
Cover crop	90–99	$80
Minimum tillage	–	–
Setback or buffer strip	50–80	$100–$250
Windbreak crop	–	–
Stubble mulching	–	$70
Wheel track ripping or dyking	50–80	$35
Contour drains	30–70	$75
Benched headlands	50–80	$65
Super silt fence	80–95	$380
Decanting earth bund	80–95	$130
Silt trap	80–95	$750–$1,300
Silt trap maintenance	–	$75/ha/yr

Source: Barber 2014.

Note: costs are in 2014 dollars.

The Franklin Sustainability project's *Doing it Right* guide to sustainable land management is another useful resource for erosion and sediment control on vegetable-growing land (https://agrilink.co.nz/wp-content/uploads/2007/12/updated_FSP-PDF-1-2.pdf).

6.10 Wetlands

Wetlands are important sediment attenuation tools, but natural wetlands have often been drained (McKergow et al. 2007). Constructed wetlands attempt to replicate natural processes and optimise treatment.

Natural seepage wetlands occur at the heads and along the sides of streams. They may be known as seeps, flushes, valley bottom or riparian wetlands, but are rarely identified in regional wetland inventories (McKergow et al. 2007). Sediment removal by seepage wetlands has not been well studied, although some research has been undertaken on nutrient removal at Whatawhata, Waikato (McKergow et al. 2007).

Remnant farm wetlands can be used by farmers to intercept and attenuate diffuse losses of sediments, nutrients, and faecal contaminants. The potential value of maintaining and enhancing lowland remnant wetland areas on farms needs to be reassessed, because they can provide important attenuation, markedly reducing the likely export of contaminants from catchments (Tanner et al. 2015). Constructed wetlands in the Waikato region include studies in the Toenepi catchment for the removal of subsurface drainage nutrients (Tanner et al. 2005).

For constructed and facilitated wetlands, construction and operating costs are relatively low provided that suitable land is available (McKergow et al. 2007). Detailed information and resources on constructed wetlands and performance are available elsewhere (McKergow et al. 2007; Sukias & Tanner 2011; Tanner et al. 2012; Wright-Stow et al. 2018), but there is frequently a focus on nitrate removal (e.g. Praat et al. 2015).

The constructed wetlands reported by Sukias and Tanner (2011) were on dairy land in the Toenepi catchment, Waikato, and at Bog Burn, Southland. Sediment was not reported, but total phosphorus concentrations and loads in many years increased after passage through the wetlands. (Note that both wetlands had the original topsoil from the site returned into the base of the excavated wetland as a plant growth medium and source of organic carbon to support denitrification; Sukias & Tanner 2011).

An overview of potential edge-of-field to waterway mitigation options for agriculture, including nutrient and sediment mitigations positioned in surface and subsurface drainage pathways, is provided by Tanner et al. (2020). Also provided was information on drainage ditches, detention bunds, and constructed wetlands for nutrient and sediment removal, plus other resources. Many of the options have the potential to reduce multiple contaminants and provide biodiversity), and can be 'stacked' (used in combination) with other mitigations for further reduction (Tanner et al. 2020). The authors reported that care is needed to ensure no unintended impacts or 'pollution swapping', and that further information is needed on the degree of aggregation and settling of suspended solids (sediment and organic material) in diffuse run-off. There is also a need for more on-farm demonstration and learning to build the capability of farmers, rural professionals, and regulators (Tanner et al. 2020).

6.11 Urban

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, including WRC. Similarly, most regional and district councils have produced guidance as part of voluntary and/or regulatory controls for managing erosion and reducing sediment (e.g. Environment Bay of Plenty 2010; Northland Regional Council 2012).

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

For earthworks activities, including construction of subdivisions, roads, etc, WRC has produced its own erosion and sediment control guidelines for soil-disturbing activities (Environment Waikato 2009). These are available at: https://www.waikatoregion.govt.nz/services/publications/tr200902/, updated in 2014. A range of factsheets provide details of the mitigation devices or practices and how to install them.

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
- a number of treatments combined
- re-establishing vegetation cover as soon as possible
- mulches in combination with topsoil rather than subsoil (Basher, Moores et al. 2016).

Information on erosion mitigation treatment performance for urban areas is presented in Table 5.

Table 5. Summary of key studies providing information on erosion mitigation treatment performance for urban areas

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Reference
Surface erosion	Mulch	Sediment loads from mulched topsoil and mulched subsoil plots were c. 94% and 85% lower than those in bare topsoil and bare subsoil plots, respectively	Sediment load (t/km^2)	New Zealand	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	Summarised in Basher, Manderson et al. 2016
	Temporary or permanent seeding	Sediment load reductions >90%	Sediment load (t/km^2)	International	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	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	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	Moores & Pattinson 2008

Erosion type	Mitigation treatment	Summary	Effectiveness metric	Study location	Reference
		Two ponds treated with PAC had overall sediment removal efficiency of c. 99%		New Zealand	Larcombe 2009
		Several ponds treated with PAC had overall sediment removal efficiency of c. 99%		New Zealand	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	Babington & Associates 2008

Source: Basher, Moores et al. 2016

USLE is the Universal Soil Loss Equation

PAC is Polyaluminium Chloride

While there is abundant guidance on available ESC techniques for different erosion processes (and land uses), 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. (Table A1 in Appendix 1 provides further information.)

For the Pumice soils in the Taupō urban area, Simcock (2006) provided recommendations for managing stormwater overland flow paths and gullies, as well as controls to minimise erosion during subdivision. These included encouraging earthworks when infiltration was greatest, reinforcing gullies so that dense vegetation is established, and applying ESC controls such as sediment fences, erosion socks and blankets, etc.

7 Erosion and land management in hill country

7.1 Stock treading on pastures

Several studies at Whatawhata, Waikato, have examined the effects of pastoral treading on sediment loss in hill country (Nguyen et al. 1998), or the effects of sheep treading on bare ground, sediment generation, and soil infiltration (Tian et al. 1998; Elliot et al. 2002; Elliott & Carlson 2004; Tian et al. 2007). Increases in sediment and nutrient loss are directly associated with an increased percentage of bare ground, which is associated with treading damage of pastures from sheep grazing during winter in hill country (Russell et al. 2001; Elliott & Carlson 2004). Sediment loss in hill country pasture is directly related to the percentage of bare ground (Russell et al. 2001; Elliott & Carlson 2004; Belliss et al. 2019), with, for example, soil erosion on bare ground being estimated at 100 times greater than on pasture (Dymond & Herzig 2015).

A summary of the impact of stock-track formation on hill-country erosion and sediment supply from various studies across New Zealand (including some from Waikato, discussed above) was undertaken by Rosser (2006), who found that once runoff is concentrated into a single channel the potential for erosion is much greater. This study concluded that although the increases in sediment yield from stock tracks at the hillslope scale are significant, the impact is small at a catchment scale.

7.2 Intensive winter grazing of forage crops

Intensive winter grazing of cropping land refers to grazing livestock on an annual forage crop at any time from 1 May to 30 September of the same year (MfE 2023b). It is commonly used as additional livestock feed in winter. Surface soil erosion from grazed winter forage crops is typically much greater than for other land uses, such as pasture (McDowell et al. 2003; MfE 2023b, c).

Intensive winter grazing of cropping land is associated with large areas of pugging and bare ground, which is associated with high rates of sediment and nutrient loss (North et al. 2018; Belliss et al. 2019).

In the Waikato region as a whole, the conditions associated with winter forage cropping (such as bare ground) in agricultural hill country land (7° slope or more) meant that 1,536 ha of winter forage and 801 ha of pasture were considered high risk (Belliss et al. 2019). Belliss et al. reported that approximately 40,600 tonnes of sediment was likely to be lost from the Waikato region land-mapped as risky winter forage crop areas. The percentage of area of hill country in the Waikato defined as 'risky' for this sediment loss was estimated at about 0.4% (Belliss et al. 2019).

Further research by North et al. (2022) reported that the Waikato region had 0.6% of hill-country agricultural land as bare ground due to winter forage grazing. Of this, 1,140 ha had what was considered to be a good level of certainty obtained by the satellite method used. Additional areas of bare ground due to winter forage grazing were detected but with lower certainty. The total area of bare ground due to winter forage grazing from low to good certainty ratings was 2,982 ha for Waikato region hill-country agricultural land (North et al. 2022).

7.3 Headwater wetlands and treading

Pastoral seepage wetlands (also known as seeps, flushes, valley bottom or riparian wetlands) are common in the hilly and undulating parts of New Zealand, and generally occur within the headwater areas of catchments and along the sides of streams (Hughes et al. 2013). A study on a seepage wetland in the Toenepi catchment, with Granular soils, on a steep unproductive area of a dairy farm, showed that the direct effect of cows' unrestricted grazing in this deep wetland was relatively limited, with low sediment concentrations observed at a lower weir, possibly due to effective sediment trapping in the grass and rough surface of the wetland (Hughes et al. 2013).

When cattle were allowed to graze the wetland, an increase (attributable to cattle-generated disturbance) in pollutants occurred only once out of 18 grazing days, when a cow became trapped (and then removed itself) in the wetland (Hughes et al. 2016). Excluding livestock from the study wetland was concluded as being unlikely to result in a marked reduction in pollutant loads (Hughes et al. 2016).

Cattle access and treading can cause a range of issues, such as affecting biodiversity and increasing fluxes of sediment and organic material entering streams (Hughes et al. 2013). A study in the Tutaeuaua Stream catchment, draining to Lake Taupō, indicated that unrestricted cattle grazing contributed to reduced plant cover, so that sediment (mineral and organic) was available to contribute to the turbidity signal at the outlet (McKergow et al. 2012).

7.4 Spaced tree planting

Use of wide-spaced trees, in particular poplar and willow, is a common practice for mitigating shallow landslides and gully erosion. Space-planted trees can reduce erosion by up to 70%, although this is dependent on an optimal spacing of c. 10–15 m (Hawley & Dymond 1988; Douglas et al. 2013; Schwarz et al. 2016). Density of planting is an important consideration because the effect of trees on soil stability decreases with distance from the trunk. Tree basal area is also an important factor, with trees with a diameter at breast height less of than 10 cm having an impact equivalent to grass cover on erosion (Marden & Seymour 2022).

Different species have varying root traits that contribute to soil stability (Phillips et al. 2015). There are important reasons why poplar and willow have been adopted as space-planted trees for erosion control in New Zealand. While pine and eucalyptus can be more effective at reducing landslide at distances less than 10 m from the base of the tree, willow/poplar have greater effective distances, up to 20 m (Spiekermann et al. 2022). Plantings are effective at reducing rainfall-triggered shallow landslides when about 15 m apart, and at reducing gully erosion when spaced much closer. They can be established from unrooted poles, have fast growth rates, can be planted in the presence of livestock, and may cost less than other planting systems.

However, more important than the tree species is targeting the most erosion-prone areas of the landscape with adequate tree densities, as 80% of landslides occur on less than 15% of the land (Spiekermann et al. 2022).

Long-term monitoring of eroded land in the Mangarama, Pōkaiwhenua, and Matahuru catchments in Waikato has shown that, when appropriately applied as part of a catchment management plan, space-planted trees can contribute to a reduction in the area of actively eroding land (Hicks 2001, 2005). More recently, soil stability surveys in the Matahuru catchment using 2012 and 2017 aerial imagery showed that soil conservation (space planting) increased over that period, but the area affected by natural erosion has also increased in response to several damaging storms that occurred between surveys (Norris 2023). While surveys and monitoring provide the *distribution* of planting, they do not explain the *effect* of planting.

7.5 Plantation forestry

Afforestation is a recommended erosion control practice for shallow mass movement, as well as for gully erosion, which are the primary forms of erosion in New Zealand’s hill country

(Basher 2013). Forests enhance slope stability through the structural reinforcement of soil by the presence of roots, as well as their impact on soil moisture (Phillips et al. 2012). Closed-canopy forest is expected to reduce erosion by 90% over 20 years and reduce catchment sediment yields relative to grassland (Fahey & Marden 2000; Basher 2013). Widespread conversion of pasture land to exotic forestry has been suggested as a potential contributor to long-term declines in national-scale erosion estimates of erosion for New Zealand (Dymond et al. 2010).

However, the impact of production forestry on erosion processes is also affected by management practices, including harvesting, earthworks, and roading (Eyles & Fahey 2006; Phillips et al. 2012). Such impacts can be mitigated, in part, through improved engineering of forestry roads and the use of harvest technologies that reduce soil disturbance. The period following harvesting is critically important, because the maximum effect of trees on soil stability does not occur until after canopy closure, at approximately 8–10 years after planting (Marden et al. 2014). This period of vulnerability also coincides with loss of root structure from previous rotations (Phillips et al. 2005; Marden et al. 2006; Phillips et al. 2012).

In some cases, retirement of land most vulnerable to erosion (e.g. slopes greater than 35°) from forest production and reversion to native shrubland may be the best option. Canopy closure can also have an impact on streambank erosion, as light limitation to riparian vegetation can lead to changes in channel morphology that can increase sediment yields of the catchment (Davies-Colley 1997). Such effects could be managed with appropriate riparian plantings.

Within Waikato (Coromandel Peninsula) it has been observed that very few slope failures are initiated in closed-canopy forestry land as a result of intense storms (Marden & Rowan 2015), although areas of recent harvest generated 25% of the sediment during a storm. In general, slope failures were determined by precipitation intensity and topography rather than vegetation, with 75% of slope failures occurring under native forest on steep slopes. At Whatawhata, streams draining catchments afforested with *Pinus radiata* had higher measured suspended sediment load (+80%) relative to grazed pasture, although nitrogen and phosphorus leaching were reduced (Quinn & Stroud 2002). This was attributed to changes in channel morphology in a catchment with previous pasture history. Over the longer term afforestation has been part of a successful integrated catchment management strategy at Whatawhata (Quinn et al. 2007).

7.6 Native forest and successional species

Similar to exotic forestry, native forest and shrubland cover reduce erosion by up to 90% (Basher 2013). Erosion rates of pasture are 8–17 times higher than for native forest and 5–6 times higher than for shrubland, as estimated from sedimentation records in North Island hill country (Page & Trustrum 1997). Such effects are dependent on the tree age and degree of canopy closure.

The roots of successional species such as kānuka and mānuka rapidly exploit the soil and also decay slowly, leading to a shorter window of vulnerability to slope failure relative to exotic forestry species (Watson et al. 1999; Marden & Phillips 2015). At 10 years old kanuka–mānuka stands can reduce shallow landslides by 65%. At 20 years old the effect can be up to 90%, while landslides are typically absent in stands over 20 years old (Marden & Phillips 2015). Widespread reversion of pasture land to shrubland has been suggested as a potential contributor to long-term declines in estimates of erosion for New Zealand (Dymond et al. 2010).

Natural regeneration of land highly susceptible to erosion under production forestry in the Gisborne region has the potential for wider benefits for soil conservation by reducing erosion (Lambie et al. 2021). Regenerating mānuka–kānuka shrubland is available for honey production, but the viability of shifting from pines to native forest is dependent on landowner impetus, and the value of services such as cultural and biodiversity values provided by native forest (Lambie et al. 2021).

Within Waikato, the suspended sediment load of a stream draining a native podocarp forested catchment was 39% that of a primarily pasture catchment at Whatawhata (Quinn & Stroud 2002). Long-term monitoring of eroded land in the Mangarama, Pōkaiwhenua, and Matahuru catchments in Waikato have shown that, when appropriately applied as part of a catchment management plan, reversion to shrubland can contribute to a reduction in the area of actively eroding land (Hicks 2001, 2005).

7.7 Roads and tracks

Several international studies have reviewed or modelled surface erosion and sediment delivery to streams from roads, including in Australia (Farabi & James 2005; Fu, Newham, Field 2009; Fu, Newham, Ramos-Scharrón 2009). A limitation to developing improved models of road erosion and delivery is access to data (Fu, Newham, Ramos-Scharrón et al. 2009).

There is also a lack of studies in New Zealand on sediment generated from unsealed roads in hill country, although some studies have been undertaken, particularly for forestry, such as that by Coker et al. (1993). Twelve New Zealand studies, including one in Coromandel, were reviewed by Fransen et al. (2001), who concluded that road use by logging trucks is not expected to significantly affect the long-term natural erosion rates from forested catchments.

In the Waikato region a 2017 survey of soil stability and disturbance (including bare soil) found that farm and forest tracks contribute most to overall disturbance, with an exposure of bare soil of 0.95% of the total sampled area. Sixty-eight percent of the land-use disturbance was from farm or forest tracks, highlighting the importance of managing tracked areas to minimise sediment movement waterways (Norris & Wyatt 2023).

8 Erosion and land management in lowland

8.1 Stock treading on pastures

Stock treading on pastures causes pugging and soil compaction, which can lead to bare ground, burial of pasture, degradation of soil quality (Singleton & Addison 1999; Drewry et al. 2008), and sediment loss, particularly via overland flow (Monaghan et al. 2017; MfE 2023c).

Soil pugging typically occurs when soil pores (macropores) are filled with water, in wet, soft soil, causing deformation under animal treading, deep hoof imprints, and a smeared soil surface (Singleton & Addison 1999; Drewry et al. 2008; Houlbrooke et al. 2021). Soil water infiltration can be reduced by pugging of pastures, resulting in overland flow carrying sediment and nutrients.

Pugging has had a long-term effect on the physical properties and structure of Allophanic and Gley soils on Waikato and Northland dairy farms (Singleton & Addison 1999; Singleton et al. 2000). The Gley soils are the Te Kowhai silt loam and Hauraki clay loam, while the Allophanic soil is the Horotiu silt loam. Singleton and Addison (1999) showed a decline in values for soil physical properties on Waikato dairy farms, from those that were never trodden, to normally grazed, through to those that were previously pugged. Hydraulic conductivity and soil macropores were reduced, suggesting that practices that minimise pugging damage, such as on/off grazing, should be encouraged (Singleton & Addison 1999).

A number of other Waikato studies have examined soil pugging and compaction, also reporting the detrimental effects of treading on soil structure (Zegwaard 2006). Recovery of soil by natural processes can occur after winter grazing and pugging events, with one study examining recovery on Waikato Gley and Allophanic soils (Drewry et al. 2003). That study showed that hydraulic conductivity was greatly reduced after pugging but recovered over 14 weeks.

Despite these studies, research on the effect of soil compaction and treading on soil drainage properties is lacking from New Zealand, including Waikato. Studies of nutrient, contaminant and sediment loss via runoff are also limited (Hu et al. 2021), including Waikato, with many being from Otago (e.g. McDowell et al. 2005; Curran-Cournane et al. 2011). However, several Waikato studies have examined sediment loss on hill country (Nguyen et al. 1998; Tian et al. 1998, see section 7). Soil structural degradation from treading damage increases the risk of runoff and flooding, so the potential effects, including sediment losses, are likely to have a greater incidence with extreme weather due to climate change, but this requires further evaluation (Houlbrooke et al. 2021).

8.2 Intensive winter grazing of forage crops

Cattle treading and grazing on winter forage crops has been identified as a large source of sediment losses (e.g. McDowell et al. 2003; Burkitt et al. 2017; Monaghan et al. 2017). Surface soil erosion from grazed winter forage crops is typically much greater than for other land uses. For example, Donovan (2022), in a study that included Waikato catchments, reported that modelled surface soil erosion from winter forage crops was 11 t/ha/yr, compared with 0.83 t/ha/yr from pasture. In that study an effect of animal treading was included, which on average increased soil erodibility by 3.3–9%. Donovan (2022) reported that the most pronounced effects occurred in winter due to the impacts of intensive forage crop grazing.

Soil type influences the loss of sediment via overland flow. For example, winter swede crops were established on both an imperfectly and a well-drained soil in Manawatū. Burkitt et al. (2017) showed that sediment losses from overland flow were 5.5 times greater on the imperfectly drained Pallic soil compared with the well-drained Brown soil. Also, considerable visual soil pugging damage occurred on the imperfectly drained soil (MfE 2023c). Donovan

(2022) reported that soil erodibility was generally inversely related to soil permeability. Sediment can also be dislodged and moved by direct hoof action downslope in winter forage crops (Penny et al. 2016).

To build on earlier satellite mapping of intensive winter grazing of forage crops in hill country (Belliss et al. 2019; North et al. 2022), more recent research included all lowland as well as hill country, and ground-truthing in the field during 2022. Crops can vary by region; in the Waikato, brassicas can be grown in summer, or maize in summer and then a winter oat crop (Belliss et al. 2023). They also reported from their study that Waikato winter-grazed forage crops are predominately brassicas (over 90%), with the remainder being cereal crops.

Belliss et al. (2023) also reported that the Waikato region has 4,818 ha (0.4% of all agricultural land including hill country) identified as winter forage area, excluding heavily grazed pasture. Of this, 2,358 ha (0.2% of all agricultural land, including hill country) is winter forage and bare ground, with a good level of certainty obtained by the satellite method used.

Management of CSAs in winter-grazed crops is also important, as discussed in sections 4 and 6.

8.3 Farm lanes and tracks

Farm tracks, gates, and raceways, particularly on dairy farms, have been identified as major sources of sediment, nutrient and bacteria loss (Lucci et al. 2010; Monaghan & Smith 2012). Although assessments of laneway sediment contributions to catchment-scale discharges have indicated that laneways make a minor contribution to annual sediment loads, laneways are a potentially important local source to streams in summer, when streams are low, especially if poorly designed lanes discharge to water (Monaghan & Smith 2012). Although all of these studies have been conducted in other regions, it is likely that similar issues apply in Waikato.

In a 2017 survey of soil stability, particularly of bare ground, farm tracks (excluding buildings and yards) contributed to 77% of bare soil on dairy farms and 37% on drystock farms across the Waikato region (Norris & Wyatt 2023). However, the overall percentage of bare soil on these land uses was small: dairy systems had the highest proportion of bare soil caused by land-use activities (0.75% of the sampled area), followed by drystock (0.3%), forest plantations (0.17), and horticulture/cropping (0.13%) (Norris & Wyatt 2023).

8.4 Vegetable cropping

There are several studies on the impacts of vegetable cropping and market gardening on erosion and sediment loss (e.g. Basher et al. 1997; Basher & Ross 2001). Rates of soil redistribution by water and tillage erosion were determined in three fields under long-term continuous vegetable production on clay loam: strongly structured soils derived from volcanic ash at Pukekohe (Basher & Ross 2002). Most of the soil redistribution is caused by water erosion, with tillage erosion accounting for 10–20% of the soil redistribution. The soil redistribution rates were two orders of magnitude higher than sediment export measured at the soil catchment scale. These and earlier studies indicated the importance of the winter–spring period for sediment generation.

Intensive vegetable production can degrade soil structure and reduce soil carbon, which can lead to soil erosion. On Granular soils in Pukekohe, net soil loss in paddocks was estimated as ranging from 30 to 7 t/ha/yr (Basher & Ross 2002), with much higher rates of erosion and deposition within the paddocks. This suggested that soil redistribution rates in paddocks are much higher than sediment export when measured at a small catchment scale.

On Allophanic soils near Ohakune, mean erosion rates were low in paddocks (5 and 16 t/ha/yr). However, there was a wide range of erosion and deposition within the paddocks (–145 (indicating erosion) to +514 t/ha/yr (indicating deposition)) (Basher et al. 2004). The study reported that water erosion was the dominant mechanism, and no wind erosion was observed.

9 Erosion in urban areas and mining

9.1 Urban areas

9.1.1 Overview and types of erosion

Development associated with urban earthworks and roading is a major source of sediment generation. All councils have controls on ESC associated with earthworks, including WRC. In recent years there has been increasing emphasis on ESC for earthworks in urban environments, infrastructure projects, and (latterly) forestry in some regions. The growth of ESC in urban environments has been driven by extensive land and infrastructure development in the main centres, particularly where there is the potential for severe effects in receiving environments, such as in Auckland. In part, the growth in ESC reflects international trends and the development of products and services related to ESC, as well as the recognition that these are more 'controllable' than what occurs in the rural environment, because the capital asset values are often greater and the visibility of these activities is high.

The predominant erosion process in urban environments is surface erosion (splash, sheet, and rill). Surface erosion typically occurs on bare ground, such as land exposed by earthworks. Factors that influence surface erosion include slope angle and length, aspect, soil texture, compaction, and rainfall, especially rainfall intensity and duration.

Areas with deep Pumice soils in the Taupō region are likely to be prone to tunnel gully erosion. For example, in the Acacia Heights area, Taupō, the catchment is vulnerable to sheet and gully erosion if vegetation cover is removed or degraded on Pumice soils (Simcock 2006).

9.2 Other sources – mining

The effects of historical mining include disposal of mine tailings into streams and rivers. Mining, along with other land activities that cause erosion, result in sedimentation, which causes reductions in water clarity, smothering of organisms, deterring the migratory stages of native fish, and reduced algal growth due to reduced light penetration, resulting in lower benthic primary production and invertebrate density (Harding et al. 2000; Cavanagh et al. 2018). Several studies on the impacts from gold mining, including sedimentation in the Waitaia, Waiomu, and Buffalo catchments in the Coromandel Peninsula, were reviewed by Harding et al. (2000). Stream species' taxonomic richness was reduced in affected sites downstream of mines in these catchments, leading to changed invertebrate community composition.

In the Coromandel, Clement et al. (2017) reported an ongoing moderate threat to the aquatic ecosystems in the Ohinemuri and Waihou rivers arising from a legacy of mining in small, short, steep catchments between Waiomu and Thames, where large amounts of mine waste were deposited on the floodplain during flood events in the early twentieth century. There is a sizeable legacy store, and probably ongoing suspended sediment movement and redistribution.

Roads in mining areas, including quarries, can also be sources of sediment (Cavanagh et al. 2018). Further details related to mining are provided in Cavanagh et al. 2018, including environmental effects, and the development of mine environmental life-cycle guides, which collate the minerals sector environmental planning tools and provide guidance from mine operation to post-closure. Examples for the Waikato region include rehabilitation (revegetation) of the abandoned Tui mine, at Mt Te Aroha, to reduce sediment and other contaminant losses, and the Waikato coal mine (Cavanagh et al. 2018). Further details and references for the Waikato region are available in Cavanagh et al. 2018.

10 Discussion

10.1 Information sources

There are significant amounts of information available on erosion control methods and approaches, much of it tailored to local conditions and regions. All regional councils and district councils have information on practices, what plants to use, etc. on their websites, either as downloadable factsheets, guidelines, or reports.

WRC has developed the 'Waikato Prioritisation Framework', a tool underpinned by spatial analysis, for prioritising soil conservation, estimating costs, and visualisation. The tool provides two riparian management mitigations (fencing and woody vegetation) and four hillslope mitigations based on land limitations and the presence of active erosion (Norris et al. 2021).

Currently the most comprehensive 'one-stop-shop' for information on farming/agricultural best practices as they pertain to controlling erosion and reducing sediment getting into waterways is located on the 'LandscapeDNA' website (https://landscapedna.org/). This work was, in part, supported by the Our Land & Water National Science Challenge. The site provides a range of actions that identify on-farm methods suited to the physiographic conditions of any locality in New Zealand, including the Waikato region. For some actions, detailed information on costs and performance are also provided. Each action is supported by appropriate references.

10.2 Modelling

This section reports on catchment sediment modelling to provide a brief context. A parallel study of catchment erosion and suspended sediment load modelling for the Waikato region is currently being undertaken by MWLR using the latest version of SedNetNZ (Dymond et al. 2016; Smith et al. 2019).

Sediment modelling has been carried out for parts of the Waikato region using several different approaches (Palmer et al. 2013, 2015; Betts et al. 2017; Haddadchi & Hicks 2016), including application of an earlier version of the SedNetNZ model. National models of erosion and sediment yield estimation also include the Waikato region (Hicks et al. 2011; Donovan & Monaghan 2021; Donovan 2022; Neverman et al. 2023). Such models help provide the link between erosion sources and processes and sediment loads within catchments, which enables mitigation efforts to be prioritised for catchments with either the greatest sediment loads and/or the greatest likelihood that mitigation will reduce sediment loads.

Fernandez and Daigneault (2017) assessed the economic implications to agriculture of the adoption of mitigation alternatives for erosion control in the Waikato District and found that achieving surface erosion targets is more expensive than mass-movement targets, and results in different responses in terms of regional-level costs, land use, enterprise net revenue, and adoption of mitigation alternatives.

Donovan (2022) provided the first national-scale soil erosion model to incorporate the impacts of grazing on ground cover (Cgr) and soil erodibility (Ktr) into the Revised Universal Soil Loss Equation (RUSLE) framework. Surface erosion rates for winter-forage paddocks (11 t/ha/yr) were substantially higher than for pastoral grasslands (0.83 t/ha/yr), woody grasslands (0.098 t/ha/yr), forests (0.103 t/ha/yr), and natural soil production rates (≤1–2 t/ha/yr). The RUSLE model represents surface erosion processes only and does not include other processes such as landslide or gully erosion.

The impact of climate change on erosion and suspended sediment loads has been evaluated across New Zealand, including the Waikato region. Sediment loads were estimated for future climate change scenarios by Neverman et al. (2023). That study estimated that a disproportionate increase in mass movement erosion would be expected in soft-rock hill country, while many catchments would be likely to experience large increases in sediment yield by the end of this century. Changes in total suspended sediment loads under future climate scenarios were predicted to be 28–57% for 2040, and 25–121% for 2090 in the Waikato region (Neverman et al. 2023). That study concluded that it is important for policymakers and managers to consider spatial variations in the magnitude and extent of climate impacts when assessing the feasibility of policy and mitigation plans, and to prioritise erosion mitigation efforts.

10.3 Research gaps and data needs

The following knowledge and data gaps were identified while preparing this report. Considerable knowledge about erosion and sediment process has been gained from studies in other regions in New Zealand, so we have reviewed these where they are relevant to the Waikato region.

1 Cattle treading and winter forage crops

The effect of cattle treading on soil physical properties has been well studied in Waikato. However, the effect of cattle treading on soil drainage properties is lacking. Studies of sediment loss via runoff in cattle-grazed intensive winter cropping are also limited, as many of the studies are from Otago. (Several of those studies were small-scale plot studies so may not be representative of loads at larger scale.) Intensive winter grazing on forage crops has been identified as a large source of sediment losses in other regions, but further research is needed for crops used in the Waikato; i.e. predominately brassicas (over 90%) with some cereal crops. Further research is also needed on the effectiveness of mitigations under a range of stock types for grazed intensive winter cropping, given that much of the available research is from southern New Zealand.

2 Waikato-specific treading damage and sediment loss

Soil structural degradation from treading damage increases the risk of runoff and flooding, so the potential effects (including sediment losses) are likely to have a greater incidence with extreme weather due to climate change, but this requires further evaluation. There is a gap in the literature for the Waikato region on mitigating treading damage and treading-induced sediment loss.

3 Farm plan monitoring

Farm plans are an important tool to reduce sediment loads to streams. With new NPS-FM regulations requiring widespread implementation of farm plans in Waikato from 1 August 2023, further research is needed to monitor farm practices and associated farm data to enable full evaluation of the impact these will have in the long term in the Waikato region. The capture of standardised data will help provide an understanding of the relationship between trends in water quality and on-farm action.

4 Effectiveness of mitigations and monitoring

A reasonable amount is known about the various erosion processes and the 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, are relatively scarce, particularly in relation to different soil types, regions, and climatic variables such as triggering storm rainfalls. This applies equally to the Waikato region.

There is a need to conduct monitoring to better understand the effectiveness of different ESC measures in Waikato catchments. At a catchment scale, data and information should be prioritised to ensure the best results from the investment occur.

5 Detainment bunds

Research on detainment bunds has been undertaken in the Bay of Plenty region but is likely to be relevant for similar soils in the Waikato. Further research is recommended, including on costs vs benefits, sediment size characterisation, longer-term studies, and the causes of reduced infiltration in dairy pastures.

6 Slash entrainment by landslides

In plantation forestry, storm-induced, post-harvest shallow landslides evolve into debris flows that entrain wood debris from slopes and in gullies/streamlines. While not a significant problem for much of the Waikato region's forests, the Coromandel Peninsula has experienced issues similar to those seen on the East Coast following intense rain storms or cyclones such as Cyclone Gabrielle. There is thus a need to develop a risk assessment and risk management approach for any forestry land that is steeper than 25˚, is likely to be affected by rainfall-triggered landslides, and has sensitive downstream communities, waterways, lakes or estuaries.

7 Edge-of-field mitigations and wetlands

Further research is needed to ensure no unintended impacts or pollution swapping occur with edge-of-field mitigations. There is a need for more on-farm demonstration and learning to build the capability of farmers and rural professionals. Sediment removal by seepage wetlands has not generally been well studied, although some research has been undertaken in the Waikato.

8 Riparian management

There are a number of barriers and knowledge gaps inhibiting more effective use of riparian management (including clear goals by communities), and buffer placement, width and length need further assessment. There has been very little quantitative research on rates of bank erosion or mitigation of bank erosion in New Zealand. Careful riparian mitigation design is needed for non-uniform runoff flow, and there are ongoing effects of legacy deposits of sediment in pastoral streams. It is difficult to separate the effect of livestock exclusion from riparian areas from the impacts of other concurrent mitigations in catchment-scale studies.

9 Other

Further research is needed on the impacts associated with the transition of land use from pine plantation to pasture, or to native/regenerating species such as kānuka and mānuka, and other mitigations. This includes the management of wilding seedlings, and the post-harvest window of vulnerability where rainfall-triggered landslides have the potential to recruit and deliver woody debris from slopes to downstream floodplains.

11 Summary of key findings

Both in general terms, and for the Waikato region, the effectiveness of various control treatments for erosion 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.

1 Erosion and sediment reduction, by land use

- 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 for minimising soil loss by surface erosion.
- In cropland, ripping of wheel tracks reduced erosion by up to 95% on strongly structured clay soils.
- At Pukekohe, a cover crop trial produced a relatively small reduction in soil loss (26–38%), though in other studies this was up to 90%.
- Surface soil erosion from grazed winter forage crops is typically much greater than for other land uses such as pasture and is related to the area of bare ground. A recently studied mitigation, ‘strategic grazing’ (from top of slope), in grazed winter forage crops greatly reduced sediment losses.
- Careful management of critical source areas is important to reduce sediment losses.
- Detainment bunds and similar structures generally work well for reducing sediment loss, but it is important to optimise the design and allow adequate settling time. Such structures may be less effective in high-flow events.
- In urban environments, many studies have reported an order of magnitude or greater reduction in sediment loads and concentrations resulting from the use of sediment controls. 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. This also applies to mining and highway construction.

2 Erosion reduction for landsliding using space-planted trees

- A small number of quantitative studies have measured the effectiveness of individual trees or small groups of trees in pastoral farmland.
- Reductions in landsliding using space-planted trees can range from 70 to 95%, but measured or assessed reductions are often far less than this because plantings are inadequate.
- Individual mature trees influence the amount of landsliding within a radius of c. 10 m.
- Poor survival of trees has been identified as a major constraint on the performance of space-planted trees (due to poor pre-treatment of poles, poor planting technique, site factors, and stock damage).
- Trees younger than about 8 years, before canopy closure, are less effective than older, closed-canopy trees.

3 Plantations and roads

- Mature, closed-canopy, indigenous or exotic forest typically reduces sediment yield by 50–90% compared to pasture catchments and landsliding by 90%. Forests are also used to control severe gully erosion and reduce rates of earthflow movement.
- 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 they have the potential to generate significantly more than when in operation.
- There appear to have been no New Zealand studies that are forestry-specific to test whether the ESC design criteria in council guidelines are appropriate.

4 Bank erosion and riparian buffers

- 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, and this is a definite research need.
- 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.
- 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, vegetation density, etc). The first few metres of a buffer play a dominant role in sediment trapping.
- A combination of 'soft' biological erosion control and 'hard' engineering works is used to control bank erosion, along with stock exclusion.
- Riparian buffer strips are commonly used to reduce sediment input from surface erosion to streams and have been shown to reduce sediment input by over 50%.
- Research suggests that 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.

5 Summary of erosion and sediment reduction from ESC practices

In summary, the commonly used values for erosion and sediment reduction as a result of ESC practices are as follows:

- 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%.

6 Other findings

- The impact of climate change on erosion and sediment loads suggests a disproportionate increase in mass movement erosion compared to other erosion processes would be expected in soft-rock hill country, while many catchments are likely to experience large increases in sediment yield by the end of this century.

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

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), which 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 runoff 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 that 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. A culvert can connect a drain to a stable outfall and sump 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 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 dyking	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	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	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	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	Hicks & Anthony 2001
Contour furrows	Furrow constructed with slight gradient to break up slope to control runoff	Slope, spacing, contributing area, soil type	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	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	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	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	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,	Hicks & Anthony 2001
Surface recontouring	Smoothing the land surface to enhance runoff, reduce ponding and soil water content	Location, topography, soil materials	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	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	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	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	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	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	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	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	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	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	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	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	Hicks 1995