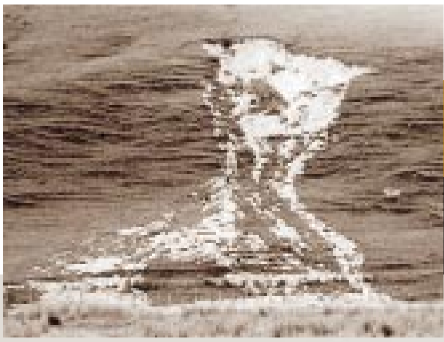

Soil Conservation Technical Handbook

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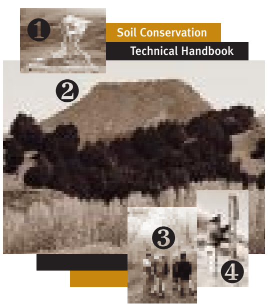

Cover Photography

❶ ***Slip erosion.*** *Photo: H Cairns.*

❷ ***Mount Hikurangi and poplars, Central North Island.*** *Photo: Guy Vickers.*

❸ ***A graded bank and space planted trees on an earthflow.*** *Photo: Don Miller.*

❹ ***Pole planting.*** *Photo: H Cairns.*

Preface

New Zealand has a history of land management that has resulted in soil erosion; silted-up streams rivers and estuaries; algal blooms and dense growth of aquatic weeds from nutrient-rich runoff. While considerable progress has been made in achieving more sustainable land production, significant problems still remain.

National awareness of soil erosion on hill country in New Zealand was polarised by storm events in the 1930s and 1940s, mostly in the Esk Valley, the Wanganui catchment, Marlborough and the Waipaoa basin. These and subsequent storms initiated soil erosion on a massive scale on the then recently developed pastoral hill country.

The strong northwest winds on the dry plains on the east coasts of the North and South Islands have caused tremendous soil loss in the past. It is only after the control of rabbits and the establishment of wind breaks and vegetative cover on the bare earth that this form of erosion has been bought under control.

It was primarily because of the fears that low-lying communities would be inundated if soil erosion continued unchecked, that the Soil Conservation and Rivers Control Act was passed in 1941. This Act established catchment boards and enabled the appropriation of government and local body funds to assist with the construction of erosion control measures and flood protection works.

Why are we so interested in sustainable land management and promoting the work in the Soil Conservation Technical Handbook? I can list four key reasons.

- Soil erosion affects downstream communities and the natural environment by increasing the risk of flooding and causing damage through silt depositions.

- Our reputation for “quality goods from a quality environment” depends on sustainable land use practices. Soil erosion is a very visible negative impact of pastoral land use. That image may affect our “clean green” image and trade in the future.

- We care about future generations, and that means ensuring ample soil remains available to sustain agricultural production capacity.

- We want to protect our biodiversity. Our terrestrial biodiversity is dependent on the quality of our soils and its carrying capacity and we want to protect our freshwater and estuarine aquatic biodiversity.

Soil conservators have long been a corner-stone of sustainable land management in New Zealand. Techniques have been developed over the years based on engineering and scientific principles, as well as some trial and error and time-honoured Kiwi ingenuity that adapts techniques to regional conditions.

For the first time in New Zealand we have in one place, a comprehensive range of practical field-tested soil conservation practices and techniques. This handbook has been written by experienced soil conservators drawing on their own and their colleagues practical experience, under-pinned by the science undertaken on the subject for the last 50 years.

Another important area of land management, namely riparian management, is not covered in depth in this publication. Instead, readers are referred to the MfE publication *“Managing Waterways on Farms”*. This publication is complementary to the Handbook, as they are both based on the same principle of gathering together field-tested techniques and allowing for additional information to be added.

This Handbook is a valuable resource for regional council land management officers. It is also useful for anyone interested in understanding erosion processes and wanting to learn more about preventing and rehabilitating sites. Readers can expect to gain a working knowledge of erosion types and practical recommendations for prevention and rehabilitation.

Finally I want to acknowledge the stewardship role of the New Zealand Association of Resource Management (NZARM), who represent one of the main groups of practitioners who will be using the information in this Handbook. This Association has demonstrated its support for the project by undertaking the publishing and printing of this document. I commend NZARM for its foresight. It is this sort of initiative that will ensure that the Handbook will be used by its members and most importantly be updated when new information and practices come to hand.

Denise F Church
Chief Executive
Ministry for the Environment
June 2001

Introduction

The *Soil Conservation Technical Handbook* is a comprehensive collection of know how about soil conservation in New Zealand. Information has been gathered from individual knowledge and personal notes along with past often unpublished, or scarce copies of, printed material. Some of this material is derived from internal regional council manuals and papers.

The main forms of erosion in New Zealand are covered in this Technical Handbook.

- **Mass movement erosion** – which occurs when heavy rain or earthquakes cause whole slopes to slump, slip or landslide. Most hill slopes steeper than 15 degrees are susceptible to mass movement, and those steeper than 28 degrees generally have severe potential. Storms are the primary triggers. This is the most common form of erosion in the hill country.

- **Fluvial erosion** – which occurs when running water gouges shallow channels or deeper gullies into the soil. On sloping land the gullies can cut deep into the subsoil or undermine surrounding soils.

- **Surface erosion** – which occurs when wind, rain or frost detach soil particles from the surface, allowing them to be washed or blown off the paddock. Surface erosion can occur on any land which is exposed to wind and rain but occurs largely outside the hill country.

- **Sediment erosion** – activities involved in earthworks, plantation forests, cropland and pasture management may all result in significant sediment loads being mobilised and often entering watercourses.

The Handbook is divided into two main parts. Part A covers the forms and processes of the main types of erosion in New Zealand. Readers can expect to gain a working understanding of erosion types, their typical geographic locations, as well as the overall principles of control. Descriptions are written from a practical point of view. More technical descriptions can be found in the references provided. A table at the end of each chapter summaries the main control technique headings and is cross-referenced to Part B.

Part B describes the control techniques. In most cases the Handbook will provide enough information for the practitioner to put together a soil conservation programme. Where more details (mostly engineering) are needed readers are referred to more specialised text. Often techniques apply to more than one erosion type and situation, for example maintaining good pasture cover is important in many situations. In these cases, general guidelines are given, as it is recognised that regional conditions will often dictate specific actions required.

The Handbook has been formatted so additional information can be added at anytime. It is anticipated that additional written material will be prepared in the future on associated land management topics and issues (for example indigenous biodiversity) as the demand requires. Space has also been provided for personal notes.

Part A
Principles

Contents – Part A

Tables

Chapter 1 Wind Erosion

Wind Erosion

1.1 Introduction

Wind erosion is the detachment and transportation of soil particles by wind when the airstream passing over a surface generates sufficient lift and drag to overcome the forces of gravity, friction and cohesion. Once a particle has been dislodged from the surface, it may be transported in suspension or by saltation or by surface creep. In high country, soil particles are often dislodged by needle ice formation and then removed by wind.

“Wind erosion, unlike soil erosion by running water, is often a rather subtle process, despite the quantity of sediment removed. Physical indicators of wind erosion, such as sand shadows behind obstructions and sediment ripples in fields, tend to be less obvious to the observer than the rill channels or large gullies cut by fluvial processes. Loss of topsoil by wind erosion over a relatively short time period can significantly decrease soil fertility and crop yield. Plant nutrients bound to soil colloids and organic matter can be removed from fields within small soil units (aggregates <0.2 mm diameter) that are readily transported by wind.” (Nickling and FitzSimons, 1985)

Wind erosion can also downgrade air quality and contribute to air pollution. Dust particles in the range of 0.25 to 10.0 microns aerodynamic diameter can originate from farms and be carried up to 10,000 metres elevation in the regional airmass. The table below gives a useful overview of some of the effects of wind erosion.

1.1.1 Impacts on land use

For wind to erode soil, the following conditions need to be present:

- poorly aggregated soils

Table 1.1 Some physical and economic effects of wind erosion (after Wilson and Cooke, 1980)

Physical Effects	Economic Consequences
Soil Damage	
1 Fine material, including organic matter, may be removed by sorting, leaving a coarse lag.	1, 2, 3 Long-term losses of fertility give lower returns per hectare.
2 Soil structures may be degraded.	
3 Fertilisers and herbicides may be lost or redistributed.	3 Replacement costs of fertilisers and herbicides.
Crop Damage	
1 The crop may be covered by deposited material.	1-6 Yield losses give lower returns.
2 Sandblasting may cut down plants or damage the foliage.	1-4 Replacement costs, and yield losses due to lost growing season.
3 Seeds and seedlings may be blown away and deposited in hedges or other fields.	
4 Fertiliser redistributed into large concentrations can be harmful.	
5 Soil borne disease may be spread to other fields.	5 Increased herbicide costs.
6 Rabbits and other pests may inhabit dunes trapped in hedges and feed on the crops.	6 Increased pest control costs
Other Damage	
1 Soil is deposited in ditches, hedges, and on roads.	1 Costs of removal and redistribution.
2 Fine material is deposited in houses, on washing and cars, etc.	2, 3 Cleaning costs.
3 Farm machinery, windscreens etc. may be abraded, and machinery clogged.	
4 Farm work may be held up by the unpleasant conditions during a blow.	4 Loss of working hours and hence productivity declines.

- surface soils that are loose, dry and finely divided
- wind that is strong enough to move soil.

In general, the finer and drier the soil, the easier it is eroded by wind when exposed through lack of vegetative cover. In New Zealand, wind erosion can occur from seashore to mountaintops. Areas exposed to either coastal winds (prevailing westerly) or föhn winds the nor'westers), have been known to erode severely while soils were exposed. Basher and Painter (1997) cite background rates <0.2 t/ha/yr, extreme storm event losses >3000t/ha, and "average" storm losses ranging from 20–125 t/ha

These losses result in soil quality deterioration. In South Canterbury, Cuff (1981) estimated the following losses if 5 mm of soil depth is lost; this would be equivalent to 50 t/ha:

Active wind erosion, Hakataramea. ***Photo: MWD.***

- nitrogen – 175 kg
- phosphorus – 45 kg
- potassium – 500 kg
- magnesium – 325 kg
- calcium – 525 kg

Since shallow soils retain less moisture than deeper soils, the cost of erosion may also be expressed in long-term production losses. Hayward (1969) gives examples of chou moellier crop yields in North Otago on soils of different depths:

- for topsoil depth of 300–375 mm, yields averaged 55 t/ha.
- for shallower soils near hilltops with depths of 75–225 mm, yields averaged 20 t/ha.

Benny and Stephens 1985 reported soil losses of 11-41 tonnes/ha/year on unprotected soils in South Canterbury, compared with 1.5 – 1.8 tones where conservation measures were practised. Wheat yields on the unprotected sites averaged 3.1 tonnes/hectare compared with 3.7 tonnes on the protected sites. Basher (1997) provides more detailed figures on erosion rates and areal extent for all erosion types occurring in the Canterbury Region, including wind.

1.2 Forms, processes and extent of wind erosion

1.2.1 Forms and processes

When wind blows across bare ground, grains of soil or rock are eroded if the stress exerted on them by air turbulence exceeds the forces that resist movement – that is, gravitational stress, together with friction and cohesion amongst the surface particles. Once entrained in the flowing air, grains are transported so long as the stress exerted on them by wind exceeds the force exerted by gravity. If wind stress declines – due to a drop in wind velocity – or if grains' momentum reduces – due to particle collision, or passage through vegetation – they are deposited.

The physics of the process constrains wind erosion to places where velocity and turbulence are high: exposed coasts; plains or broad valleys; and mountain ridges.

Wind erosion occurs only in places where soil is susceptible. Clay is rarely eroded by wind. Although its particles are extremely small, they have high cohesion. At the other extreme, gravel or stone fragments are rarely eroded. Although they lack cohesion, their particles are sufficiently large for the force of gravity to outweigh all but the most extreme wind stress.

Silt grains are easily eroded from topsoil by wind, because their particle size is very small and their cohesion is moderate. Sand grains are also eroded from topsoil, from beaches and from riverbeds, because their particle size is still sufficiently small to be entrained by wind, and their cohesion is low.

There are three characteristic forms of wind erosion:

- Wind blow: Just a millimetre or two of silty or sandy topsoil is stripped away, leaving no perceptible erosion scar. The transport process is visible as a cloud of dust. Silt or sand eventually settles downwind, many kilometres away. If repeated and persistent, deposits accumulate around the stems of growing vegetation as a thick even blanket of new soil.

- Wind scabs (deflation surfaces): Several centimetres of topsoil are stripped away by repeated wind blow, from a patch of ground several square metres in extent. The surface of the patch may be more resistant subsoil or a "lag" of gravel and stones left behind after fine particles have been blown from the topsoil. When large volumes of soil are eroded from scabs, much may be deposited a short distance downwind, forming drifts up to a metre high piled against obstructions like fences, shrubby vegetation, or hill slopes.

- Dunes: Many metres depth of sand is blown across the landscape leeward of beaches, as a result of alternate erosion of grains from the dune's windward side, of transport across its crest, and of deposition on the dune's leeward side. Different forms of coastal sand dune are described in Chapter 7, Sand Dune Stabilisation. At some places in New Zealand's inland landscape, thick deposits of river silt or volcanic ash have also been shaped into "fields" of small dunes, individually a few metres high and long.

For greater detail, see Bagnold (1941) for a definitive account of the physics of wind erosion, Painter (1978) for an account of the New Zealand landscape's susceptibility to wind erosion, and Cooke and Warren (1973) for comprehensive descriptions of the geomorphology.

1.2.2 Wind erosion research

Wind erosion has been the subject of research in the USA since the 1930s (see Fryrear et al's 2000 study). The first Wind Erosion Equation (WEQ) to quantify wind erosion was published by Woodruff and Siddoway in 1965. In 1996, Shao et al developed a physically based Wind Erosion Assessment Model (WEAM) to estimate erosion event movement across continents. A more process-oriented Wind Erosion Prediction System (WEPS) is under development (Hagen, 1991). Fryrear and colleagues describe a Revised Wind Erosion Equation (RWEQ) based on the parameters wind force, surface roughness, soil wetness, and crop residue or crop canopy.

Fifty years of wind erosion research by the USDA, Agricultural Research Service at Kansas State University was celebrated with a symposium in 1997, the proceedings of which may be accessed at www.weru.ksu.edu/symposium/proceed.htm.

In New Zealand, the problem was recognised as early as 1858 by Ferdinand von Hochstetter in his book, New Zealand. Its physical geography, Geology and Natural History. The first attempt to quantify soil losses resulting from wind erosion was that by Campbell (1945), who used a portable blower on a number of North Island east coast soils. He varied the speed of the blower to simulate soils under pasture and cultivation. The values of soil loss ranged from nil to 1668 t/ha/yr.

The forms and processes of wind were first described by Cockayne (1913) for sand country, and by Cumberland (1944) for arable land and depleted tussock rangeland. Much of the research into forms and processes has been undertaken in sand country; well-known work includes that of Brothers (1954), Cowie (1967), Hicks (1975) and Hesp (1990). Some research into the geomorphology of wind erosion on arable land is contained in unpublished reports and theses by Painter (1977, 1978) and his students. More detailed investigations have been carried out in recent years by Basher et al (1997, 2000).

A major review of erosion risk on arable soils (Ross et al, 2000) has been prepared for Environment Canterbury and is an essential reference on this topic.

In New Zealand's environment, the major factors affecting the occurrence of wind erosion, and its extent and severity, are:

- climate (wind patterns, precipitation, frost action)
- soil (texture, moisture, structure, organic matter content)
- topography (exposure, elevation, terrain roughness, localised funnelling of wind)
- cultural practices (cultivation, vegetation depletion).

Looking at these factors, it is clear that the near-surface soil water content is an important influence on wind erosion rates in New Zealand, where the evaporative energy supply can be very high and can rapidly reduce the near-surface water content. The soil's resistance to evaporative flux, combined with soil erodibility (for the predominantly light textured soils of New Zealand) determines whether a soil will erode.

1.2.3 Extent in New Zealand

New Zealand Land Resource Inventory (NZLRI) survey assessed wind erosion (NWASCO, 1974-79). Data from this survey were summarised by Eyles (1983) and are reproduced in the following table. The distribution of wind erosion as mapped in the same survey is shown in Appendix II.

Table 1.2 Erosion rankings, North and South Islands (after Eyles, 1983)

	Erosion Ranking	Area (ha)	Area (%)
North Island*	1 slight	255,500	48.5
	2 moderate	131,700	25.0
	3 severe	67,400	12.8
	4 very severe	16,500	3.1
	5 extreme	55,800	10.6
South Island **	1 slight	1,620,900	77.9
	2 moderate	388,600	18.7
	3 severe	58,000	2.8
	4 very severe	12,000	0.6
	5 extreme	1,500	trace

* Areas are those of map units in which wind erosion was recorded, with the given ranking.
** Areas are those of map units in which wind erosion was the dominant type.

In 1984, Salter used NZLRI data to undertake a more detailed review of the distribution and severity of wind erosion in New Zealand. He found that approximately 13 percent (3.4 million hectares) was affected. Wind erosion affects 4.6 percent of the North Island, mainly in three environments:

- the mobile, coastal dunes on the west coast of Northland and the Rangitikei-Manawatu that have not yet been afforested or have poor grass cover
- high-altitude (>700 m), volcanic ash-mantled, slopes in the central North Island that have poor vegetation cover due to frequent strong winds and cool temperatures
- low-altitude, loess-mantled argillite hill country and alluvial terraces in the eastern North Island with low-fertility soils and severe seasonal soil moisture deficits.

In the South Island, wind erosion affects 19 percent of the land, mostly on loess-mantled terraces and slopes in low-rainfall, seasonally dry eastern regions subject to frequent strong föhn winds:

- extensive alluvial plains in Canterbury, Marlborough and Southland with silty alluvial soils on younger terraces and loess soils on older terraces, that are susceptible to wind erosion when cultivated
- loess-mantled downlands in Canterbury and North Otago, subject to wind erosion when cultivated
- large inland basins in central Otago, Canterbury and Southland with loess-mantled terraces and moraines where extensive grazing by sheep and rabbits has led to severe vegetation depletion
- the steep, dry mountain lands of Canterbury, Otago and Marlborough with severe summer soil moisture deficits and widespread vegetation depletion
- hill country with shallow soils, discontinuous loess cover, severe summer soil moisture deficits and localised vegetation depletion in North Canterbury

- the exposed rolling uplands of Otago where vegetation is depleted.

According to the NZLRI survey, the area potentially subject to wind erosion is much larger than the area already affected. Approximately 27 percent of New Zealand being susceptible: 7.1 million hectares of the North Island, and 5.8 million hectares of the South Island.

1.3 Principles of control

The techniques available to control wind erosion have one or more objectives in common:

- reduce the cause of erosion (eg, reduce local windspeeds)
- enhance resistance to erosion (eg, reduce soil erodibility)
- reduce the undesirable consequences of wind erosion (eg trapping saltating soil, reducing physiological damage to plants).

In 1997, Basher and Painter review the extent to which these objectives have been attained. They note that wind erosion control in New Zealand has been dominated by the use of vegetative cover to reduce entrainment of soil particles or to provide a barrier which reduces wind velocity. There has been little use of tillage to increase surface roughness and produce non-erodible aggregates, in spite of advocacy by soil conservators.

Baker (cited by Ross et al. 2000) similarly emphasised the various options now available to increase surface roughness and retain soil. Basher and Painter (1997) also consider that there is greater opportunity to use irrigation to increase surface soil moisture content, and reduce the hazard at times when soil would otherwise be susceptible to wind erosion. Mitigation of wind-borne dust emission, usually by spraying water or waste oil, from rural roads, construction sites, quarries and other industrial locations is increasingly practised.

1.4 Appropriate control practices

Table 3 summarises wind erosion control practices currently used on arable land, and at susceptible sites in the hill country and mountain lands. Control techniques include:

- shelterbelts
- pasture species and management
- cultivation and drilling practices
- stubble management
- adhesives and tackifiers
- irrigation.

For wind erosion control practices on sand country, refer to Chapter 5

Table 1.3 Summary of management practices for control of wind erosion.

Control Practice	Factors to Consider/ Technique		Refer to Part B for Practice Description
Shelterbelt	Siting Design Establishment Design description (various)		14.1 14.2 14.3 14.4
Pasture management & species	Revegetation	– Lowlands – Hill country – Mountain lands	4.1 4.2 4.3
	Pasture management	– Lowlands – Hill country – Tussock	2.1 2.2 2.3
Cultivation & drilling practice	Minimum tillage Direct drilling		1.3 1.4
Stubble management	Stubble retention		1.5
Others – adhesives & tackifier – irrigation			

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Chapter 2 Sheet and rill erosion

Sheet and rill erosion

2.1 Introduction

Running water removes soil and organic matter from gentle sloping land and steeper sites by a variety of processes which often start off as splash erosion leading to sheet wash and as the conditions change this will lead into rill erosion which in time on the deeper soils – that is, loess or volcanic material – may develop gullies. This chapter will concentrate on sheet and rill erosion of soil by overland flow of water, on arable flat-rolling land, downlands and lower foothills. Sheet erosion may often co-exist with rill erosion, and one may lead into the other.

2.1.1 History of sheet/rill erosion research

Despite the concern expressed about the magnitude of erosion and its impact on productivity, there have been few quantitative studies of surface erosion on arable land in New Zealand. Campbell (1945) showed that surface runoff as a percentage of rain under good grazed pasture was 42.2 percent compared to 0.3 percent for forest. Benny and Stephens (1985) estimated South Canterbury soil losses on a 12-degree slope of 40 t /ha/yr under annual cultivation, 23 t/ha/yr with ploughing one year in three, 3 t / ha/yr with continuous cropping and stubble mulching, and 0.4 t / ha / yr under permanent pasture.

Hunter and Lynn (1988, 1990) made measurements after storms in Canterbury. Basher (1997) reviewed the soil losses in Canterbury and identified high rates during storms of up to 11 mm through sheet and rill erosion. For cropping paddocks, there was considerable redistribution of the soil within paddocks as the soil was initially moved off slopes by rill erosion and deposited in swales, leaving a great variation of topsoil depths. There was a greater percentage of shallow topsoils under cropping than pasture, sufficient to impact on crop yields.

Basher et al (1997) published a summary of soil loss measurements at Pukekohe. This study showed that of the soil eroded within a paddock, a significant proportion was redeposited on lower slopes while a smaller proportion was delivered to streams. (Thompson and Basher 1999) identified some interesting factors due to an intense storm event at Pukekohe on 21 January 1999 where over 135 mm rainfall fell in four hours (exceeding the 1 in 100 year event). The soil was prone to downslope movement where slopes exceeded 4°. Paddocks steeper than 2° average slope which had seedbed preparation (eg, by rotary hoeing) had erosion rills, predominantly along wheel tracks, leading to more compound rill and sheet erosion further down the paddock as the runoff water increased in velocity. Erosion rates in some fields reached values as high as 600 t/ha. This meant an average loss of about 5 cm over the field, mainly due to rill erosion (sheet was considered only minor form); however, most soil was redeposited in nearby hollows or roadside drains.

2.1.2 Impacts on land use

Surface erosion can cause reductions of one to three-fifths in crop yield, two to four-fifths in pasture growth and up to nine-tenths in tussock biomass. Most of these production losses are reversible with appropriate soil conservation management.

In dryland areas like North Otago, Canterbury and Marlborough, soil losses on cultivated paddocks is still a regular occurrence. In North Otago between January and March 1986, it was estimated that 240 ha on 24 properties lost an average of 50 t/ha of fertile soil (5 mm depth of topsoil). This equates to 12,000 t of topsoil, which would require fertiliser estimated to cost $300,000 (1986 figures) to replace the major nutrients lost (Otago Regional Council, 1989).

Cuff (1978) estimated that typical nutrients lost after 10 mm topsoil is eroded equated to:

Total Nitrogen	350kg/ha
Total Phosphorus	90 kg/ha
Total Potassium	1000 kg/ha
Total Magnesium	650 kg/ha
Total Calcium	1050 kg/ha

2.2 Types, processes and extent

When rainwater runs off across bare ground, particles of soil or rock are eroded if three conditions exist:

- The soil's infiltration capacity is exceeded, so that water can build up instead of soaking into the soil. This condition may be met on dry soil during intense rain, but it more commonly occurs where infiltration capacity has been reduced to zero by water soaking in and saturating the soil beforehand. A related and equally common situation, is where water seeps from saturated soil and flows across its surface – that is, infiltration capacity turns negative.

- The water layer is sufficiently thick for gravitational stress on it to exceed capillary forces holding water to the soil's surface, so that water starts to flow instead of merely ponding.

- The stress exerted on soil particles by laminar or turbulent flow of water, is greater than the forces resisting movement – gravity, together with friction and cohesion amongst the soil particles.

Once entrained by water, particles are transported so long as the force of flowing water is sufficient to keep them clear of the surface (suspension) or bounce them along it (saltation). If water stress declines, for instance due to a drop in velocity where slope gradient lessens, or due to a drop in mass where some water soaks into the ground, then particles are deposited. This also happens if particles' momentum is reduced, for instance where they encounter vegetation at the bare ground's edge.

Fan deposited at slope foot, below rilled wheel tracks, Pukekohe. *Photo: D Hicks.*

The physics of the process determines where surface erosion is found in nature:

- areas subject to intense rainfall

- soils with low infiltration capacity or which quickly saturate

- depressions or breaks in slope, where soil water can converge and seep out.

Surface runoff rarely has sufficient mass or velocity to transport boulder or stones. Transportation of gravel occurs only if runoff is voluminous and fast. Sands and silts are most commonly transported by surface runoff, as they are easily entrained by a low volume of runoff moving at a slow velocity. Clays are less commonly entrained, as their cohesion gives greater resistance; but once in motion, their small particle size ensures they are transported a long distance before settling.

Three forms are left behind:

- Sheet wash is the almost-imperceptible removal of a few millimetres of topsoil at a time from parts of a slope. The process is visible as discontinuous sheets of surface runoff. A thin layer of soil is usually deposited a short distance away, where runoff slows and soaks in.

- Scabs are distinct scars where several centimetres of topsoil are removed from patches of slope several square metres in extent, by thin broad sheets of coalescing surface runoff (sheet flow). A distinct layer of soil is deposited if surface runoff encounters an obstacle, for instance dense grass or rising ground; but if not, soil is transported off the slope. It may be deposited at the slope foot if gradient lessens sheet flow's velocity sufficiently for particles to settle; if not, eroded soil will be delivered into the nearest permanent watercourse.

- Rills are long narrow miniature channels, where anything from 10 to 50 cm of topsoil is removed by surface runoff concentrated into thick narrow threads. Its volume and velocity being greater than sheet flow, rill flow usually transports eroded soil off slopes and into streams. Repeated erosion of the same rill may develop it into a gully (see Chapter 4, Gully Erosion).

Refer to Bagnold 1966 for a definitive account of the physics of surface erosion by water; Henderson 1983 for an account of the New Zealand landscape's susceptibility; and Leopold, Wolman and Miller 1964 (Chapters 8 and 10) for a comprehensive description of the geomorphology.

2.2.1 Extent

Surface erosion ie including sheet and wind (note it is difficult to separate soil loss from sheet and wind erosion) is found throughout NZ. NZLRI identified that 23.3 percent of the North Island and 74 percent of the South Island is susceptible to surface erosion. The following percentages indicate agricultural land that is susceptible to surface erosion processes:

- Otago 88 percent
- Canterbury 86 percent
- Nelson-Marlborough 77 percent
- Southland 59 percent
- Northland 41 percent
- Hawkes Bay 30 percent.

The trend drops to 6-9 percent in regions such as Taranaki, East Coast and Gisborne. where mass movement erosion predominates (Clough and Hicks 1993).

In the South Island, particularly east of the Southern Alps, loess is the most extensive soil-forming material. It underlies 7.45 million hectares – just over 51 percent of the soils (Raeside, 1964). However in some areas the amount of loess may be small; the stony soils on the Canterbury Plains are an example. In the North Island, the soils most susceptible are those formed from loess, volcanic ash, and pumice.

2.3 Principles of control

There are a number of interrelated factors, which can initiate and accelerate surface wash and removal of soil particles. Some common examples in New Zealand are:

- overgrazing by domestic farm animals (eg, due to large blocks with sunny and shady aspects)
- overgrazing by animal pests such as rabbits, hares, goats and feral animals

Localised rill erosion West Otago. **Photo: Otago Regional Council.**

- burning of native grassland/tussock and inter-tussock species
- burning of scrub and plant pests (eg matagouri, gorse and broom)
- burning of cereal crop stubble and removal of beneficial organic matter
- cultivation up- and down-slope and cultivating slopes over 20°
- cultivation at regular intervals growing similar crops/pasture
- compaction by stock and machinery and the formation of compaction pans in the soil
- which reduces normal water infiltration and increases overland flow
- cultivation of soil leaving a very fine tilth (ie, with a high percentage of particles smaller than 5-10 mm).
- forest harvesting with skidder hauling machinery
- dozing steep slopes

Maintaining and improving ground cover to ensure that all the surface layer has living or decomposing vegetative material on it will help protect soil particles from rainfall events. Control measures become more critical on steeper land ie greater than 12° slope where soils are loessial, of volcanic origin or sandy in nature.

Principles of control fall into three groups:

- Firstly, there is a need to carry out water management to ensure that surface runoff water is removed safely and does not speed up or concentrate so earthworks such as graded banks, contour furrows, strip cropping and floodbanks are constructed.

- Secondly, it is important to ensure that a healthy, vegetative ground cover exists over the soil for as long as possible. Practices that maintain or improve the soil fertility, soil organic matter, soil flora and fauna as well as utilising the best plant species for the site (eg, drought grasses for dryland districts and water-adapted plants for wetter sites) should be adopted. This would include practices such as cultivation management, conservation tillage, soil drainage and aeration and Land Use Capability management.
- Thirdly, it is important to ensure that ongoing soil, plant and farm management practices are maintained or improved on all susceptible sites.

2.4 Appropriate Soil Conservation Practices

See Table 2.1 below.

Table 2.1 Summary of management practices for control of sheet and rill erosion

Type of erosion	Primary Soil Conservation Principle	Factors to Consider	Examples of Practices*
Splash and sheet erosion (collectively called sheet erosion)	Ensure effective ground cover, soil structure and health be maintained and improved. Create a stable seedbed.	Rainfall, storm frequency, infiltration capacity Topography and aspect Slope angle, slope length Geology, regolith (loess, ash) Soil type (depth, texture, structure, percentage of organic matter) Past tillage and vegetation type and rotations Land use – pastoral, cropping, horticultural, forestry or urban use Stock type	Water control Conservation tillage Drainage and aeration Earthworks Stubble mulching Rotational cropping Pasture sward maintenance Matching crop and pasture species to the site Timing cultivation when soil conditions are right (low risk of erosion) Adjusting grazing pressure to soil conditions i.e. avoid heavy stocking when risk of erosion is high
Rill erosion	Ensure effective ground cover, soil structure and soil health be maintained and improved. Create a stable seedbed.	As above (often on steeper slopes)	As above,

*May use any one or a combination of them

Descriptions of the various practices for control of surface erosion are found in sections of Part B:
1. Cropland Management for Surface Erosion Control
2. Pasture Management for Surface Erosion Control
3. Fencing Management for Surface Erosion Control
4. Pasture Revegetation Practices
9. Runoff Control Practices – Lowland

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Chapter 3 Shallow Mass Movement – slip erosion

Shallow Mass Movement – slip erosion

3.1 Introduction

Slip erosion is a shallow and rapid sliding or flowing movement of the soil and subsoil, exposing a slip surface which is approximately parallel to the slope. Debris comes to rest in the area from the base of the exposed slip, to the toe of the slope. There can be some rotational movement, leaving a concave "slip surface" or failure plane. The failure plane is normally less than 1m (but sometime up to 2m) below the original surface.

It is most evident during or immediately after heavy rain. The basic reason for this is saturation of the soil, which increases the weight of the soil mass, lubricates the failure plane, and turns pore water pressure positive. The resisting forces are shear strength of the soil, cohesion of the material, and tensile strength of plant roots in the soil. The large scale clearing of forest cover from the 1870s on the hill country in New Zealand eventually resulted in widespread and accelerated slip erosion as well as other forms of mass movement.

This type of erosion is widespread on hill country throughout New Zealand. It is a natural process that occurs on all types of terrain and under all types of vegetation. Accelerated slip erosion may occur on unstable terrain when native forests are removed and replaced with grass, or between rotations of plantation forestry. Most slip erosion occurs during high intensity rainfall or prolonged wet periods when the regolith becomes saturated, pore pressures rise, and slope failure occurs.

Slip erosion is classified as either soil slip or earth slip in the NZLRI. (Eyles 1985) Treatment and recovery tend to be different for each type.

3.1.1 History of slip erosion control

Severe storm events like the Esk Valley floods in 1938 left extensive areas of hill country covered in shallow slips. Farmers realised that the poor quality of the pastures may have contributed to the slipping as well as the loss of forest cover. Rabbits were widespread; pasture management was almost non existent with few fences and almost no fertiliser having been applied. In the late 1940s experiments were made in several places throughout New Zealand with aerial seeding and the application of fertilisers. This eventually led to huge improvements in hill country pastures and a reduction in erosion (McCaskill, 1973).

However, it was shown that, in unstable areas, better pastures alone would not solve soil erosion. Poplars and willows were planted as unrooted poles into farmland in an effort to reduce soil loss and hundreds of thousands of poles were planted on hillsides in the following 50 years. Poplars were shown to have an extensive rooting system, and they could dry out the soil by transpiring moisture during spring and summertime. In recent years block planting with seedling trees has become more extensive. Pines, gums and wattles have been shown to have similar qualities in binding the soil together as well as being able to remove moisture from the soil throughout most of the year.

Heavy stock grazing on hill land susceptible to slip erosion can lead to pugging in wet weather, with rainwater stored in hundreds of depressions made by hooves. Continued saturation of the surface may lead to failure of the slope. Improved livestock management by subdivision and other grazing practices can help reduce the risk slip erosion.

The effective control of slip erosion requires good planning and recognition of areas where slips may occur. Often farmers will actively plant poles on sites that have already slipped. It is usually best to plant on sites that have a potential to slip and careful examination of an area can identify these places. Land use capability surveys are a key to identifying areas where preventative planting should be established.

3.2 Types, processes

Mass movements of soil or rock occur when stresses (downslope component of gravity pulling soil down the slope, pore water pressure, loading by vegetation, seismic waves propagating through the soil) exceed resistances (in-slope component of gravity holding soil to the slope, friction and cohesion of soil particles, reinforcement by vegetation roots). Slope failure occurs by three processes, acting singly or in combination: falls, slides, and flows.

The operation of three processes in varying combinations; differences in the soil properties that aid or resist failure; and the variety of triggering mechanisms – physical or chemical weathering, changes in pore water pressure during rainstorms or wet weather, undercutting or overloading of slopes, passage of earthquake waves – produce many different forms of mass movement. There is no standard nomenclature (despite several attempts at international standardisation).

3.2.1 Falls

Falls are a sudden rupture, followed by free fall of soil rock fragments, away from a near-vertical slope. The rupture is manifest as a fresh shear surface (failure plane) on the bluff or scarp, with a pile of loose debris (talus cone) beneath.

Earthslip erosion, Te Pohue. ***Photo: Hawke's Bay Regional Council.***

Soil slip, Taranaki. ***Photo: M. Tuohy.***

3.2.2 Slides

Slides result from elastic deformation, followed by sudden rupture and sliding of a soil or rock mass, down a steep slope. If movement is slight, the rupture is visible as tension cracks around the head and sides of a soil block that is otherwise intact. If movement is greater, the rupture is exposed as a sloping shear surface in the upper slope, with a disintegrated soil block (debris tail) farther downslope.

3.2.3 Flows

Plastic deformation, followed by inter-particle shear and flowage of soil or rock mass, down a low-angle slope, forms a flow. If flow is slow, it manifests itself as surface rumpling of an internally deformed soil mass. If it becomes rapid, it is manifest as a disintegrated jumble of soil fragments (flow debris) deposited within downslope of the failure zone. A failure plane separates the soil mass or flow debris from intact regolith, but is rarely exposed. A flow usually induces some slide-type failures in the more rigid soil around its margins; these become more-or-less intact soil blocks rafted along in the flow debris.

3.2.4 Shallow mass movement in New Zealand

In New Zealand, a practical distinction is drawn on the basis of failure depth – whether the mass movement is shallow (in the soil) or deep (in underlying regolith). This separates mass movements which may be easily stabilised and routinely undertaken, from those where stabilisation is difficult but may need to be attempted (Chapter 4, Deep-seated Mass Movement- Slides, Slumps and Flows).

Four forms of shallow mass movement are common in the New Zealand landscape. The distinctions are again practical, differentiating two forms which can be controlled by vegetative techniques alone from two for which engineering measures are usually needed:

- Slips – These are shallow landslides in soil or weathered regolith on steep slopes (Figure 1 – photo). They are also found on low-angle slopes where regolith is susceptible to rupture and deeply-weathered rock with a high clay content. Occasionally found where steep slopes (otherwise stable) are mantled by volcanic ash or loess.

- Earth flows – These are shallow flows on low-angle slopes (Figure 2 – photo), where regolith is susceptible to plastic deformation, notably weathered mudstones which contain swelling clay minerals such as bentonite or montmorillonite. Earth flows are also found in colluvium (slip debris) on footslopes and occasionally found where low-angle slopes (otherwise stable) are mantled by weathered volcanic ash, loess or till.

- Debris avalanches are shallow, rapid landslides in regolith on upper mountain slopes (see Chapter 6 (Part A), Mountain Lands Erosion for description).

- Debris flows – shallow, rapid flows in colluvium (avalanche debris) on lower mountain slopes (see Chapter 6 for description)

Crozier 1986 gives detailed descriptions of the four forms, illustrated by many New Zealand examples. The physics of slope failure is complex, but essential to understanding the circumstances under which any control technique can (or cannot) work. Readers are referred to Carson and Kirkby (1972) (Chapters 5 to 7) for a definitive discussion of the topic. Scheidegger (1984) also provides a useful summary of the physics.

3.2.5 Extent of shallow mass movement

The NZLRI identified 7,351,600 hectares of land as susceptible to soil slip or earth slip erosion (refer to Appendix II). 1,044,800 hectares were identified as susceptible to earth flows (refer to Appendix II); most of this is terrain affected by shallow flows, though some deep-seated flows may be included. 2,821,900 hectares of land were identified as susceptible to debris avalanches from debris flows, Appendix II be taken as indication extent of these also.

3.3 Principles of control

Revegetation trials in Gisborne (Quilter, 1993) and in the Wairarapa (Lambert, 1993) have shown that it takes up to 20

Earthflow, Hawke's Bay. ***Photo: Water & Soil Division, MWD.***

years to restore productive pastures on erosion scars and this may only be 70-80 percent of dry matter production from uneroded ground. The successful introduction of pasture plants onto eroded sites requires retirement from grazing, annual fertiliser applications and careful stock management. The cost of remedial work may be uneconomic compared with other opportunities for farm investment. Protecting land from erosion is therefore a more attractive investment than repairing erosion after the event.

3.3.1 Preventive works

The prevention of soil slip erosion usually requires a modification to pastoral farming practices. Susceptible areas on farms are readily identified by a succession of slip scars dating back to the time of development, and in many places even before forest clearance.

There are several options for reducing the risk of soil slip erosion. Improving pasture vigour by introducing deeper rooting species and regular applications of fertiliser will no suffice. It must be accompanied by:

- Spaced planting of trees in pasture, to provide the soil with root reinforcement, or

- Retirement from grazing, followed by planting with commercial timber trees, or

- Reversion to native scrub cover

3.4 Appropriate control practices

Descriptions of the various practices for control of shallow mass movement are found in chapters/sections of Part B:	
3.2	Fencing Management Practices for Erosion Control – Hill Country
4.2.	Pasture Re-Establishment – Hill Country
8.2. (8.3)	Managed Reversion of Retired Land – Hill Country
12.	Pole Planting

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Chapter 4 Deep-seated Mass Movement – slides, slumps and flows

Deep-seated Mass Movement – slides, slumps and flows

4.1 Introduction

New Zealand has some spectacular examples of deep-seated mass movements. Lake Waikaremoana and Lake Tutira in Northern Hawkes Bay were both formed by massive collapses of earth and rock into deep gorges. In recent times, the Abbotsford block glide in Dunedin demonstrated what happens when unstable slopes are modified for urban development. Less spectacular, but similar movements of soil, rock and vegetation regularly damage roads, railways, even houses, in many parts of the country. Huge investments in afforestation or structural works have been undertaken to reduce damage from such events.

Geology, water and gravity are the main factors in deep seated mass movement. The softer rocks of the Tertiary period, experience slumping and earth flows in many forms. Up to 41 percent of farmland in the Gisborne District is susceptible to earthflow erosion. Other examples of deep seated movement include, collapses of coastal cliffs, large slumps which occasionally form a temporary blockages in rivers and streams, and regional landslides where geological formations slowly collapse through an area several square kilometres in extent.

4.2 Types, processes and extent

The processes by which deep-seated mass movement occur are the same as those already described for shallow mass movement in Chapter 3. The distinction is one of scale – in addition to failing at depth in the regolith, deep-seated mass movements extend over many hectares of land; in extreme cases, several square kilometres. Their impact on land use is similarly large-scale. New instances of failure are uncommon, but the New Zealand landscape is dotted with historic (and prehistoric) failures where ongoing movement restricts use of the land for farming and forestry or threatens roads and railways.

Deep mass movements may be differentiated into three forms: slides (or block glides), slumps, and flows. The distinctions relate to feasibility of stabilisation, and what types of measure are worth attempting. Crozier (1986) gives further information about the three forms, illustrated by examples from the New Zealand landscape.

4.2.1 Slides (block glides)

A slide is a large block of soil and regolith, which moves sideways along a sloping shear plane in underlying rock. Most of the moving mass stays intact, though its edges break up into smaller blocks and fragments. The best-known example in recent years has been the Abbotsford slide, which left houses severely damaged at its upper edge where the sliding block separated, but more-or-less intact on other parts of its surface. Elsewhere in the country, it is not unknown for farming to continue on slowly moving block glides, so long as fences and tracks can be adjusted across their edges.

4.2.2 Slumps

Slumps are made up of several blocks of soil and regolith, which move in an arc above a curved shear surface (rotational failure plane) in underlying rock. The moving mass is separated from the slope behind by a high vertical rupture or

Slump during Cyclone Bola. **Photo: Landcare Research.**

Deep earthflow, hill country cleared of bush, near Karitane, Otago. ***Photo: D Hicks.***

"headwall". It breaks into an uneven surface of backward-tilted segments separated by lower ruptures or "scarps". Drainage is disrupted, and swamps or pond develop in depressions between each segment and scarp. A well-known example is the Ruru slump at Tinui in the Wairarapa, which is slow-moving and has been farmed for over 60 years.

4.2.3 Flows

Flows are made up of soil and regolith, which moves by inter-particle or inter-layer shear above a failure plane in underlying rock. The failure plane may be either planar or curved. The surface breaks into hundreds of hummocks, roughly aligned as arcuate ridges transverse to the direction of flow, and separated by tension cracks which form low scarps. Drainage is extremely disrupted. A typical example is the landscape either side of Highway 1 at Kilmog Hill, north of Dunedin.

4.2.4 Extent of deep-seated mass movements

The initial failure of a deep-seated slide, slump or flow is rapid and catastrophic. Many are triggered by earthquakes, although heavy rainfall or basal undercutting by streams are other common triggers. The mass movement debris semi-stabilises and revegetates, sufficiently for indigenous forest to establish within several hundred years. However, underlying regolith and drainage remain disrupted, creating the right conditions for secondary failure. Secondary failure usually happens at a slow rate, on patches of the debris rather than all of it, in some years but not every year.

Deep-seated slides, slumps and flows are widespread in New Zealand's tectonically disturbed landscape. The 109,900 hectares of terrain recorded as susceptible to slump erosion by NZLRI (Appendix II) is at best a partial indication of their extent; mapping recorded slumps on soft marine sediments but excluded deep-seated mass movements on the harder greywackes and metamorphic rocks. Institute of Geological and Nuclear Sciences (IGNS) has recently compiled a nationwide list of deep-seated mass movements greater that 1,000,000 cubic metres in volumes. The data used for the list have come from geological maps and inspection of aerial photographs (McSaveney et al 1998). The IGNS maps, though currently unpublished, are available on request.

4.3 Conservation measures to control erosion on deep-seated mass movements

Secondary failures, on the surface of existing deep-seated mass movements, may be stabilised by a mix of vegetative, soil drainage, and runoff control measures.

Stabilisation of primary failures is difficult and sometimes impossible. Engineering techniques are essential to success and have rarely been attempted in New Zealand's sparsely populated landscape – only at a few places, where deep-seated mass movements threaten lines of communication or urban areas. Consequently, there are no standard practices available for inclusion in Part B.

Practices are better-developed in several countries overseas, where the landscape is susceptible to deep-seated slope failures, and dense populations need to be protected. New Zealand's geotechnical engineers generally adapt the overseas practices, as and where needed here. Interested readers are advised to obtain information from Japan, Taiwan, Hong Kong, the United Kingdom, France, Canada or the United States; these being the countries where relevant engineering practice appears most advanced.

4.4 Appropriate control practices

Table 4.1 Control techniques for deep-seated mass movements on different geomorphology.

Erosion Type	Geomorphology	
	Crushed Argillite	Other Sedimentary Rocks
Flows	Erosion control forestry	Pole planting
	Dewatering	Dewatering
	Debris dams	
Slides	Dewatering	Dewatering
	Pole planting	Pole planting
Slumps	Erosion control forestry	Erosion control forestry
	Dewatering	Dewatering
		Pole watering

Descriptions of the various practices for control of deep-seated mass movement are found in chapters/sections of Part B:	
3.2	Fencing Management for Erosion Control – Hill Country
8.2. (8.3)	Managed Reversion of Retired Land – Hill Country
10	Dewatering Techniques for Deep-seated Mass Movements
12	Pole Planting
13	Erosion Control Forestry

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Chapter 5 Gully Erosion

Gully Erosion

5.1 Introduction

Gully erosion is "the removal of soil or soft rock material by water, forming distinct narrow channels, larger than rills, which usually carry water only during and immediately after rains" (Bates and Jackson 1980).

Tunnel gully erosion is "a compound erosion form initiated by the subsurface concentration and flow of water, resulting in scouring and the formation of narrow conduits, tunnels or pipes. Soluble, dispersive or low strength material is removed, ultimately resulting in collapses, visible either as 'holes' in the land surface, or as gullies developed by the collapse of pipes – followed by continued erosion" (Eyles 1985). Tunnel gullies are also called "tomos'"or "under-runners".

5.1.1 History of gully control

Many gullies occur naturally in the New Zealand landscape. They are often formed as a result of geological phenomena such as volcanic eruption or faulting and crushing of marine sediments. Over long periods of time, these natural gullies often become stabilised as the channel reaches a stable gradient, the side walls of the gully achieve a stable slope, and the natural vegetation becomes well established.

During the nineteenth and twentieth centuries, when large areas of land were cleared for pastoral development, the changes in runoff patterns and areas of exposed ground often resulted in old gullies reactivating, and new gullies being initiated. Sometimes the erosion occurred quickly, immediately following the development phase. In other situations, a number of years or even decades passed before the erosion became evident.

Following the enactment of the Soil Conservation and Rivers Control Act 1941, the Soil Conservation and Rivers Control Council (Soil Council) was established, and catchment boards were set up around New Zealand to promote soil conservation, prevent or mitigate soil erosion, and prevent damage by floods.

"In the early days of the Soil Council, soil conservation in the southern half of the North Island meant gully control" (McCaskill, 1973).

While the principles of gully control were reasonably well understood, the early soil conservators had to develop specialised practices for different parts of New Zealand (often by trial and error) to achieve success. From the outset, it was recognised that vegetative protection (trees and ground cover) provided the main long term method of control.

A historical account of gully control practices, initially developed in Soil Conservation Reserves before being used for subsidised soil conservation work on private land, is given by McCaskill (1973)

5.2 Types, processes and extent

A gully is a distinct channel, carved into a hillslope or valley bottom by intermittent or ephemeral runoff. Such channels are carved where the force exerted by flowing water – a function of its mass and velocity – exceeds the subsoil's resistance – a function of gravity (holding it to the slope) together with properties of its surface particles (binding them together, and resisting the tractive stress of water). (A definitive account of the physical processes which form gullies can be found in Leopold et al, (1964), Chapter 10-11.)

The processes – removal, transport and deposit of particles by flowing water – are exactly the same as for surface erosion and stream erosion. What makes gully erosion distinct is the scale and frequency at which processes operate:

- sheetwash or rilling – in topsoil; ephemeral during rain
- gullying – in subsoil; intermittent during and after rain
- stream bed scour and bank collapse – in alluvium or weathered rock, continuous but slight during low flows; intermittent but severe during floods.

There are four main forms of gully, although some gullies may be a combination, gully erosion often occurs either in association with one or more other erosion types. These types are U-shaped, deep-seated, tunnel and mountain gullies.

5.2.1 U-shaped gullies

U-shaped gullies are formed in loose to non-cohesive, uncompacted lithologies. They are initiated by channel gullying and exacerbated by waterfall gullying and even. They tend to form a box or U shape.

U-shaped gullies develop in clearly identified stages. When overland flow occurs during or following rainfall, stormwater runoff is concentrated into depressions. Rill erosion is initiated when there is downward scour of the topsoil. This may occur where the surface is less resistant to particle detachment or where flow velocity is increased by an abrupt gradient change. Rills deeper than 60 cm deep and wider than 30 cm are classified as gullies (Brice, 1966).

As the downward cutting continues, a gully head forms and recedes upstream; as the gully deepens and widens there is lateral erosion of the gully sides. A waterfall may develop at the gully head where overland stormwater flow plunges from the ground surface into the eroding channel. Sometimes there are a series of small waterfalls in the channel itself. The depth to which a gully will erode depends on the subsoil. Downward cutting will continue until a more resistant layer is reached.

U shaped gully on alluvial tephra deposits.
Photo: Environment BOP.

5.2.2 Extent of U-shaped gullies

U-shaped gullies occur on weathered recent sands, on unconsolidated (alluvial) Pleistocene sands, on Quaternary tephra deposits, and on gravels. This form of erosion is widespread throughout New Zealand where soils and soil structure are susceptible to fluvial erosion. It will often occur when surface vegetation is in poor condition and stormwater runoff is concentrated.

U-shaped gullies commonly occur on loose, non-cohesive or uncompacted soils such as loess, pumice, volcanic ash, alluvial sands and gravels. U-shaped gullies may form on very flat slopes once the gully process is initiated by a small abrupt gradient change or nick point. Trials at Rerewhakaaitu have demonstrated that the gully erosion process can be initiated on unconsolidated exposed ash soils where slopes are greater than 7°.

5.2.3 Deep-seated gullies (V-shaped gullies)

Deep-seated gullies form where hillslope watercourses cut through surficial regolith into unstable rock beneath. They are common on three kinds of hill country:

Soft marine sediments: Here the process is entirely physical. The sediments are at best weakly cemented by calcite and are often just indurated (compacted). Where vegetation is removed from an ephemeral watercourse – for instance by land clearance for farming or forestry – there is no obstacle to entrainment of sediment grains by running water. The watercourse cuts a deep trench headwards and its over-steepened sides collapse. Sediment is delivered into the permanent stream at the slope foot and re-worked along its course through the valley bottom. If the quantity of sediment is large, it aggrades as a fan (at the gully mouth) or a terrace (in the valley bottom). Such gullies usually stabilise as narrow, deep slits in a hillslope. Occasionally they develop into branching networks that dissect the entire slope.

Cemented marine sediments: This process is both physical and chemical. Alternate wetting and drying disaggregates weathered rock exposed in the bed of an ephemeral watercourse. Calcite cement is leached by weakly acid soil water, percolating towards the bed. Once calcite bonding is lost, any swelling clay minerals (bentonite and montmorillonite) expand. Leaching and swelling may be accelerated if pyrite (small quantities are present in some marine sediments) renders soil water more acid than normal. The watercourse begins cutting into the loosened rock; as it cuts down, fresh rock is exposed to physical and chemical weathering. Downcutting often triggers slips or earthflows around the gully's sides and head.

If such a gully is stabilised by vegetation while incipient, it remains narrow and V-shaped. If not, it develops into a branching network of channels incised tens of metres into "badland" terrain, several hectares in extent.

Crushed rocks: Where rocks have been crushed by movement along faults or by intense folding during uplift, soil water can percolate deep into the crushed rock and weathering is more rapid. If a watercourse crosses such a crush zone, it is eroded much more easily than the hard rock to either side.

Such a gully may remain small, deep and narrow where hard rock downslope bars downcutting or hard rock upslope constricts backcutting. Where a crush zone extends through a slope, the gully may extend over several hectares and coalesce with a similar feature on the other side of a ridge.

There is no single New Zealand publication which gives a comprehensive account of deep-seated gullies. Some relevant descriptions are found in reports by Gage and Black (1979), De Rose et al (1998), and Phillips, Marden and Miller (2000)

5.2.4 Extent of deep-seated gullies

These gullies occur throughout New Zealand on steep hill country or colluvial slopes. In the North Island, they are confined largely to crushed argillite, jointed mudstone, and jointed fine siltstone in association with earthflow and soil slip erosion forms. In the South Island, most deep-seated gully erosion is on greywacke and sub-schists on

V shaped gullies on crushed argillite country.
Photo: Gisborne DC.

colluvial slopes, in association with sheet and scree erosion.

V shaped gullies can occur in the following situations;

- as finger gullies in Tertiary and lower Cretaceous deposits
- on mudstone hill country in association with soil slip, slump, and earthflow erosion
- on crushed argillite hill country as bifurcated or amphitheatre gullies
- On greywacke or schist hill country as shallow talus colluvial material, deeper greywacke which may have been structurally altered or have a high argillite content, or as weathered greywacke.

5.2.5 Tunnel gullies

These gullies are formed in variable lithologies from a concentration of underground water flow above a less permeable soil layer. The gully process is initiated by underground 'piping' as lateral flow of soil water entrains particles. The pipes enlarge to form tunnels that may ultimately collapse to form gullies.

Tunnel gullies form in situations where there is a variation in permeability within the soil profile, and water is able to infiltrate into the subsurface layers. Subsurface water is concentrated where there is non-cohesive or soft lithology overlying more resistant layers. The flow of water along the resistant layer initiates 'piping', where the soils are soluble, dispersive or prone to fluvial erosion. The 'piping' erosion process forms tunnels. As the tunnels enlarge, they can collapse to form holes or continuous gullies as surface erosion features.

Following collapse of the tunnel gully, the normal gully erosion process continues.

5.2.6 Extent of tunnel gullies

Tunnel gully erosion occurs on susceptible soils and lithology throughout various parts of New Zealand. Going by the NZLRI data, tunnel gully erosion is more extensive in the North Island, and less extensive but more severe in the South Island.

Tunnel gully. *Photo: M. Tuohy.*

Gully erosion is found in the North Island on the strongly weathered sandstone downland and hill country of Northland and the colluvial slopes of the tertiary hill country. Tunnel gullies have been recorded in Northland, Coromandel, Waikato Basin Central Volcanic Plateau, Manawatu-Wanganui hill country, Hawkes Bay and the Wairarapa. It occurs on the following rock types:

- In soils derived from strongly weathered sedimentary rocks (humid climate)
- On tephra deposits (cool humid climate)
- On colluvial footslope deposits on sedimentary hill country (humid climate)

In the South Island, tunnel gully erosion occurs mainly on loess hill country soils, and has been noted in Northeast Marlborough, coastal North Canterbury, Banks Peninsula, South Canterbury/North Otago Downlands, Otago Peninsula and Mid-Clutha Valley. It occurs on loess-mantled slopes and mixed loess/colluvium slopes with yellow-grey earth soil groups (pallic soils) in sub-humid to semi-arid climate.

5.2.7 Mountain gullies

These form where debris avalanche scars and debris flow deposits are eroded by runoff. They are found in the greywacke and schist mountain lands of both islands; and are present in low forested ranges (below 1000 metres a.s.l.), as well as the alpine tussock lands.

Chapter 6, Mountain Lands Erosion, describes mountain gullies, noting that they are a natural phenomenon and nearly impossible to control.

The NZLRI map does not show deep-seated gullies' location separately from the other forms. They are concentrated in distinct regions, and on distinct geological formations:

- soft marine sediments: sand of the Kaipara and Manukau barriers; sands and silts of the dissected terrace country extending from Hawera to Pohangina; pockets of sandy gravel marginal to the hills of Wairarapa, Marlborough and North Canterbury; dissected glaciofluvial gravels in inland Canterbury and Otago
- cemented marine sediments: mudstone formations containing swelling clay, throughout Gisborne, Hawkes Bay and Wairarapa; also small pockets in Marlborough and North Canterbury.
- crushed rocks: argillites of late Cretaceous and early Tertiary age, marginal to the Raukumara Range (Gisborne), Urewera Range (northern Hawkes Bay) and Haurangi Range (eastern Wairarapa).

5.3 Principles of control

5.3.1 U-shaped gullies

- Control stormwater runoff over the gully head
- Control stormwater runoff through the gully floor

- Stabilise the gully head
- Stabilise the gully floor
- Stabilise the gully sides.

The following practices are used in controlling U-shaped gullies:

- Control of runoff over gully head or away from the gully head. There is a wide range of options including diversions, flumes, pipes and drop structures.
- Reduction in peak runoff rates in combination with stabilising gully head and controlling runoff over gully head.
- Planting of gully head (small gullies only)
- Planting of strong points at critical locations.
- Retirement of gullies in association with runoff control.
- Ground contouring to "smooth out" small gullies on low terraces (in combination with runoff control and surface vegetation).

Where the soils or geology is susceptible to u shaped gully erosion, the following matters should be considered to ensure that gully erosion is avoided:

- Avoid exposure of bare ground, particularly on overland flow paths
- Avoid concentration of stormwater runoff as far as practicable
- Avoid digging drains to discharge pounded water where the soils are non-cohesive and susceptible to fluvial erosion, and the discharge point is uncontrolled
- Avoid uncontrolled discharge of stormwater over steep drop-offs
- Reduce peak flood flows within catchments by using flood detention structures and vegetation as far as practicable
- Control stormwater runoff so that overland flow paths are well stabilised

5.3.2 Tunnel gullies

- Divert and control overland flow to controlled surface outlets
- Retain a dense ground cover on overland flow paths
- Stabilise by planting poles directly in collapse holes, and also in between them.

When tunnel gully erosion problems are only slight to moderate, and occur as holes or depressions, remedial works can be undertaken by pole planting using oversized willow poles planted directly in the tunnel gully hole. Where the erosion feature has formed collapsed gullies, pair pole or staggered pole planting can be carried out. In some cases, seedling trees within protectors may be used as an alternative to poles.

In more severe situations where the tunnel gullies become totally collapsed and exposed, and the gully erosion continues to worsen, more extensive works are required to remedy the problem. In these situations, works include diversion and control of overland flow to controlled surface outlets, and revegetation of dense stable ground cover. Contouring to infill gullies in association with runoff controls may also be an option. Other revegetation options are also likely to be required. These include tree planting (including space planting or afforestation) and temporary or permanent retirement of the affected area from grazing.

Attempting to control tunnel gullies by ripping and compacting the tunnels, will only provide temporary relief, as the soils are inherently susceptible to tunnel gullying, and this method of treatment only addresses the symptoms of the problem, not the cause.

Preventative works to control tunnel gully erosion are normally only employed when there is evidence of tunnel gully erosion occurring. In these situations, space planting of willow or poplar poles, or protected seedling trees are common methods used to address the problem. Planting can be carried out following the line of the gully erosion if it is evident. In Northland, coral tree (Erythrina spp.) poles can be planted as an alternative to willow poles.

In areas where the soils are known to be susceptible to tunnel gully erosion, normal sustainable farming practices such as maintaining a dense pasture sward, controlling animal and plant pests, minimising bare ground etc should be used to reduce the risk of tunnel gully erosion occurring.

5.3.3 The key principles to control V shaped gullies include

- Control stormwater runoff from the surrounding catchment
- Maintain negative pore water pressure in soil and rock, around the gully's head and sides (de-watering)
- Increase shear strength in surrounding soil and rock (tree root reinforcement)
- Stabilise the gully floor (debris dams or live dams).

Control of V-shaped gullies and the associated erosion that normally occurs with the gully erosion, is largely dependent on control of the eroding channel floor. Once control of this has been achieved, then other works to control erosion on the sides of the V-shaped gully can be used. This often requires using a number of practices in conjunction with each other, or in succession. The main approaches, in order of importance, are stabilising the gully floor, stabilising the sides of the gully system or reducing the peak runoff through the gully system

The Ministry of Works have successfully demonstrated at Kaitangata Station (Gisborne District) that gully control can be achieved by using runoff control as the initial control measure, in conjunction with a range of other practices (Hall 1970).

In almost all situations, long-term control will rely on stabilisation of the unstable land mass. This is generally achieved through some form of tree planting. There are a number of planting options that may be used. Tree planting options include pole planting of the immediate gully toe slopes using poplar or willow pole material, wide space planting of trees on the gully and adjacent slopes with grazing underneath, or afforestation over a reasonable proportion of the gully catchment.

Because V-shaped gullies normally occur in conjunction with other types of erosion, preventative works are aimed to address a range of erosion forms on the land susceptible to gullying.

Many of the V-shaped gullies have been formed following the removal of indigenous vegetation on steep land and the conversion of the land to pasture. A pastoral land use may not be sustainable without intensive soil conservation planting, and often some form of afforestation may be the only sustainable land use option to avoid or mitigate erosion problems.

When these susceptible areas are afforested, the tree roots help bind the land, and evapotranspiration from the trees pumps water from the soil to reduce the volume and rate of stormwater runoff. A dense vegetative ground cover (particularly on the gully floor) helps to ensure a stable channel, which also assists in reducing the risk of gully erosion.

Therefore, the key to prevention or stabilisation of V shaped gullies is the establishment of vegetation, particularly trees.

5.3.4 Others

Stabilisation of debris avalanche/flow gullies requires engineering measures. Their cost is high, and can only be justified where roads or railways pass through the ranges. Even here, such measures are rarely attempted. Elsewhere in the mountains, the gullies are simply left to revert; a process which will take decades if not hundreds of years.

Ground contouring is sometimes used in conjunction with runoff control and surface revegetation on U-shaped gullies and tunnel gullies. While the costs of recontouring can be high, the land can be brought back into a more productive use. The contouring operations also provide an opportunity to direct stormwater runoff to a safe controlled outlet.

5.4 Appropriate control practices

Table 5.1 Control techniques for different gully forms.

Gully Types	Control Principles
U Shaped Gullies	Runoff Control Systems Tree & Pole Planting Surface Protection: Vegetative and Non-Vegetative Mechanical Infilling or Contouring
V Shaped Gullies	Runoff Control Systems Structures to Stabilise Gully Head/Floor Tree & Pole Planting Surface Protection: Vegetative and Non-Vegetative
Tunnel Gullies	Runoff Control Systems Tree & Pole Planting Surface Protection: Vegetative and Non-Vegetative Mechanical Infilling or Contouring

Descriptions of the various practices for control of deep seated Gully Erosion are found in chapters/sections of Part B:	
3.2	Fencing Management for Erosion Control – Hill Country
3.3	Fencing Management for Erosion Control – Mountain Land
8.2. (8.3)	Managed Reversion of Retired Land – Hill Country
11	Gully Control Structures
12	Pole Planting
13	Erosion Control Forestry

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Chapter 6 Mountain Lands Erosion

Mountain Lands Erosion

6.1 Introduction

Mountain land erosion includes needle ice (frost heave), sheet wash, wind blow, periglacial creep of soil and rock fragments, together with erosion of gullies by debris avalanches, debris flows and torrents.

Natural or geological erosion has been defined as the gradual wearing away of the land by water, wind and gravity. It is sometimes called "normal" erosion but this term is open to criticism on the grounds that in nature normality is difficult to define. In mountain lands natural erosion becomes increasingly prevalent at higher altitudes.

"Induced" (or "accelerated") erosion results from the disturbance of the environment by human activities. ("Induced" is the better term.) For management, it is important to distinguish between natural and induced, but there are many situations where there is no clear answer as to whether the erosion is induced or part of the natural cycle.

Spectacular mountain land erosion is not a recent development in New Zealand. Strange (in 1850) and Colenso (in 1884) climbed to various high points on both islands and described various landslides and severe erosion.

The short tussock grasslands of the high country are a recent vegetation type. Three thousand years ago the high country of both island was a mosaic of forest, scrub and tall tussock. Short tussock was present as a successional plant community on small areas burnt by natural fires, such as those resulting from lightning strike or volcanic eruption. There was a sudden increase in fire frequency 900 years ago when the Maori arrived, and this continued, in particular, when Europeans arrived. Because of the fires, much of the lowland and montane forests was replaced by short tussock grassland.

In the 1850s and 1860s, settlers brought herbivores such as sheep, cattle, deer, chamois, thar, goats and rabbits to this grassland. Regular fires continued as part of the European land management practice and although regulated by 1913 legislation, periodic burning continued unabated until the Soil Conservation and River Control Act in 1941 enforced fire control. From the 1870s through the 1940s, rabbits proliferated through the tussock. Too-frequent burning, followed by too-heavy stocking, followed by rabbits, depleted the short tussock grasslands; and to a lesser extent, the high-altitude tall tussock. Topsoil was exposed to surface erosion by ice, water and wind.

6.1.1 History of research

One of the earliest accounts of soil erosion in the high country (Gibbs and Raeside, 1945) showed that a quarter of the land was extremely eroded, with less than 50 percent of the topsoil remaining, and that only 20 percent of the area had slight or no accelerated erosion. Gibbs and Raeside calculated that the surveyed soil depletion amounted to a total loss of about 1.5 billion tonnes of soil. Research in the last four decades has increased our understanding of the types, magnitude, frequency and triggers of erosion in the New Zealand mountain lands. Much of the work, however, has been into the

Screes and gullies on grazed tussock rangeland, Torlesse Range, Canterbury. *Photo: D Hicks.*

larger discrete forms like debris avalanches and mountain torrents, rather than the more extensive forms produced by frost heave and wind (Whitehouse 1984).

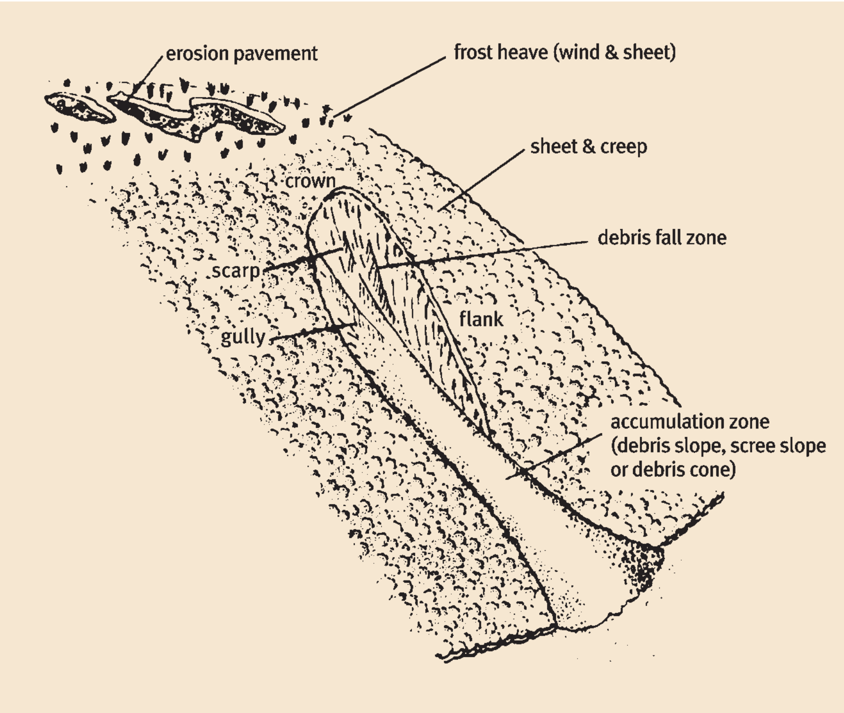

Fig 6.1 Diagram of common forms of mountain land erosion in New Zealand (after Cunningham, 1978)

6.2 Types, processes and extent of erosion in the mountains

6.2.1 Frost heave (needle ice formation)

Needle ice formation will be defined here as a separate erosion process which enables particles to be removed later by sheet and wind erosion process. The needle ice process is more severe where bare ground exists and is found in all mountain areas especially higher than 900 m above sea level. Ice pulverises the top of exposed soils and on drying the material is easily removed by wind or rain.

Gradwell (1960) and Soons and Greenland (1970) observed needle ice and noted that the growth of ice needles depends mainly on the rate of heat loss and the availability of water. Hayward and Barton (1969) used a movie film to record the disruptive action of needle ice and showed 22 freeze-thaw sequences moving surface material up to one metre down slope. Subsequent advances in our knowledge of this slow erosion, operating in the Southern Alps have not been extensive (Whitehouse, 1984).

O`Loughlin (1984) reports slopewash rates of 150 t/km^2/yr measured on bare subsoil surfaces exposed to frost heave in Hut Creek, Craigieburn Range. Following planting of Pinus contorta on the site, soil loss declined rapidly from tree age 4, until at tree age 10 soil loss was negligible.

Altitude and climatic zonation plays a significant role in the major process of needle ice formation where we find frost heave occurring in the semi arid inland basins of Otago and Canterbury from as low as 300-350 m above sea level, particularly where winter frosts and permafrost occur. Frost heave commonly occurs near Alexandra and the intermountain basins of Canterbury – that is, the Mackenzie Basin, where altitude can vary from 350 m (flats and terraces) to 1500 m, or to the tops of the mountains.

6.2.2 Sheet erosion

Sheet erosion is the removal of a thin surface layer of topsoil or subsoil by a layer of water flowing over the land. The impact of raindrops on the exposed soil breaks up the surface layer and loosens particles, which can then be moved. If it continues for some time an infertile stone pavement results.

Soil, defined as particles less than 2 mm in diameter in Hayward's study (1969), appears to be eroded from surfaces covered with rock particles (scree and erosion pavement) at about (0.012 +/- 0.004 kgm^2/yr. This is some four times faster than from totally vegetated sites (0.0028 + 0.0005 kg/m^2/yr and some three times less than from non-vegetated surfaces other than scree.

6.2.3 Wind erosion

In the mountain lands wind erosion is widespread on exposed tops, sunny faces, and areas that have had the vegetative cover denuded. It is possibly more pronounced in the South Island due to the persistent and often prolonged North West foehn winds.

Wind moves soil particles by the processes of deflation and abrasion. (The chapter on wind erosion gives a fuller description of these processes.) The amount of soil in transit in the wind has been measured at six sites in the

Rakaia, Waimakariri and Ashburton Basins by Butterfield (1971), using 7-cm diameter traps located at various heights above the ground. Over the year of measurement, wind erosion was greatest in early spring to early summer with the lowest levels of erosion occurring during mid summer (January) and in winter. Because of the difficulty, wind erosion rates have not been measured in the high country since Butterfield's study.

Recent research work using caesium-137 (Hewitt, 1996) into surface soil losses in Central Otago on the lower foothills and terraces near Alexandra (300–320 m above sea level) has shown that a sunny side slope lost 50 percent of its expected caesium-137 input through erosion of top soils. This was equivalent to a loss of 3.4cm of soil over 40 years. Shady side slopes and foot slope sites gained caesium-137 through net soil deposition mainly from the northwest winds. This information indicates that the surface soil losses are not as severe as first thought (even though bare ground may be significant at certain times, such as after a drought or rabbit infestation).

Frost heave, sheet erosion and wind erosion are the only mountain land erosion processes for which soil conservation would normally be attempted. While natural, they have been accelerated at low to middle altitudes by 150 years of vegetation disturbance – burning of tussock grassland, followed by sheep grazing, followed by rabbit infestation, followed by weed colonisation. In these zones, the erosion can be reduced by avoidance or restriction of burning, revegetation of depleted tussock, lenient grazing management, and rigorous control of pests and weeds.

Other erosion processes occur on alpine slopes and ridges, where soil conservation would not normally be attempted. Techniques for their control are beyond the scope of this handbook. They are described here just to remind readers that these processes are encountered in the mountains; are natural; and are difficult to control.

6.2.4 Periglacial erosion

At high altitudes, soil in the mountains is extensively disturbed by periglacial erosion processes. Frost heave, already described, is one of these. Repeated freeze-thaw cycles sort the skeletal soil into "patterned ground", with stone rings or stone stripes separating patches of silty or sandy soil.

Soil creep is a slow, plastic flow of surficial soil and rock debris downslope, creating solifluction terraces or solifluction lobes. At high altitudes it is driven by changes in stress and resistance, as the soil alternately freezes and thaws. Scree creep is a related phenomenon, occurring on talus slopes beneath bluffs. The talus initially accumulates from rockfall or debris avalanches. Where vegetation can establish, it stabilises; but where it cannot (or if it is breached), the shattered pieces of rock may be slowly shifted downslope by freeze and thaw of water in the cracks between.

6.2.5 Debris avalanches

Debris avalanches are slide-type mass movements of soil or rock on steep mountain slopes. They are triggered by the same mechanism as shallow landslides (soil slips) – see Chapter 4 – and start in a similar position, a hollow which concentrates soil water draining from farther upslope. Once triggered, the mountain slope's steepness ensures that landslide debris, instead of coming to rest on the slope, keeps moving. Slope length enables the debris to build up momentum sufficient to start scouring away vegetation and soil in its path. The result is a long, narrow scar stretching from upper slope to slope foot, with a jumbled deposit of soil, rock and timber at the base. Repeated debris avalanching may build up a talus cone in the lower part of the scar.

6.2.6 Debris flows

A debris avalanche may transform into a debris flow as it descends. This happens if the debris incorporates sufficient water or air in its downward passage to turn it to fluid. The fluidised debris keeps moving across the valley floor instead of coming to rest at the slope foot. If the floor is wide, repeated debris flows will build up an alluvial fan, tapering from and angle of 20° or more at its apex, down to 5 or 6° at its foot where the debris gives out or settles. If the valley floor is narrow, the debris will turn and flow downstream for distances of several hundred metres until it gives out. This will be at a point where channel gradient is about 5 to 6°, and a graded deposit of alluvium interspersed with boulders and timber will be left.

6.2.7 Mountain gullies

A debris avalanche's linear scar is a natural conduit for runoff from the upper mountain slope above and around it. Subsoil is exposed in its sides, and shattered rock in its base. Many such scars turn into gullies, but it is important to remember that such gullies are maintained as much by occasional debris avalanches during storms as by runoff during lesser rainfalls. The same holds true for gullies in the fans and valley-bottom deposits left behind by debris flows.

6.2.8 Torrents

A torrent is a permanently flowing stream going down a mountain or flowing along a mountain valley bottom. It differs from normal streams in that its gradient is steep, typically exceeding 5° and occasionally in excess of 20, interspersed with rapids and waterfalls.

A torrent's steep gradient, combined with frequent passage of short sharp floods, and a sediment load of coarse gravel and small boulders, give it great erosive energy. The bed and banks are eroded in almost every flood; the small, discontinuous pockets of coarse alluvium are rapidly worked downstream, and supplied to larger streams and rivers which exit from the mountains. Where slopes are susceptible to debris avalanches and the avalanches can reach the channels, alpine torrents are also subject to passage of debris flows. These cause even more erosion and deposition than the floods.

The definitive studies of mountain erosion processes are published in Japanese, Chinese, German or Italian. For an English-language summary, refer to Scheidegger (1988). Susceptibility of the New Zealand landscape is summarised in Chapters 6 and 19–22 of Soons and Selby (1992).

6.2.9 Conservation measures to control natural erosion in mountains

Engineering measures cannot prevent the processes described above, but they can control their impact; either stopping or diverting them before they cause damage. There are no standard practices for the control of debris avalanches, debris flows or mountain torrents in New Zealand as few highways or railways pass through the mountains and control measures are rarely tried. Readers are advised to seek information from one of the countries where such measures are extensively implemented due to settlement and infrastructure in the mountains. Overseas practice appears to be most advanced in Japan, Taiwan, Switzerland, Austria and Italy.

6.2.10 Erosion rates in mountain lands

The most significant aspect of mountain land erosion is the large quantities of silt and material removed from catchments and deposited downstream into lakes onto alluvial flood plains, or transported out to sea. Sediment yields from some basins in the Southern Alps are amongst the highest in the world. Yields vary from about 100 $t/km^2/yr$ for basin in the dry intermountain areas (Twizel and Forks Rivers) to about 15,000 $t/km^2/yr$ for basins in the western part of the Southern Alps (Hokitika, Cleddau and Haast Rivers) (Hicks D.M. et al 1996).

The most accurate measurement of sediments in Otago comes from Falls Dam, an irrigation reservoir on the upper Manuherikia River. Six hundred thousand tonnes of silt, clay and sand have accumulated behind the dam since 1935. For an assumed reservoir trap-efficiency of 80 percent, this is removal of 44 $t/km^2/y$, from the area of drainage basin above the dam (Bishop et al, 1984). This is a denudation rate of 0.02 mm/yr in the driest part of the mountains. The highest figures, from basins in the western part of the Southern Alps, have a large margin of errors (Hicks et al 1996). Even after allowing for this, they demonstrate the enormity of erosion where rainfall is between 3000 and 10,000 mm a year.

6.3 Principles of control

Much of the surficial soil erosion is insidious in nature, although debris flows and the like may come only after a major storm. The following factors contribute to erosion in the mountains:

- geology and soil type
- altitude, slope and aspect
- climatic influence related to above microtopography, freeze/thaw regime and growing season
- burning native grassland (especially snow tussock and associated species)

and not spelling from stock or a very hot fire

- overgrazing after a burn
- depleted, open ground cover subject to the severe climate and other elements
- low fertility soils with a poor carbon to nitrogen ratio and low organic matter content
- animal pest population increases by rabbits, hares, possums, goats, thar, chamois and feral deer
- plant pest population ingression(eg, gorse, briar, matagouri and *Hieracium* species)

The principles of control for surficial erosion are very similar to that for sheet and rill erosion on the lower plains and downlands but occur in a more diverse climatic environment. Control measures often must be taken at higher altitudes, where plant-growing days are very short.

The primary principle is to manage the land in its present form by maintaining or improving the vegetative protective cover and the soil health status especially the organic matter content. Success in erosion control on these high altitude properties can often only be made by changing land management (such as burning and grazing management) systems over the entire farm unit and not on a paddock (or block) basis.

There has been considerable research work carried out into soil conservation management on the mountain lands in New Zealand by various organisations since the 1941 Soil Conservation Act was passed. This included work by the Forest Research Institute at Craigieburn and in the North Island on the Ruahines, by DSIR Grasslands Division, Ministry of Agriculture, AgResearch, MWD Soil Conservation Centres, Landcare Research, Tussock Grasslands and Mountain Lands Institute, The Hellaby Trust, various universities, catchment authorities (which are now part of the regional councils)are some of these.

6.4 Appropriate control practices

Table 6.1 Summary of mountain erosion types and management practice

Type of erosion	Factors to Consider for Management Practice	Examples of Practices (Not inclusive)
Frost heave*	Type and condition of present vegetation	Retirement fencing
Sheet*	Soil type (% topsoil/subsoil left & % organic matter) Geology	Erosion control fence Cattle-proofing Rotational grazing
Wind*	Rainfall, storm events Aspect (sunny versus shady)	Summer grazing Aerial oversowing and top dressing
Soil creep**	Altitude & slope Timing Past management (burning, grazing) Plant & animal pests Land Use Capability class and land use Tenure & ownership (leasehold, freehold, Crown reserve) Access Economics of practice	Mulching Erosion control forestry Protection forestry Retirement planting Feed banks Feral animal control Destocking and spelling Burning management
Streambank***	As above plus:	Above as applicable, plus:
Scree *	• size of catchment	• water diversion
Gully***	• type of regolith	• mulching
Debris avalanche**	• type of vegetation required • erosion rate and ease of repair • spring dewatering	• toe stabilisation • engineering structures

* = surface erosion, ** = mass movement, *** = fluvial.

The geomorphology of the types of erosion above are mostly schist, greywacke and volcanic ash.

Descriptions of the various practices for control of Mountain Land Erosion are found in chapters/sections of Part B:	
2.3	Tussock Management for Surface Erosion Control
3.2 (3.3)	Fencing Management for Surface Erosion Control – Hill Country and Mountain Land
4.3	Pasture Revegetation – Mountain Lands
6	Burning Management – Mountain Lands
8.4 (8.3)	Managed Reversion of Retired Land – Mountain Lands
13.5	Forest Management Practices – Mountain Lands

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Chapter 7 Sand Dune Erosion

Sand Dune Erosion

7.1 Introduction

Sand dune ecosystems are very fragile ecosystems, which persist under extremely difficult conditions, and their management has been a challenge to New Zealand land managers for a very long time. Dunes are affected by:

- wind, salt, and generally low temperatures from cold sea breezes
- the substrate of mobile sand, which combined with wind, can "sandblast" seedlings and mature plants, and can bury or expose established plants
- temperatures, whose fluctuations can be very large, with frosts in depressions or basins during winter but which can rise rapidly during calm sunny days;
- amount of moisture for plant growth, which is often small because the moisture-holding capacity of sand is limited
- summer droughts that can be quite severe
- nitrogen, which is the most limiting element because it is easily leached out.

7.1.1 History of sand erosion control

On conventional sand dunes, the following stages of reclamation/stabilisation are recognised:

1 establishment and protection of a stable foredune parallel with the coast (see section "Foredune").

2 fixation of the unstable sand area behind the foredune and further inland with binding plants (see section "Main dune")

3 establishment of a permanent vegetative cover using grasses and legumes for pasture development, or trees for afforestation, or native plants for the restoration of reserves and other high value areas (see section "Main Dune").

For details on the first three stages, see van Kraayenoord and Hathaway (1986a) (pages 69-77), and more recent findings, described in the following sections of this chapter. Reference should also be made to the very recent Auckland Regional Council publication, The Coastal Erosion Management Manual.

As a primary sand stabiliser, marram grass (Ammophila arenaria) has been given most prominence. Although it is an introduced plant, it has proven itself as a sand dune stabiliser throughout New Zealand. Since the early 1920s, marram grass has been planted, more recently with mechanical planters, to stabilise sand dunes because it is easy to propagate and establish.

The New Zealand silvery sand grass (Spinifex sericeus, previously hirsutus) is also a true sand binder, found on fore dunes (Whitehead, 1964), but it is not easily propagated (Sale, 1985). Through the voluntary assistance provided by Beach Care and Coast Care groups, spinifex has in recent years gained more prominence in dune revegetation programmes. Detailed propagation methods may be found in regional council leaflets, such as Bay of Plenty Regional Council Information Brochure no. 6. (See also Bergin, 1999.)

The other New Zealand sand binder, pingao (Desmoschoenus spiralis), is usually found a little further inland where under favourable conditions it forms rather irregular hillocks (Whitehead, 1964; van Kraayenoord and Hathaway, 1986a). Hillocks can lead to wind funnelling and thus to localised erosion, which is to be avoided. Pingao is more difficult to propagate than marram grass, but Herbert and Bergin showed that it could be used in duneland rehabilitation (see Bergin and Herbert, 1998). Pingao is highly sought after in Maori weaving due to its yellow colour.

7.1.2 The "natural character" of sand dunes

The preference or desirability of using native plants versus introduced plants for sand dune stabilisation to maintain the natural character of dunes continues to be the subject of much debate (Gadgil and Ede, 1998). In their comprehensive review of sand dune stabilisation research and practice, they say, "Greater success, especially in emergency situations and remote areas, is likely to be achieved by preliminary use of exotic species to fix nitrogen and establish continuous cover, followed by gradual enrichment or replacement with native plants. This approach would satisfy requirements for both erosion control and a return to the natural character of the dunes."

7.1.3 Preventive works

Preventive works focus on avoidance of activities that may disturb the fragile vegetation on sand dunes. Where blowouts have occurred, steps must be taken immediately to remedy this, so as to avoid the problem escalating rapidly.

Human activities, such as walking, can often be channelled onto stable areas formed by walkways and board walks. But 4-wheel drive and other motorised activities are less easily controlled, and barriers may have to be put in place. Building activities in dune areas should be prohibited where possible; otherwise they should be strictly regulated in Coastal Hazard Strategy documents and supervised.

Animal grazing and browsing should be strictly controlled if it cannot be prohibited altogether. Domestic animals can usually be excluded from dunelands with the co-operation of land occupiers. Feral animals should be tightly controlled.

7.1.4 The Coastal Dune Vegetation Network

The Coastal Dune Vegetation Network (CDVN) was formed in 1997. It provides linkages between a wide range of agencies, interest groups, iwi, nurseries, and consultants having a mutual concern for the rehabilitation of degraded sand dunes, particularly revegetation techniques incorporating indigenous coastal species. Financial members include Regional and District Councils, forest companies owning sand dune forests, and the Department of Conservation.

For more information, contact the CDVN secretary, Forest Research, Private Bag 3020, Rotorua. Phone (07) 347 5899; fax (07) 347 5332.

7.2 Forms, processes, extent

Sand dune ecosystems are regarded as very fragile because they persist under extremely difficult conditions. Dunes are the most dynamic ecosystems in our environment; human activities or those of animals very easily disturb them. They require constant vigilance and maintenance if they are not to affect various assets. The erosion process in sand dunes is primarily driven by wind that lifts, transports and deposits sand grains into mobile, unvegetated accumulations of sand, called dunes. The dunes may become vegetated and stabilised by highly specialised pioneering plants that tolerate the sand-blasting effect of the wind.

When discussing sand dune stabilisation, three types of dune are recognised: foredunes, main dunes, and dunes derived from sandy cliffs. All dunes have been formed by wind action on sand grains, derived from eroded rocks. At the beginning, wind lifts, transports and deposits sand grains into mobile, unvegetated accumulations; these may then become stabilised by highly specialised pioneering plants. The stabilised dunes can become a single ridge along the coast, or dune systems extending many kilometres inland.

The **foredune** (or frontal dune) immediately faces the sea and is the most recent sand dune in a sandy or gravelly beach system. It is the ridge of sand immediately above the high tide mark and may be covered by pioneering plant species such as spinifex, pingao or marram.

The sandy foredune is part of the beach itself and, along with the in-shore seabed, this system forms a natural buffer between the sea and the land. The beach and its associated dune system are able to absorb the energy of the waves, unlike a hard rocky shore, which both reflects the waves and is eroded by them. This mobile beach is able to absorb wave energy because of its gentle slope and the mobile and homogeneous texture of the sand. It protects the area behind the fore dune.

The **main dune** (or back dune) is the sandy area behind the unstable fore dune. The main dune is usually well vegetated and thus does not require stabilisation. However, inappropriate management can lead to local areas of instability which then do require stabilisation, as for fore dunes. In many parts of New Zealand, pasture or introduced forest trees have replaced the original sand dune vegetation.

Sandy cliffs that consist of indurated sand can erode to form sand dunes. Streams often dissect the cliffs so that valleys have been formed, and these can act as funnels for coastal winds. High-velocity winds can abrade the sandy cliffs to form moving dunes that can invade agricultural lands, local reserves, or other assets.

The total area of coastal sand dunes in New Zealand is 305,000 ha, according to NZLRI Data. Of this, 240,000 ha are in the North Island, especially along the western coasts of Northland, Waikato, Rangitikei and the Manawatu; they range from 3- 20 km in width (van Kraayenoord, 1986a). Coastal sand dunes in the South Island are scattered throughout Nelson, Marlborough, Canterbury, Otago, and Southland.

Patrick Hesp (2000)states that sand dunes are a distinctive feature of about 1100 km of the New Zealand coastline. The sand is derived from erosion debris transported along the coast by coastal currents. Rivers bring down the debris, but in some coastal locations, the sand is derived from Pleistocene sandy cliffs, as at Awhitu Peninsula. Most sand is predominantly quartz but some may have such a very high mineral content that it is mined (ironsands). Seashells and rock fragments may be found among sand grains, which can range from coarse sand (2.0–0.2 mm diameter) to fine sand (0.2–0.02 mm).

7.3 Principles of control

The control of sand dune erosion is based on mitigating the effect of wind on sand transportation. This is usually done by assisting common colonising plants with supplementary planting, or by using non-vegetative materials, such as straw/hay bales and various wind-stilling barriers. Barriers, board walks, and fencing can regulate human and animal traffic. Domestic animals rarely have a place in dune management practices, unless very carefully controlled. Animal pests should be strictly controlled in these fragile ecosystems.

During periods when the dune is relatively stable, vegetation may become established spontaneously from creeping plants such as spinifex and pingao, or these plants may be established from nursery grown stock. In large, unstable areas, marram may be planted, often by means of mechanical planters. The most effective planting is done in very early spring when moisture is available and desiccating winds less frequent.

Regular inspections and prompt maintenance should prevent erosion in dune systems, since these ecosystems are very easily disturbed. In particular, the occurrence of blowouts should be prevented where wind excavates the regular contour of the dune by funnelling. This can destabilise not only the foredune but also the main dune and the areas behind it, usually by covering them with unwanted sand. Hesp (2000) describes the process and his figure 2 illustrates this.

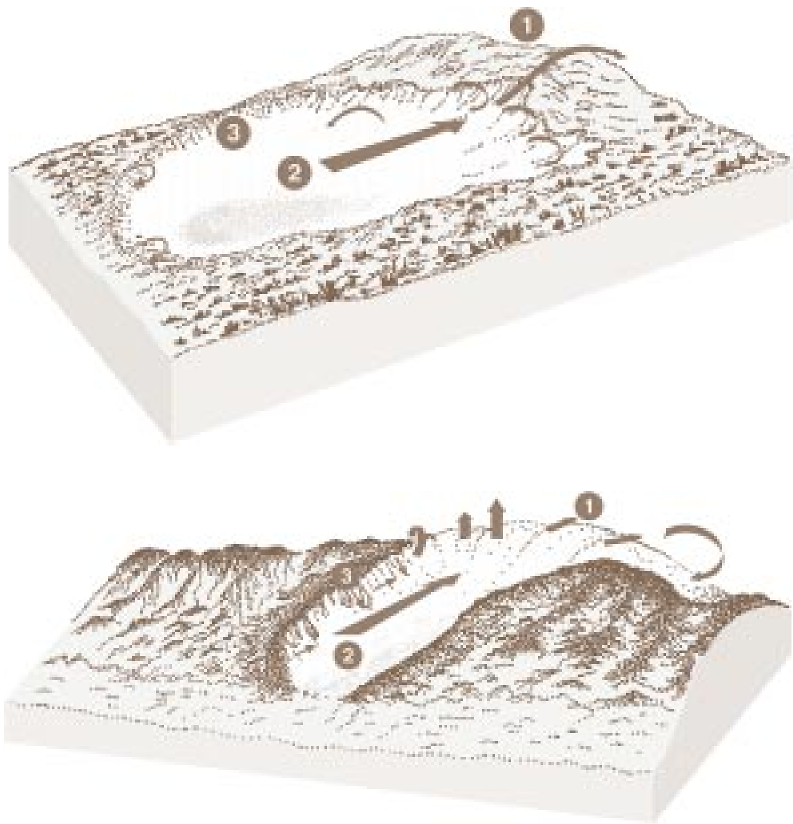

Fig 7.1 The two blowout sand dune types and their typical windflow patterns (P Hesp).

1. Depositional lobe

2. Deflation basin

3. Erosional walls

Because of the usually unwanted sand deposition, it is imperative that blowouts be controlled as soon as practicable, irrespective of the time of the year. If planting is unlikely to be effective, non-vegetative means such as straw/hay bales may have to be used, and various wind stilling barriers, such as brushwood fences or sheltercloth may have to be erected. Frequently, both vegetative and non-vegetative materials have to be used at the same time. In some situations, a reshaping of the contours may have to precede the erection of barriers or the planting of vegetation, if the funnelling effect of the wind may destroy any reinstatement efforts.

7.4 Appropriate control practices

Descriptions of the various practices for controlling sand dune erosion found in chapters/sections of Part B:	
5	Sand Dune Stabilisation Practices
15	Shelterbelts

7.5 Bibliography

The publications from the Coastal Dune Vegetation Network (CDVN) are essential reading for sand dune managers, as well as the Auckland Regional Council's Coastal Erosion Management Manual. Various regional councils have already produced their own locally adapted bulletins and leaflets; a few examples are given.

CDVN Technical Bulletin Series

Bergin, D O & Herbert, J W 1998, Pingao on Coastal Sand Dunes. CDVN Technical Bulletin No. 1. Publ. New Zealand Forest Research Institute Ltd, Rotorua. 20 pages

Bergin, David 1999, Spinifex on Coastal Sand Dunes. CDVN Technical Bulletin No. 2. Publ. New Zealand Forest Research Institute Ltd, Rotorua. 32 pages

Bergin, David 2000, Sand Tussock on Coastal Sand Dunes. CDVN Technical Bulletin No. 3. Publ. New Zealand Forest Research Institute Ltd, Rotorua. 16 pages.

Hesp, Patrick A 2000, Coastal Sand Dunes – Form and Function. CDVN Technical Bulletin No. 4. Publ. Forest Research, Rotorua. 28 pages.

Auckland Regional Council

The "Coastal Erosion Management Manual", available from ARC in hard copy format at $129.00 incl. GST, or as a CD-ROM at $49.00 in MWS format. Phone (09) 3662000.

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"NSW Govt. Coastline Management Manual". This is being updated by Dr Rod Kidd of the NSW Dept of Land and Water Conservation. The manual may be found at:

http://www.environment.gov.au/marine/manuals_reports/coast_manual/index.html

Regional Council and Department of Conservation publications:

Several regional councils have produced a number of leaflets/publications on sand dune rehabilitation and management. This list is not comprehensive:

Environment Waikato

- Dune Care Code
- Spinifex Seed Collection and Propagation
- Pingao Seed Collection and Propagation

- Guidelines for Spinifex Seed-Head Collection
- How Beaches and Dunes work, Coastal Fact Sheet 13
- Why Dunes are important, Coastal Fact Sheet 14
- Care Groups in Action, October 2000
- Waikato Region Beachcare Newsletter, Christmas 1999
- Website http://www.ew.govt.nz/educationprogrammes/beachcare/

Northland Regional Council

- Guideline for Stabilising Sand Blows
- Guideline for Protecting Vegetation on Cliffs
- Guideline for Pasture Management on Sand Country
- Guideline for Establishing Permanent Tree Cover on Sand Country

  [Note: these guidelines are based on those prepared for the Awhitu Peninsula Land Group, and are also available from the Group and from Environment Waikato]
- Website http://www.nrc.govt.nz/

Bay of Plenty Regional Council

- Coastcare BOP Programme: Coastal Plants, Spinifex. Coast Care Info. Brochure No. 6
- Website http://www.boprc.govt.nz/search/

Otago Regional Council

- St Clair to Lawyers Head: Sand Dune Management Programme
- Ocean Grove Recreation Reserve: Sand Dune Stabilisation Programme
- Website http://www.orc.govt.nz/

Department of Conservation

- Project Crimson Supporters Kit, see also Website http://www.projectcrimson.org.nz
- NZ Native Plants in Design – Coastal Forests
- Website http://www.doc.govt.nz

Chapter 8 Earthworks

Earthworks

8.1 Introduction

Earthworks can induce major, but usually short-lived, changes in sediment yield. American information suggests that that the sediment yields from urban developing areas can be extremely high, sometimes reaching values of 50,000 t/km²/yr (Novotny et al 1981). Figures of 10–12,000 t/km²/yr are quoted from areas undergoing construction in New Zealand (Herald, 1989; Williamson, 1991).

Studies in the Auckland region bear this out, with construction sites yielding 10–100 times more sediment than untouched land (ARC 1992a; ARA, ARWB 1983a, Swales 1989). Another relevant study gathered sediment yield data from five different land uses around the Auckland.

Table 8.1 Annual soil loss in the Auckland region Auckland Proposed Regional Plan: Sediment Control, September 1995)

* Predicted over 20 year period

Landuse	Measured (t/km²/yr)	Average Annual Soil Loss* (t/km²/yr)
Pasture	49	46
Market Gardening	49	52
Developed Urban – Industrial	107	100
Developed Urban – Residential	24	24
Earthworks	6,600	16,800

The predicted yields are a statistical estimation of sediment yields averaged over periods longer than the flow record. A 20-year average was used, as it was considered to be acceptably long-term, (Hicks 1994). The confidence limits of the long-term annual yield varied from a factor of two for the urban and pasture information up to a factor of 4-5 for earthworks. The ARC report considered that the larger, more infrequent storm events yielded disproportionately more sediment from earthwork sites than smaller events. In comparison, the very frequent event yielded most sediment from the established urban areas (because of sediment exhaustion with higher storms).

8.1.1 Impact of earthworks erosion on the environment

Earthworks result in elevated levels of sediment in waterbodies and added deposition on their beds and banks. Water clarity and aesthetic appeal is reduced. High suspended solids concentrations damage or kill stream plants and animals. Reduced plant growth flows through the food chain, to reduce insect and fish numbers. Increased channel erosion and remobilisation of sediments may maintain high suspended solids levels for several years. The suitability of water for uses such as irrigation, rural water supplies, stock watering and recreation can be reduced (ARC, 1996).

Watercourses can be in-filled, causing loss of flood capacity. Sediment can be deposited on floodplains, causing crop and pasture losses, property damage, and burial of fences, roads and bridges. Large volumes can be discharged into estuaries and the ocean.

8.2 Types, processes and extent of erosion on earthworks

On earthworks, the basic erosion process is detachment, transport and sedimentation. Water is the usual eroding agent and transporting medium through raindrop dislodging exposed soil particles, and overland flow transporting them downslope. Channelised stream runoff also transports the eroded soil particles to the final receiving environment.

On earthwork sites there are four main erosion types:- sheet erosion, rill erosion, gully and channel erosion.

- Sheet erosion: the removal of a fairly uniform of surface soil by water runoff
- Rill erosion: small channels formed by concentrated runoff flows
- Gully erosion: deep channels scoured out by concentrated runoff flows

- Channel erosion: bed and channel banks are removed by flowing water.

Choice of practices will be dictated by the nature of soil at the construction site. Practices appropriate for stabilising sand or gravel will not work for silt or clay (and vice versa). For a discussion of how different particle sizes are detached, transported and deposited, readers are referred to Bagnold (1965).

8.3 Principles of Erosion Control on Earthworks

Erosion control measures protect the soil surface against rain and runoff. They consist of site management, water management and stabilisation. Sediment control measures capture eroded soil particles onsite. Fine textured particles are not easily retained once mobilised. Erosion control measures are therefore usually far more effective.

A simple soil loss estimation model, such as the Universal Soil Loss Equation which has been modified for construction sites, can be a very useful tool to work out what factors can reduce erosion and sediment yield.

The following principles are effective in reducing soil erosion and particle transport. They form the basis of an Erosion and Sediment Control Plan

- Keep disturbed areas small and time of exposure short. Stage construction.
- Protect disturbed areas against runoff from above the site i.e. install perimeter controls (see section 4.1.2).
- Keep on-site runoff velocities low.
- Progressively stabilise disturbed areas (section 4.1.3).
- Retain sediment on the site (section 4.2).
- Control erosion at source.
- Fit the development to the existing site conditions. Watch steep areas. Retain watercourses.
- Retain existing vegetation if possible
- Inspect and maintain control measures.
- Temporary and permanent control measures are usually quite different – ensure that design for temporary measures is conservative.

Over the last ten years, erosion and sediment control practices have evolved rapidly in some parts of New Zealand. As more has become known about the effects of sediment on receiving environments, so has the demand for effective controls become more acute. Techniques of control have continued to develop as more is discovered about their strengths and weaknesses. Some have changed significantly over the last few years (eg, sediment retention ponds); while others, like the use of haybales, have hardly changed at all. The principles of control remain the same, but ongoing change with control measures can be expected.

The techniques discussed in this section follow basic principles and will, if implemented and maintained correctly, give good results within their design limits. Remember however, that all of these measures can be expected to change over time.

A simplified layout of erosion and sediment control practices is displayed below. Dust is included as it can be a problem from earthwork sites. This layout includes a selection of the most common measures and is far from exhaustive. Every site is unique and a combination of these, and other practices, can be expected. Innovative site thinking should be encouraged provided new measures are based on sound principles.

8.4 Appropriate control practices

Table 8.2 Control techniques for erosion resulting from earthworks.

Erosion Control	Practice
Site Management	Site planning and project management that recognises and addresses erosion and sediment control considerations. Runoff Control Systems
Water Management	Diversion channels/bunds Check dams Contour drains Flumes
Stabilisation	Grassing Mulching Geotextiles
Sediment Control	**Practice**
	Sediment retention ponds Sediment retention bunds Silt fences/haybales Storm water inlet protection Pumping
Dust Control	**Practice**
Planning	Dust management plan
Implementation	Water Dust suppressants Surface stabilisation Other options

Descriptions of the various practices for controlling earthworks erosion found in chapters/sections of Part B:	
15	Runoff Control Practices for Earthworks
16	Soil Management Techniques on Earthworks
17	Structures for Runoff and Sediment Control on Earthworks
18	Dust Control Measures for Earthworks

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Chapter 9 Sediment Control – Non Earthworks

Sediment Control – Non Earthworks

9.1 Introduction

This chapter looks at sediment from sources other than earthworks (eg, from forestry), from various cultivation practices and pasture activities, and finally from channel processes and mass movement erosion. Sediment derived from these sources such as these can make up much of the sediment load of some of the streams and rivers of New Zealand.

Historically, any measures that might have been undertaken to control eroding sites were usually initiated from an on-site perspective. Reasons such as "it will limit production", or "that slip should be plant/grassed" were common in justifying remedial works. The initiating reason could simply be that erosion offended good farmers' sense of stewardship towards their land. Government assistance in the form of subsidies and grants was often available for these works.

Today's perspective, however, can be quite different. Off-site water quality considerations have become much more prominent (particularly with the "effects" base of the Resource Management Act 1991 (the RMA)). Control measures have become much more selective and focused. To some extent this could be because we have more knowledge on various practices and know better their strengths and weaknesses. Some of our traditional practices were just not very effective. More importantly however, government monies has declined on one hand, while on the other there is much more pressure to ensure that adverse sediment related effects do not occur from various activities.

Traditional soil conservation has been almost exclusively undertaken on rural land. Although the terms "sustainability" and "effects" underpin the RMA, it could be argued that historical controls have been on point source discharges whose effects have been easier to control. Activities such as quarries with point source discharges have been controlled for years. Non-point discharges, such as sediment from grazing activities, have always difficult to deal with. Forestry is one of the few rural activities where controls have been imposed for a considerable length of time, but cropping and farming have never been subject to specific controls in the past. Controls are now often for off-site reasons compared to the on-site rationale that was more usual in the past.

9.2 Sediment control from surface erosion in plantation forests

In New Zealand approximately 6 percent of the land area is in plantation forestry. Of this area, approximately 90 percent is planted in Pinus radiata. Most of the comments on sedimentation from plantation forestry concentrate on Pinus radiata forests, referred to generally as "pine forests".

Sediment yields are generally accepted to be less than from an equivalent pasture site for most of a forest growing cycle (McLaren 1996). However, there is a short period during logging when sediment levels can be elevated. This is when roads are prepared for logging trucks, landings and skid sites constructed, trees felled and hauled to processing areas. There can be a lot of machinery movement and large areas of land can be bared, particularly as the common method of harvesting in New Zealand uses clearfell techniques. This happens about every 25-35 years

Forest harvesting can produce elevated levels of sediment (Vaughan, 1984), as does land preparation for planting. Harvesting is so closely followed by land preparation that the two phases essentially overlap.

Earthworks (such as roading) have the most impact on sediment yield. Vegetation felling by itself has a much lesser effect on sediment generation and yield than that from earthworks (see Hicks and Harmsworth, 1989). The impact starts when something is done to the vegetation – for example, when the felled vegetation is hauled to some collection point and then transported away. In some places, poor harvesting practices can cause significant sediment generation, particularly on steep slopes and erodible soils. These impacts are usually considered to be less than that from earthworks.

Pine forests that are carefully planted, tended and harvested, can produce forest products for rotation after rotation with minimal generation of sediment compared to other productive uses on the same land. But in many parts of New Zealand, pine forests have been planted on steep erodible land, sometimes as a preferable alternative to pasture. Many of the small forests have had minimal forward planning for future harvesting. These are the forests that have a higher potential for generation of sediment.

Increased levels of sediment arising from forestry operations (other than earthworks) can be a result of:

- loss of protective ground cover during harvest
- exposure of bare ground
- soil disturbance by skidders, tractors or cable haulers
- proximity of operations to watercourses
- concentration of runoff along vehicle tracks and haul paths.

The risk of sediment generation may be increased on:

- steep terrain
- long slopes
- loose soil or weak underlying rock
- timing of operations during wet weather

Production forestry is a commercial enterprise. Harvesting in an environmentally sensitive manner can be more expensive. Where forests are planted on steep land, there are limited options for harvesting. Often, there will be some unavoidable adverse environmental effects. The following sections deal with ways of minimising sediment generation during forestry operations.

9.2.1 Principles of erosion and sediment control

Plan ahead to minimise erosion.

The most important aspect of forward planning is to tailor the planting boundaries to match an appropriate proposed method of harvesting. The proposed harvesting system will dictate how much roading will be required, and the general layout of landings, haul tracks etc, is critical in minimising sediment generation. Forward planning of forestry operations is the most effective method of reducing problems. This needs to be followed up with good operational practice, and regular monitoring and maintenance once the works are completed.

Minimise bare ground as far as practicable.

Ground cover helps to prevent erosion of the soil surface. Some land preparation for planting (such as burning or desiccation) can completely destroy all of the surface vegetation and expose the bare ground to the erosive forces of the weather. Sometimes, the operations are undertaken to prolong the exposure of bare ground so that the new seedlings have reduced competition from weeds. When afforesting steep erodible country, consideration should be given to alternative methods of land preparation that minimise the exposure of bare ground. This could involve oversowing with grasses and legumes.

Minimise soil disturbance as far as practicable.

Many forestry operations involve soil disturbance even though they are not classed as earthworks. Such operations include stumping, hauling logs, ripping, V-blading, and root raking. These operations can often be undertaken with minimal generation of sediment, provided they are properly planned and supervised. Where there is a higher risk of adverse effects, such as on steeper country or near streams, these operations should be avoided if possible.

Protect riparian areas, and don't deposit soil or debris into watercourses.

Riparian areas are critical because any discharge may have adverse effects on the downstream water resources. Forestry operations carried out close to streams, or over streams, should be undertaken carefully so that any deposition of soil or debris into the watercourse is avoided. Where there is an increased risk of sediment entering a stream, it may be prudent to designate a protected area next to the watercourse. The accumulation of waste logging debris ("bird's nests") at landings can also lead to problems if the landings are sited above steep faces, and the bird's nest collapses.

Avoid the concentration of stormwater runoff.

Any operation that concentrates stormwater runoff increases the risk of erosion. Some of these are cultivation/ripping operations that run downhill rather than on the contour, hauling logs downhill to a common point, or locating skid sites in a low point or gully etc. Often, the effects of concentrating stormwater runoff are not evident until after heavy rainfall. These activities can be managed to reduce volume and velocity of stormwater runoff.

9.2.2 Forest planning

Forward planning includes planning to establish a forest from scratch, as well as before each stage of the forest rotation. The New Zealand Forest Code of Practice (LIRO 1993) is a valuable tool for assisting forest owners/contractors in identifying any adverse effects of a particular operation, and then in selecting the appropriate techniques to reduce potential impacts.

Inadequate forward planning often results in higher cost in the long term. Professional forestry consultants have the expertise to carry out forestry planning as well as supervise forestry operations. While it is essential to have a good contractor carrying out the forestry operations, a good operator cannot make up for poor forest planning. For example, a good ground based logging operator will have difficulty logging a steep site that should be logged by cable hauler.

9.3 Sediment control from surface erosion in croplands

Cultivation of soil is necessary to create a better seedbed, and to minimise weed competition on growing crops. It usually exposes the soil to the erosive effects of rain splash and concentrated runoff. The potential for erosion and sediment generation from a cultivated site can be far greater than from the same site under a permanent vegetative cover. Loss of soil from cultivated land can result in elevated levels of sediment in receiving waters and also impact on the sustainability of the soil resource itself.

Three different types of cultivation on three different kinds of soil are discussed here:

- market gardening on granular loams
- cropping on loess
- orchard cultivation on free-draining alluvial soils.

9.3.1 Market gardening and grain cropping on granular loams

Granular soils derived from volcanic ash are some of the most intensively used in New Zealand. Approximately 8,000 ha are used for large-scale vegetable production in South Auckland (Franklin District) (Basher, 1997), and there are smaller pockets in Northland, North Auckland, and coastal Otago. Anecdotal evidence suggests that severe erosion can occur on these soils during intense rainfalls and that this can not only adversely affect the sustainability of the soil but also lower water quality.

The Auckland Regional Council undertook a catchment study into sediment yield from vegetable growing in the early 1990s. Sediment yield from the 1.8 km^2 trial catchment site was 49 $t/km^2/yr$ over three years (Hicks, 1995). Bedload was negligible at the sampling site. Soil loss from earlier plot studies undertaken by Cathcart et al (unpubl) in the early 1970s was evaluated (Basher et al, 1997). Bare soil plots averaged 5680 $t/km^2/yr$ over a 2.5 year measurement period. The largest storms resulted in most of the soil loss mentioned in the two studies.

The very large difference in yields suggested that large quantities of soil were being mobilised within paddocks by storms but little was being transported as suspended sediment load by streams. This was considered to be a function of local drainage characteristics (whether fields discharge directly into watercourses or not) together with the strongly aggregated nature of the soil. Analysis of the soil indicated that the soil is resistant to dispersion into primary sand, silt and clay particles (silt and clay sized particles usually constitute the suspended sediment load). It was inferred that the soil which is moved in storms is transported as aggregated material and deposited within paddocks and drains when runoff velocities diminish.

When a regional plan specifically directed towards controlling sediment from the Auckland region's land disturbing activities was prepared and notified in 1993, the council did not impose any regulatory controls on outdoor vegetable production, as the catchment soil loss yield of 49 $t/km^2/yr$ was similar to that from pasture from other soil types in the region (Hicks, 1994). However, opinion continued to hold that significant soil loss was occurring under this type of land use and that this was affecting both soil sustainability and water quality.

A major storm in May 1996 resulted in flooding and sediment deposition in parts of Pukekohe township and focused public attention on the practices of outdoor vegetable growers. Discussions were then held between the Pukekohe Vegetable Growers Association, regional councils and Agriculture New Zealand, and as a result the Franklin Sustainability Project came into being. This was a three-year project with a emphasis on erosion management, although wider considerations, such as irrigation, pest control and nitrate leaching, were also included. Much of the following information has been obtained from this project.

Sheet erosion of topsoil following a storm event, Pukekohe, 1999. ***Photo: D. Hicks.***

9.3.2 Principles of control on granular loams

Granular loams are strongly aggregated, and the aggregates are not easily broken. They do not break down to fine clay, silt and sand-sized particles but to smaller aggregates. The soil aggregates are still relatively large compared to clay and silt, and can quickly settle out once flow velocities diminish. Under normal conditions, infiltration and percolation through these soils is very high. Measures to ensure that aggregate stability continues are important.

This characteristic markedly influences the type of erosion and sediment control measures that can be used. Soil particles may be relatively easily mobilised, but they are also equally easily retained once flow velocities diminish. Effective erosion and sediment control does not then merely consist of providing settling areas for suspended sediment to settle out. It comes down to minimising off site runoff and reducing on site runoff.

For each paddock, the following points need to be checked:

- Where is the water coming from?
- Where is the water going?
- How can the paddock be set up to minimise erosion and soil loss?

Six basic measures are promoted to minimise erosion and sediment loss:

- channels and interception drains to intercept above-site runoff
- benched headlands
- permanent drainage systems within paddocks
- contour drains
- raised accessways
- silt traps.

The first five are effectively runoff control measures while the last is the only sediment control measure. In addition to these measures, a number of management practices have also been suggested. These include ripping wheel tracks, growing cover crops, use of hedges and cultivation techniques.

A paddock plan will help ensure that erosion and sediment control measures are appropriate for the site and mesh in with growing practices. It should be integrated with other paddock plans to form a co-ordinated property plan, vital for runoff control. Each property plan should be integrated with adjacent property plans, where they exist.

Each measure or practice (except for permanent drainage within paddocks, which is self-explanatory) is briefly discussed below in section 3.1.3.

9.3.3 Grain cropping

Cultivation of arable loess soils in the eastern South Island and southern North Island can result in the loss of soil by water runoff and by wind erosion. This soil loss is a consequence of most of loess soils high susceptibility to structural degradation. Cultivation can readily break the soil down into individual silt grains, susceptible to erosion by both water and wind.

In Canterbury and Otago, arable soils are considered to be at more serious risk of wind erosion than water erosion (Ross et al 2000), due to strong, drying foehn winds (nor'westers). However, a report by Landcare Research (Ross et al 2000) prepared for the Canterbury Regional Council assesses the risk of erosion on arable soils; it also addresses soil loss by surface runoff and has been used extensively in compiling the following information.

Sheet and rill erosion occur when water runs off cultivated topsoil on sloping ground. Low permeability subsoil in loess limits downward water movement, and sideways flow through topsoil contributes to runoff generation at low points in fields. High erosion rates on cultivated downlands have been recorded since the 1940s and found to be closely associated with recent cultivation (Ross et al 2000).

Rill erosion is considered to most significant with up to fifty times more soil being lost through rilling than from other forms of erosion (ORC, 1995). Rill erosion induced by moderate intensity rainstorms on finely cultivated soils can deposit 20–93 t/ha of sediment at the foot of cultivated slopes (Hunter et al, 1990). Rill dimensions indicated local losses on eroded slopes of up to 410 t/ha. Hunter and colleagues also reported an earlier study of soil loss from rill erosion in the order of 50 to 101 t/ha for four sites. During a three month period in 1986, 240 ha over 24 properties lost an average of 50 tonnes of topsoil/hectare (ORC, 1995). The depth of topsoil after 60 years of intensive cultivation was found to be 100 mm shallower compared to equivalent uncultivated slopes (Hunter et al, 1990).

While mean topsoil depth did not differ significantly between areas used for pasture and areas used for cropping, topsoil depth under cropping was far more variable and there was a higher frequency of shallow topsoils (Basher et al, 1995). Basher's study found considerable redistribution of soil by erosion and deposition but little export of soil. Ross et al 2000 support this and note that erosion on downlands results in considerable redistribution of soil but little net loss. The likely reason is that there are few permanently flowing watercourses close by, to transport eroded sediment off-site.

Rilling is often worse after a drought period when soils are dry. Storms can therefore mobilise and transport large quantities of soil from land under cultivation. Storms of sufficient intensity to cause significant erosion can be expected from the larger rainfall events, such as those with a greater than a 10-year return period. Most of this soil is deposited at the foot of slopes and can cause localised problems to occur such as blocked culverts etc.

9.3.4 Principles of control

Control of water-initiated erosion on cultivated soil includes measures that increase soil resistance to erosion and those that reduce runoff volume and velocity. The condition of the soil, the rate of infiltration into the soil, the presence of subsurface pans (both natural and from cultivation), poor vegetative cover, and long steep slopes, are all factors that influence erosion on cropping areas. Retaining or improving the structural stability of the soil is a key element of control.

9.3.5 Orchards and vineyards

In the 1960s, apple and pear orchards within the Nelson Province were suffering from severe erosion problems. At that time, the Nelson Catchment Board became heavily involved with promoting erosion control works and developing practices to prevent future problems. The Board was assisted with funding from the Soil Conservation and Rivers Control Council to develop sustainable land management practices using six demonstration orchards. By 1977, effective practices had been developed and a review of the conservation works was published (Leighs, 1980). The information below is from that review.

The problems stemmed from a number of factors:

- The Moutere Soils are relatively thin and non-cohesive with little or no organic matter. The subsoil is hard clay over gravels.
- The orchards were often planted on sloping ground in a square pattern using straight rows that is best suited to flat land.
- Rainfall in the Moutere Hills area averages 950 –1050 mm/year, with dry summers and mild winters. Storms of 70 mm in 24 hours, having a return frequency of 2 years, can occur at any season.
- In an attempt to conserve moisture and carry out weed control, the ground was cultivated between the rows of trees.

Cultivation resulted in the ground being kept tilled from mid spring to mid autumn, with many owners priding themselves on the fine tilth achieved. Over time, excessive working of the soils resulted in a cultivation pan on the already hard subsoil and weakened the poorly structured topsoil. As a result, even light rains produced widespread sheet and rill erosion. Heavy rainstorms moved large quantities of soil from the upper slopes to lower ground and valley floors. It was common for the roots of fruit trees on spurs and upper slopes to be left standing on pedestals of earth, because the soil between the trees had been washed downslope to deposit on the flats and create swampy conditions burying trees and fences.

9.3.6 Principles of control

The key principles for control of the problems included:

- improving infiltration of rain and reducing overland flow runoff
- controlling subsurface and surface water, and conveying the water safely to lower flats and natural waterways
- stabilising exposed ground with grass.

The practices that were developed to address the above principles were a combination of runoff control, drainage control and erosion control.

9.3.7 Practices

The pattern of works included the following techniques:

- **Ripping of subsoil** to promote infiltration of rain and reduce runoff;
- Installation of **lateral grassed waterways** with subsurface tile drainage to collect underground and surface water;
- Installation of **main grassed waterways** with subsurface tile drainage to receive water from laterals and some direct subsoil ripping;
- Use of main **outlet grassed waterways** with subsurface tile drainage to receive water from several main tiled grassed waterways and deliver it to;
- Main **outlets or disposal systems**, usually natural streams, but could also be detention or retention ponds;

Grassing of all exposed ground and drainage systems.

9.4 Sediment control from surface erosion in pasture

Surface erosion of topsoil causes reductions of 40 percent or more in pasture growth. The severity of the impact depends on the frequency of erosion and how much land is affected. Surface erosion occurs on an annual, or more frequent, basis. In low rainfall areas where vegetation is often sparse, up to half the land can lose some of its topsoil each time, but in high rainfall districts which are usually well vegetated, topsoil loss is restricted to a tenth or less of the surface.

Farming practices that may inadvertently cause surface erosion are those that deplete ground cover. Windblow, sheetwash and rilling of topsoil can occur almost anywhere where groundcover is depleted, even on flat land. Light soils with a high silt or sand content are more susceptible than loams, heavy clays or peats.

Other practices that will lead to sediment generation include those that weaken soil strength, by physical destruction of the soil aggregates, or breakdown of the soil structure.

Very often, erosion can be aggravated or induced by stock management. In a literature review on the adverse effects of grazing on soils, Hunter-Smith (2000) noted that overgrazing can adversely affect soil properties, particularly infiltration rate, macroporosity and bulk density. The extent of the damage is influenced by a number of factors:

- slope;
- soil type, texture, and moisture content
- pasture cover and species
- stocking rate, duration, and animal species.

A number of studies conclude that winter and spring appear to produce the highest amounts of runoff and sediment transport. However, other studies also show that when the soil is dry (generally in summer), surface runoff and soil erosion increase during high intensity rainfall. Maintaining a dense grass sward and avoiding overgrazing, protect the soil surface from very intense rainstorms, particularly those that occur during summer. Retirement from grazing significantly decreases surface runoff and increases infiltration rates.

9.4.1 Principles of control

The following principles cover the control of sedimentation from pastoral land use:

- Avoid land management practices that deplete ground cover or expose bare ground / Adopt practices that encourage a dense or close ground cover.
- Avoid land management practices that weaken soil strength or break down soil structure.
- Encourage land management practices that increase infiltration capacity of the soils.
- Manage streamside areas carefully, and protect them whenever possible.

9.4.2 Practices

Any farm or pasture management techniques that minimise bare ground and help form a dense pasture sward will reduce the risk of surface erosion, limit adverse effects on soil structure, and help prevent a decrease in the rate of infiltration.

Application

While it is accepted that overgrazing of pastures cannot be completely avoided, all pastoral farmers will attempt to maintain an adequate ground cover, and minimise the risk of overgrazing as far as practicable. There are a range of different farm management practices that can be undertaken by landowners that minimise the amount of bare ground, and help encourage a dense pasture sward. These include the following:

- Have the farm well fenced so that stock grazing can be closely controlled.
- Have a reticulated water supply that is well planned to provide adequate water to stock, particularly during peak demand periods such as mid summer. Ensure that there are sufficient troughs available, so that grazing animals do not have to travel far to the nearest watering point.
- Establish a pasture improvement programme to provide a dense pasture sward, particularly on pastoral hill country.
- Provide an adequate fertiliser programme to maintain a good pasture sward.
- Avoid mob stocking or heavy set stocking during periods of drought, cold conditions or wet weather.
- Carefully site of fences, gates, troughs and farm tracks to avoid low points or overland flow paths where stormwater runoff may be concentrated.
- Keep stocking rates to a sustainable level for the classes of land that are

being grazed, particularly during wet periods.

- Use grazing pressure as a pasture management tool without overgrazing.

- Match the type and class of stock to the land capability of the property.

In general, good pastoral farming practices will also help retain a dense pasture sward, and will minimise bare ground and reduce the risk of sedimentation.

9.5 Surface erosion control for other sources of sediment

Sediment can arise from sources other than the commonly recognised ones such as earthworks, forestry, and cultivation. Sediment from mass movement erosion and stream channel processes are two.

In some areas around New Zealand, mass movement erosion is occurring on a scale that results in large quantities of sediment being regularly discharged to waterways. This sediment can then be reworked on an ongoing basis and the receiving environments may have little chance of recovery. These situations are therefore very different one-off type sources of sediment such as earthworks.

Much of the emphasis on mass movement control has been related to the on-site effects. Less prominent, but also relevant, is the effect of the ongoing injection of sediment into the receiving environments. Not all eroded material enters watercourses, but what does can have devastating effects. If sediment continues to enter watercourses, or ongoing processes continue to rework sediment deposited between regular storm induced “top-ups”, then the receiving environment may not be able to recover to its former level. The effects of mass movement erosion in these situations then not only relate to the sustainability of the on-site landuse, but also to the off-site sustainability of the receiving environments. A permanent degradation of the receiving environment can occur.

An example of this is in the siltstone country north of Napier. There are a considerable number of studies that have assessed the impact of storms and subsequent erosion in this area of New Zealand. One of these assessed the soil mobilised by a five year return period storm to be nearly 9000 t/km^2/yr (Eyles, 1971). Storms of about a 5-year return period interval appear to be about the threshold for significant mass movement erosion. Page (1992) assessed that Cyclone Bola, which occurred in March 1988 and was the largest rainfall event to be recorded in the area, generated an average of 420 m3/ha (42,000 m3/km^2) within the same catchment. Of this sediment generated, 51 percent was deposited on lakebeds and 6 percent was discharged from the lake outlet. The study considered that most of the sediment generated from this storm (89 percent) was from landslide erosion, and that sediment in secondary storage provided only a small contribution. The sediment deposited by larger storms was reworked within the streams and rivers (Page et al, 1994), during rainfalls less than the 5-year threshold.

Not all sediment generated by mass movement erosion enters a watercourse. The proximity to watercourses, slope, surface roughness, retaining vegetation, and the characteristics of the drainage pattern will all influence how much is retained on hill slopes and how much discharges to watercourses. For instance, about 50 percent of sediment generated by landslides in the Tutira area was considered to enter watercourses (Page 1992). The same report also assessed a number of other studies around New Zealand and concluded that, even with different terrain and triggering conditions, about 50-55 percent of all sediment generated from mass movement sources entered streams. This will obviously vary however, for the reasons mentioned above.

9.5.1 Sediment from channel erosion

The Alluvial Process

A watercourse develops a bed shape in response to the volume of water that the watercourse must carry, the size and volume of sediment carried, the hardness of underlying rock, the slope of the channel and the “age” or geomorphological stage of development of the catchment and its floodplain (Cathcart, 2000). A regime, which generally includes a meandering channel, some channel erosion and deposition of sediment, is just one variant. If any of the catchment characteristics are changed, the watercourse will accordingly adjust its regime to compensate. The channel may alter –for example, to a straight or braided form – as it accommodates the changes, with bank erosion and deposition also altering.

Channel erosion can contribute to undercutting and instability of adjacent land. This in turn can affect sediment generation and supply to the channel. Observation by river engineers confirms that channel instability can sometimes be related to a sudden introduction of detritus to the stream. This sets up a chain reaction, by initiating bank erosion, leading to more bedload, leading to more bank erosion. Once started, this process can be difficult to control, as it requires control over the input of material, as well as control over bedload movement and bank erosion.

Bankfull or near-bankfull is generally considered the most effective discharge in transporting sediment and reshaping the channel bed and banks. (Waters of New Zealand, 1992). In many streams this is about the mean annual flood event (this is the average of the series of annual maximum flows, which statistically has an average recurrence interval of 2.33 years – Waters of New Zealand 1992). Once eroded, deposition of clay and other fine grained materials is unlikely in streams because of a low settling velocity. Concentrated flows in channels have greater depth and velocity and sediment carrying capacity than overland flow. As a consequence most fine textured sediment derived from stream bank erosion will be reworked downstream over time.

Channel Erosion as a Source of Sediment

Stream channel erosion is a common form of erosion and can be a major source of sediment. From an "effects" perspective, sediment from channel erosion is immediately available for transport by channel flow. It is therefore different to catchment derived material may only travel short distances and can be re-deposited and retained in the catchment. A good illustration of this is the relatively small quantities of sediment that might leave a vegetable-growing area on granular soils in South Auckland compared to the very much larger quantity that can be generated within the catchment.

The contribution of sediment from channel erosion varies tremendously. Gianessi (1986) reports that a study of sediment sources in five northern Mississippi watersheds found channel erosion accounted for 15 to 28 percent of the total sediment delivered while being only 1 percent of the catchment area. Channel erosion can therefore be an important source of sediment and can have an influence on water quality quite out of proportion to the areal extent of watercourses.

The relative influence of channel erosion as a source of sediment varies similarly in New Zealand. In one study (Page et al 1992) channel erosion was considered to contribute only 2 percent of the total sediment yield from one catchment (Lake Tutira, north of Napier) during one storm although there was significant channel modification. Little sediment was found to accumulate between the larger storm events and this suggested that sediment from channel erosion in this catchment was significantly less that from mass movement erosion.

9.6 The effect of urban development on channel sediment

The change of landuse from rural to urban increases the imperviousness of a catchment surface and changes its hydrological characteristics. Increases in flood-flow frequency and size result from the changed runoff patterns. Stream channels will widen as they re-adjust to the new flow regime. Herald (1989) stated that there was a three fold increase in the width of streams draining an area that was 85 percent urbanised. Schueler (1989) supports this by claiming that most streams widen two to four times their original size if post-development runoff is not effectively controlled. These changes can start to occur once 10-20 percent of a catchment has been developed. This stream widening is primarily accomplished by lateral cutting of the stream bank resulting in undercutting of the zone adjacent to the channel, treefall and slumping. This channel widening occurs in direct response to changed flow regimes resulting from urbanisation. Flood detention measures in some urban situations throttle flood flows down to the bank full situation and which, although controlling flood peaks exacerbates channel erosion because the bank full situation (the main erosion causing flow) is continued for a longer period.

One study looking at the effects of proposed urban development predicted an average of 9,800 tonnes/year of sediment would result from widening of channels in one catchment in Auckland as the channels adjusted to altered flow regimes over a 20-year development period (from Vant et al, 1993). This sediment source was solely due to streams widening and to accommodate altered hydrology resulting from changed catchment characteristics. This was compared to 18,000 tonnes/year estimated from the earthworks phase of development (not all of which would reach watercourses), and 2,800 tonnes/year from the remaining catchment sources such as pastoral and developed urban land uses.

Channel erosion resulting from urbanisation of catchments can therefore be a major contributor of sediment to waterbodies. Modification of channels will normally last for years as stream channels adapt. The generated sediment is generally immediately available to stream flows and can have effects on receiving environments out of proportion to its relative area.

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