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THE IMPACTS OF FOREST MANAGEMENT ON EROSION AND SEDIMENTATION: A NEW ZEALAND REVIEW

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Figure 1 - In steep terrain, erosion from road, track and landing surfaces can be a major contributor to stream sedimentation

ABSTRACT

A review of predominantly New Zealand literature pertaining to the impacts of forestry management and operations on sedimentation was carried out to highlight the major sediment sources, the processes which result in sediment mobilisation, and the environmental impacts of sedimentation.

INTRODUCTION

Awareness of the impacts of erosion and sedimentation on the receiving environment has increased in recent years as issues of resource sustainability receive more emphasis. The destruction caused by extreme climatic events, such as Cyclone Bola, has also highlighted the importance of balancing land-use decisions with environmental considerations. The development and implementation of the Resource Management Act of 1991 has identified the responsibilities of land owners/land managers, and regulatory bodies to protect the environment. In response to this, the New Zealand forest industry is having to address the potential for environmental impacts resulting from specific management decisions and practices.

In an effort to identify what we know, and perhaps identify what we need to know, LIRO undertook a review of predominantly New Zealand literature pertaining to the impact of forestry operations on erosion and sedimentation.

This review has been separated into four sections. The first section briefly discusses the environmental impacts of sedimentation. In the following two sections erosion and sedimentation associated with earthworks, including roads, tracks and landings, and crop harvesting and re-establishment are discussed. In the fourth section, literature relating to alternatives for reducing erosion and sedimentation are discussed.

ENVIRONMENTAL IMPACTS OF SEDIMENTATION

Before discussing the influences which forestry operations have on erosion and sedimentation, the general environmental impacts of sedimentation will be identified.

Forestry operations can directly impact on the water-course bed or channel, through felling of trees into, or movement of machinery within stream channels. The impacts of increased sediment input into a stream may not be immediately evident as sediment can be stored in stream banks, terraces, streambeds, and behind debris dams - an important point to consider when relating specific forest operations with instream impacts and setting guidelines. Once sediment is deposited into a water-course, be that directly through earthworks, through mass movement, or by gradual accumulation, it is likely that factors secondary to the forestry operation will influence the degree of environmental impact. Examples of secondary factors include the nature of the sediment (fine versus coarse), the sensitivity of the aquatic ecosystem, the proximity and nature of downstream water use, and conservation and recreational values associated with the water-course.

Sediment Transport

Downstream sediment transport may occur either by suspension or bedload transport, depending on the nature of the parent sediment and the stream hydraulic characteristics (Figure 2).

Fine sediment (clay and silt) is likely to be transported as suspended sediment, whereas coarse sediment (sand, gravel, and boulders) is likely to move as bedload. As fine sediment transport requires less energy than coarser sediment, suspended sediment may impact much further downstream because of the ease of transport. Peak flow or storm events may result in significant bedload transport in addition to suspended sediment transport. However, this does not imply that bedload transport is confined only to these flow conditions as transport may occur when turbidity is low and flow conditions are normal. An example of this is the bedform movement in the lower reaches of the Waikato River during medium flow conditions.

The instream movement of sediment may affect freshwater and marine biota, and the utilisation (including recreation) and perception of the water resource.

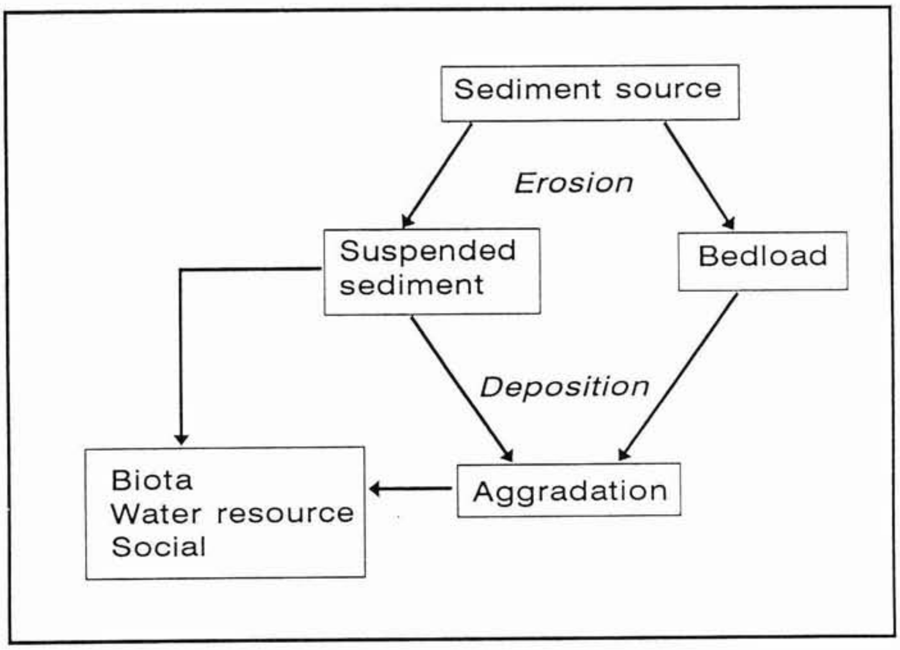

Figure 2 - Environmental impacts of sedimentation

Suspended sediment can impact biota by reducing the light penetration, limiting the amount of primary production in the food chain. Sedimentation can also lead to reductions in dissolved oxygen as the nutrients contained in the sediment are decomposed by micro-organisms. In addition, suspended sediment can impact the biota by increasing the stream water temperatures (Steel and Priest, 1981).

Sedimentation

Sedimentation can result in the infilling or aggradation of water bodies, and the choking of water filtering biota.

Aggradation within the stream channel can result in the raising of stream channels, thereby increasing the potential for flooding, and result in infilling of lakes, estuaries and harbours, impacting on water storage and navigatibility. Dredging may mitigate the impact, but may also result in increased sedimentation elsewhere downstream or down-current. Aggradation leads to changes in the channel morphology, possibly causing streambank instability, undercutting of the bank, hence increasing downstream sedimentation (Pearce and Watson, 1981; Coker et al., 1990).

The deposition of sediment in water bodies that supply hydro-electric power stations is also of concern as sediment can reduce the reservoir capacity and cause increased wear on turbines. Such concern led the Bay of Plenty Electricity Authority to investigate sediment inputs into Lake Aniwhenua (Landcare Research, unpublished data).

Aggradation of the streambed can result in decreased species diversity and abundance of burrowing, deposit feeding animals (Winterbourne, 1986). The occurrence of debris dams can have major impacts on the migration of fish present in the forest stream. High levels of sedimentation can have an impact on all stages of the life cycle for various species of fish. Graynoth (1979) noted that sediment impacted the survival, growth, abundance and distribution of ova, fry, juvenile and adult trout. Fine sediments can fill in spawning gravels thereby limiting the amount of essential dissolved oxygen that can be filtered to the ova. The layer of sediment that covers the spawning gravels can also impede the emergence of the fry into the stream (Brown, 1985).

Streams can recover rapidly after being choked with sediment. Winterbourne and Rounick (1985) cite an example of the recovery of a benthic community in a West Coast stream.

The Marlborough Sounds area is recognised as being particularly sensitive to the impacts of sedimentation. Approximately 20,000 ha of the Marlborough Sounds area is in plantation forestry (Fahey and Coker, 1992). This resource is now maturing, with much of it of a harvestable age. Much of the sediment that enters the Marlborough Sounds from the forest streams flocculates in a shallow zone near the shore (Fahey and Coker, 1992). While this flocculation is beneficial for keeping turbidity levels down, the silty layer that forms on the seabed has been shown to be devoid of marine life, and the accumulation of this layer has been linked with a decline in natural mussel beds and scallops. The deposition of sediment on the seabed within the sounds can interfere with the food source for the mussels. Nutrients contained within the sediments, although beneficial to the growth of the mussels, also benefits the growth of plankton and plankton blooms which can be toxic to mussels (Hickman, 1978).

O'Loughlin (1980) showed that there were significant increases in the suspended sediment concentrations in the near-shore environment caused by the logging of catchments which drained into the sounds. As could be expected, suspended sediment yields were highest during storms. However, it is not known whether this is due primarily to increased sediment from the logged catchments or the wave action in the sounds re-activating some of the sediment that has settled on the seabed.

ROADS, TRACKS AND LANDINGS

Studies in New Zealand and overseas have shown that roads, tracks, and landings can contribute significantly to sediment mobilisation. (O'Loughlin, 1979; Vaughan, 1984). Harvesting on steep terrain (exceeding approximately 15° to 20°) often leads to the establishment of roads, tracks, and landings by side-cutting, and the construction of fill slopes (Figure 3). This can result in increased areas of soil exposure, changes to the existing drainage pattern, and decreased soil strength producing significant sources of sediment.

Sedimentation may result from:

- movement of soil and debris directly into permanent water courses during road, track and landing construction and maintenance
- movement of soil and debris placed near permanent water-courses or a temporary water-course during periods of peak flow or overland flow
- surface erosion of road and landing surfaces, and water tables
- surface erosion of fill and sidecast materials
- mass movement of sidecast materials from the failure of over-steepened slopes
- mass movement of up-slope materials from reactivation of old erosion features
- failure due to slope toe removal.

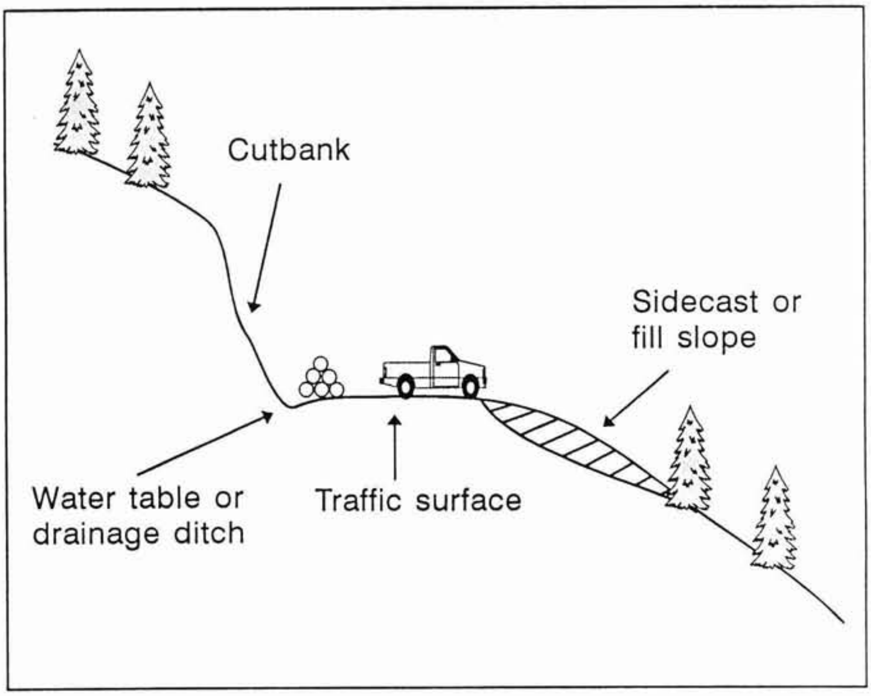

Figure 3 - Components of earthworks construction

Surface Erosion

Several New Zealand studies have reported sedimentation rates for forested catchments (Table 1).

Mosley (1980) found that approximately one-third of mobilised sediment was deposited within the stream channels, with the remaining two-thirds being trapped within vegetated areas below fill slopes and roads. It was found that sediment only reached the stream in large amounts where the road was situated next to the stream, or the road was in a valley bottom. There was considerable variation in the erosion rates from individual roads, ranging from 14 $m^3.km^{-2}.yr^{-1}$ for a 10 year old valley bottom road to 1,270 $m^3.km^{-2}.yr^{-1}$ for a one year old mid-slope road. The yield figures reported by Mosely are considerably higher than those of the other authors (Table 1), possibly reflecting the contribution of mass failure effects in the total yield (Fahey and Coker, 1992).

The contributions of specific construction features to the total sediment loss from roading systems in the Nelson region have been documented by Fahey and Coker (1989 and 1992). In the earlier study performed in south west Nelson, it was found that erosion from road surfaces was not a major contributor, identifying the fresh cutbank, drainage ditch and sidecast fill as primary sources. The importance of cutbank runoff and needle ice activity for moving material into drainage ditches was identified. This finding differed from that of the later study where cutbank erosion was not considered significant; this was considered to reflect the characteristics of bedrock exposed in the banks.

In the study by Fahey and Coker (1992), it was found that coarse sediment yield from roads for the Queen Charlotte Forest was approximately three times greater than fine sediment yield. The authors found that there was a strong relationship between the road gradient, the velocity of the runoff, and the relative sediment yield. Relative yields of coarse material from road surfaces were estimated as follows :

1° - 3° - 0.5 unit
4° - 6° - 1 unit
7° - 9° - 2 units

Table 1 - Published sediment yield rates from forest roading systems. The results shown in italics are estimates from the respective authors.

Sedimentation rate ($t.km^{-2}.yr^{-1}$)	Study area	Reference
710	SW Nelson	Mosley (1980)
37 *320 at harvest*	SW Nelson (Granite)	Fahey and Coker (1989)
67 *200 at harvest*	SW Nelson (Schist)	Fahey and Coker (1989)
62 *<100 at harvest*	Marlborough Sounds	Fahey and Coker (1992)
176	Westland	O'Loughlin (1979)

Note: The result from the study of O'Loughlin was converted from $m^3.km^{-2}.yr^{-1}$ to $t.km^{-2}.yr^{-1}$ assuming a density of 1500 kgm^{-3}.

Clay and silt-sized particles pose the greatest risk to stream water quality (Fahey and Coker, 1992) as these finer particles require less energy than sands and gravels to be transported. As a consequence, fine particles can be transported greater distances than coarser particles. Coarser materials generated by erosion were likely to be stored in local gullies for later removal during high intensity rainfall events.

In a study utilising runoff plots, similar to that of Fahey and Coker (1989 and 1992), Smith and Fenton (1993) measured sediment yield from logging tracks formed on rhyolitic pumice terrain within Kaingaroa Forest. Two track slopes (18° and 22°) and two slope lengths (10m and 25m) were used in the study, and the tracks received no post-harvest rehabilitation. The authors found that there were no clear relationships between slope length, slope angle, and sediment yield. It is likely that this finding can be attributed to the lack of significant rainfall events during the study and the lack of replication of treatments.

In northeastern United States, Reid et al. (1981) studied the impact of trucking on sediment production, reporting that roads with four or more trucks per day may yield up to 30 times more sediment than do roads not carrying traffic. Similarly, Coker et al. (1993) studied the production of fine sediment from trafficked road surfaces in the Marlborough Sounds. They concluded that traffic activity (trucking and other ground-based operations) during rainfall was likely to increase the concentration of fine particles in runoff by an order of magnitude.

Several authors have published sediment yield rates for undisturbed catchments. Fahey and Coker (1992) discuss these yields, pointing out that comparison with yields from roads is difficult as the latter yield figures do not reflect the amount of sediment which can reach stream channels.

In a rotation-length study, Hicks and Harmsworth (1989) reported that 70% of the total sediment yield from a forested catchment in Glenbervie Forest, Northland, occurred during harvesting and re-establishment. Sedimentation resulted from earthfill material which was bulldozed into sub-basin headwaters. High sediment yields associated with landing construction persisted for several years, dominating any subsequent effects of actual harvesting and re-establishment.

Mass Failure

Earthworks resulting from forest road construction in steep terrain are particularly prone to mass erosion during periods of prolonged or intense rainfall.

A storm with approximately a 1.5 to 2 year return period caused extensive sedimentation within a catchment in Tairua Forest, Coromandel (Pearce and Hodgkiss, 1987). The storm resulted in mass failure of a recently constructed landing, which caused an estimated three orders of magnitude increase in sedimentation relative to an adjacent undisturbed catchment. Sediment yield from each of the catchments was monitored for approximately three years after the major storm event.

Coker and Fahey (1993) reported the contribution of mass failure of cutbanks and sidecast slopes due to four major storms which occurred in 1990 on granite terrain in south west Nelson. A surface erosion rate of 37 $t.km^{-2}.yr^{-1}$ (Fahey and Coker, 1989) was reported for the study area. Increased sediment yield associated with the storm events were estimated at 2,800 $t.km^{-2}$, corresponding to 80 years of surface erosion.

HARVESTING AND RE-ESTABLISHMENT

The major impacts of harvesting which may be associated with erosion and sedimentation include:

(1) the physical site disturbance

(2) the loss of slope stability and increased water yield due to deforestation.

Site Disturbance

Site disturbance resulting from harvesting includes the displacement and mixing of soil and/or organic layers, and the compaction of soils. The passage of harvesting equipment and/or logs across a site has the potential to scrape-off surface organic and soil layers, exposing subsoils to the erosional forces of rainfall and runoff. Additionally, equipment and log passage may compact the soils reducing rainfall infiltration increasing the potential for runoff.

Study of the links between the degree of site disturbance and subsequent sedimentation has not been performed in New Zealand. However, it may be considered that the greater the extent of subsoil exposure and compaction on a site, the greater the potential for sedimentation.

A survey of site disturbance in New Zealand forestry was performed by Murphy (1984) in which disturbance resulting from both clearfelled and thinning operations was measured. The major findings were:

- for all operations surveyed there were no significant differences in the areas of exposed soils between flat/undulating and steep terrain, but deep disturbance was greater on the steeper slopes

- on steep slopes the use of pre-constructed extraction tracks led to less soil exposure than where there were no such tracks, but there was no significant difference in deep disturbance

- the use of highlead on steep terrain caused considerably less deep disturbance and less soil exposure than ground-based operations

- the area of deep disturbance and exposed soil was less in thinning operations than in clearfell operations.

Interestingly, Murphy (1984) did not find obvious differences in the level of disturbance between the four soil types studied (clay, pumice, sand, and gravel). The author concluded that the level of disturbance which results from specific harvesting operations was influenced by the interaction of many factors, making prediction of disturbance difficult.

Other than Murphy's survey, no New Zealand research has addressed the effects of cable operations on site quality. Overseas, Miller and Sirois (1986) compared site disturbance due to skyline yarding and skidding in Mississippi, United States. The authors found that yarding roads, which were often orientated down-slope, provided effective channelisation for runoff, thereby increasing the risk of erosion. A comprehensive study of site disturbance and landslide incidence at yarding settings in the Queen Charlotte Islands, British Columbia has been documented by Sauder and Welburn (1987). The amount and causes of yarding disturbance were related to the terrain, yarding system requirements, yarding techniques, and operation.

Deforestation and Afforestation

Slope Stability

The forest crop positively influences slope stability and hydrological properties of a site by:

(1) providing mechanical strength through the rooting systems

(2) reducing soil water contents through transpiration and interception

(3) providing protection of soils.

Many forest sites derive much of their stability from the root systems of the vegetation that they support.

Harvesting of the forest crop causes the root systems to eventually die, thereby decreasing slope and soil stability. O'Loughlin and Watson (1979) reported that roots of radiata pine in Ashley Forest lost approximately half of their tensile strength within 20 months of harvesting. However, at other sites in Canterbury and Nelson, it had been noted that mature root stumps and major structural roots had remained sound for up to five years after harvest. O'Loughlin (1981) clarifies this finding by stating that the rate at which the tensile strength decreased appeared similar for all sites, but as the initial root strength from Ashley Forest was lower than for other sites, very low strengths were reached sooner after harvest.

The loss of strength continues until such time succeeding root systems have developed if regeneration or replanting occurs. The general effects of root death following harvest and subsequent root colonisation are shown in Figure 4.

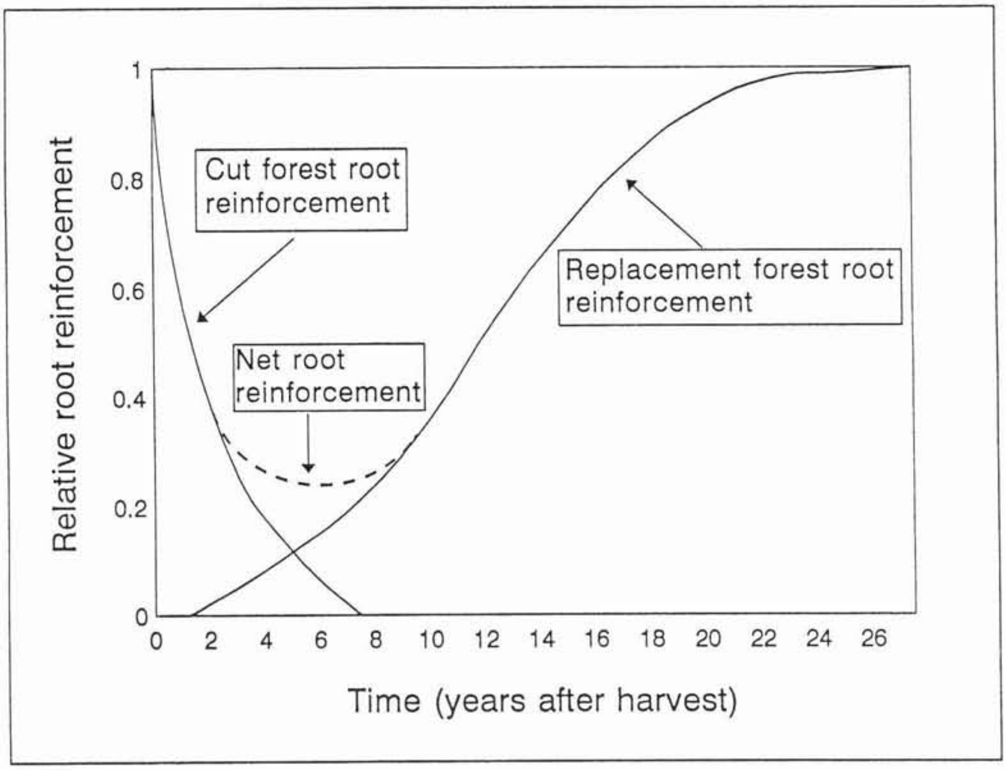

Figure 4 - Effects of harvesting and re-establishment on relative root reinforcement (O'Loughlin, 1985)

During the process of recolonisation of the soil by the successive rooting system relative reinforcement is presumed to reach a maximum value about 30 years of age and half the maximum value at 12 years of age (O'Loughlin, 1985). From Figure 4, it can be seen that between harvest and root recolonisation there is a period of approximately eight to 10 years during which relative root reinforcement is low.

Hicks (1991) clearly demonstrated that slope stability in the East Coast hill country during Cyclone Bola had benefited from mature exotic and indigenous forest covers relative to reverting scrub and pastoral vegetation with less extensive rooting systems. Also following Cyclone Bola, Watson (1990) found that forested slopes with trees under six years old had similar degrees of landsliding to pastured slopes. On slopes with trees greater than eight years of age, the degree of landsliding decreased considerably. Similar trends had been previously found by O'Loughlin et al. (1982) from a seven year study performed in North Westland. The authors found that 97% of the total landsliding and 95% of the sediment yielded by streams derived from clearfelled catchments with vegetation less than 2m in height.

Water Yield

The greater the runoff from an area, the greater the potential for water-induced erosion and sedimentation. The water yield from a catchment will be dependant on precipitation, evaporation from the crop and the soil, transpiration, and changes in soil water storage. The forest crop can influence water yield from a catchment by:

(1) interception and evaporation of rainfall from the canopy

(2) transpiration of soil water.

Changes in catchment water yield tend to be dominated by differences in canopy interception rather than transpiration (Jackson, 1973; Pearce, 1980). The percentage of rainfall that is intercepted increases considerably as trees reach the stage of canopy closure.

Studies of water yields from forested catchments in New Zealand have centred on indigenous forest cover. O'Loughlin et al. (1976) reported that for the undisturbed Maimai Forest catchments, north Westland, approximately 60% of annual precipitation left the catchment as streamflow. Similarly, Pearce et al. (1980) subsequently reported water yields of 49% to 52% of precipitation from the same undisturbed forest catchments. It was found by the same author that harvesting 75% and 100% of two of the subcatchments increased water yields to 86% and 80% of precipitation, respectively. Increases in water yield following harvesting were also seen at the Big Bush study (Pearce et al., 1982).

Pearce (1981) reported that forest removal on the Raukumara Peninsula initiated stream degradation due to increased water yield and peak flow rates. The resultant undercutting of stream banks caused progressive up-slope regrading by slide-flow mechanisms which provided large volumes of sediment to headwater streams.

WAYS TO REDUCE EROSION AND SEDIMENTATION

Two means available to reduce erosion and stream sedimentation are to:

(1) institute remedial actions to reduce potential for erosion and mass failure of earthworks

(2) use appropriate planning to limit the need for remedial actions.

Coker et al. (1990) discussed ways to reduce the potential of erosion or failure of landings in the east and north of the North Island. These included controlling drainage on landings and roads leading towards the landing to reduce the concentration of runoff on to fill slopes, revegetating of landing surfaces and fill, and recovery of fill.

The contribution of vegetation to reducing sediment yields from tracks of different gradients has been investigated by Smith and Fenton (1993). The authors measured sediment yield from isolated tracks on pumice soils with gradients of 4°, 14°, and 23°. The tracks were either left undisturbed, oversown, or oversown and fertilised. For the 14° and 23° tracks oversowing, and oversowing and fertilisation, respectively, showed increasing potential for reducing sediment yield.

Cook and King (1983) described a process that uses sediment barriers, called filter windrows, at the bottom of fill slopes adjacent to streams to prevent sediment entering the waterways. The windrows, which were constructed from slash were built up against cull logs, proved to be both inexpensive and effective.

Certain methods can be used during the construction of roads, tracks and landings to minimise impacts. Endhauling of spoil, benching and compacting fill slopes, and benching cutbanks all help minimise construction impacts on sediment yields.

Tractors have been widely used for construction of forest roads and tracks. More recently, hydraulic excavators or backhoes have been utilised as they often have advantages over the more traditional bulldozers, particularly on environmentally sensitive sites (Robinson, 1992). Balcom (1986) discussed four techniques that utilise hydraulic excavators for forest road construction in sensitive terrain. The four techniques were:

(1) pull-back and end-haul sidecast material from existing roads and landings

(2) removal of brush from the road prism

(3) full bench construction with end-haul

(4) closing out entire roads by pulling back as much of the sidecast material as the resulting grade width can hold.

The New Zealand Forest Code of Practice provides practical alternatives for mitigating the impacts of road construction on the environment (LIRO, 1993).

The use of riparian buffer strips to mitigate the impacts of up-slope sediment mobilisation has been reviewed by Hicks and Howard-Williams (1990), Gilliam et al. (1992), and Murphy (1992). These reviews highlight that little research has been performed in New Zealand to address the role of riparian buffers to reduce forestry impacts on waterways.

In a planning exercise carried out by Visser and McConchie (1993), the impacts of fixed width riparian buffer strips on harvest plans were evaluated by assessing roading and landing requirements, and hauling distances. The authors found that the area required for buffer strips was related to the stream density.

Graynoth (1979) reported on the sediment yield from three subcatchments in the Nelson region, two of which were clearfelled. One logged subcatchment had a 30m wide riparian buffer strip. The unlogged catchment and the one with the buffer had similar yields, which were far below that of the logged catchment without the riparian buffer strips.

Pearce and Griffiths (1980) reported that suspended sediment loads resulting from selective logging in Okarito Forest were not affected by the presence of a 20 to 50 m wide riparian buffer zone. As the authors pointed out the sediment losses from sites with no buffer were exceptionally low (< 1ppm) making assessment of the buffer effectiveness inappropriate.

Riparian buffers also prevent logging debris such as slash from entering the waterway system. This can effect the patterns of sedimentation and hence the impacts that it may have. Logging debris can create debris dams which will trap sediment in stream. Eventually, as they decay, these dams give way, mobilising large amounts of sediment (Hicks and Harmsworth, 1989).

SUMMARY

Review of New Zealand literature pertaining to the impacts of forestry operations and management on sedimentation has identified the major sediment sources, mobilising processes, and subsequent environmental impacts. The relationships between processes and impacts are shown in Figure 5, and summarised below:

- two major groups of sediment sources are:

  (1) earthworks associated with roads, tracks and landings

  (2) planted or harvested slopes

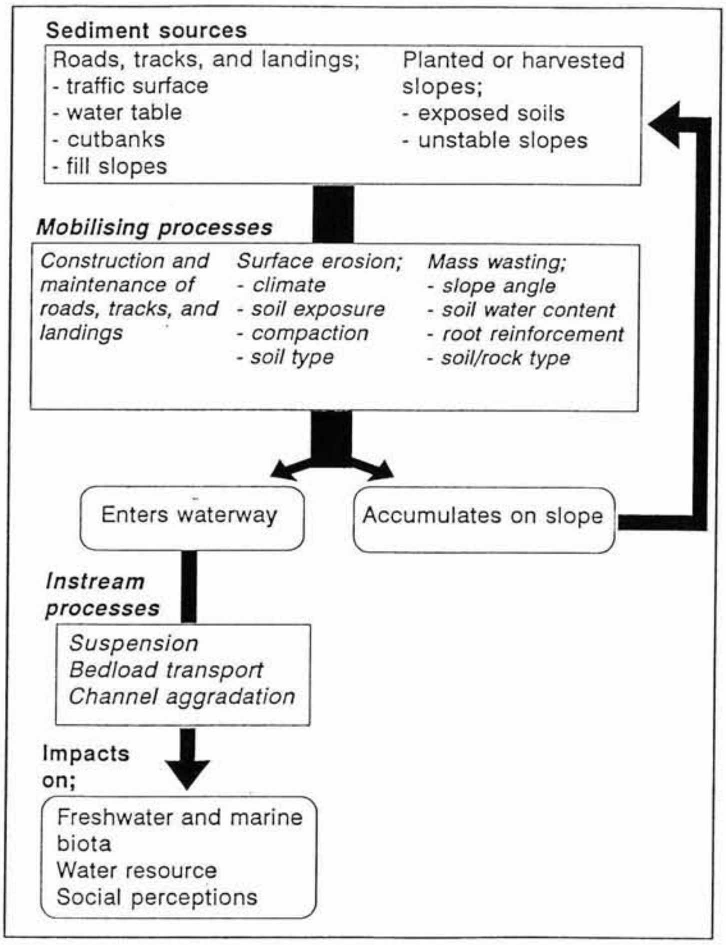

Figure 5 - Summary diagram showing relationships between sedimentation processes and impacts

- specific components of earthworks which have been identified as sediment sources are the traffic surfaces, water tables, cutbanks, and fill slopes

- the processes which result in sediment mobilisation are mechanical transportation during earthworks construction and maintenance, surface erosion, and mass wasting or failure

- mobilised sediment may either accumulate elsewhere on slope or enter the waterway. This will depend on the mobilising processes, and on-site factors such as slope and proximity to the waterway

- material which does not immediately enter the waterway is likely to do so at a later time, depending on the mobilising processes

- sediment which enters a waterway may remain in situ, or be transported downstream by suspension or bedload transport. These processes may occur over several years following the initial mobilisation of up-slope materials

- sedimentation can impact freshwater and marine biota, utilisation of the water resource, and social perceptions of the waterway either locally or regionally, depending on the extent of the impact and time-frame of concern.

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